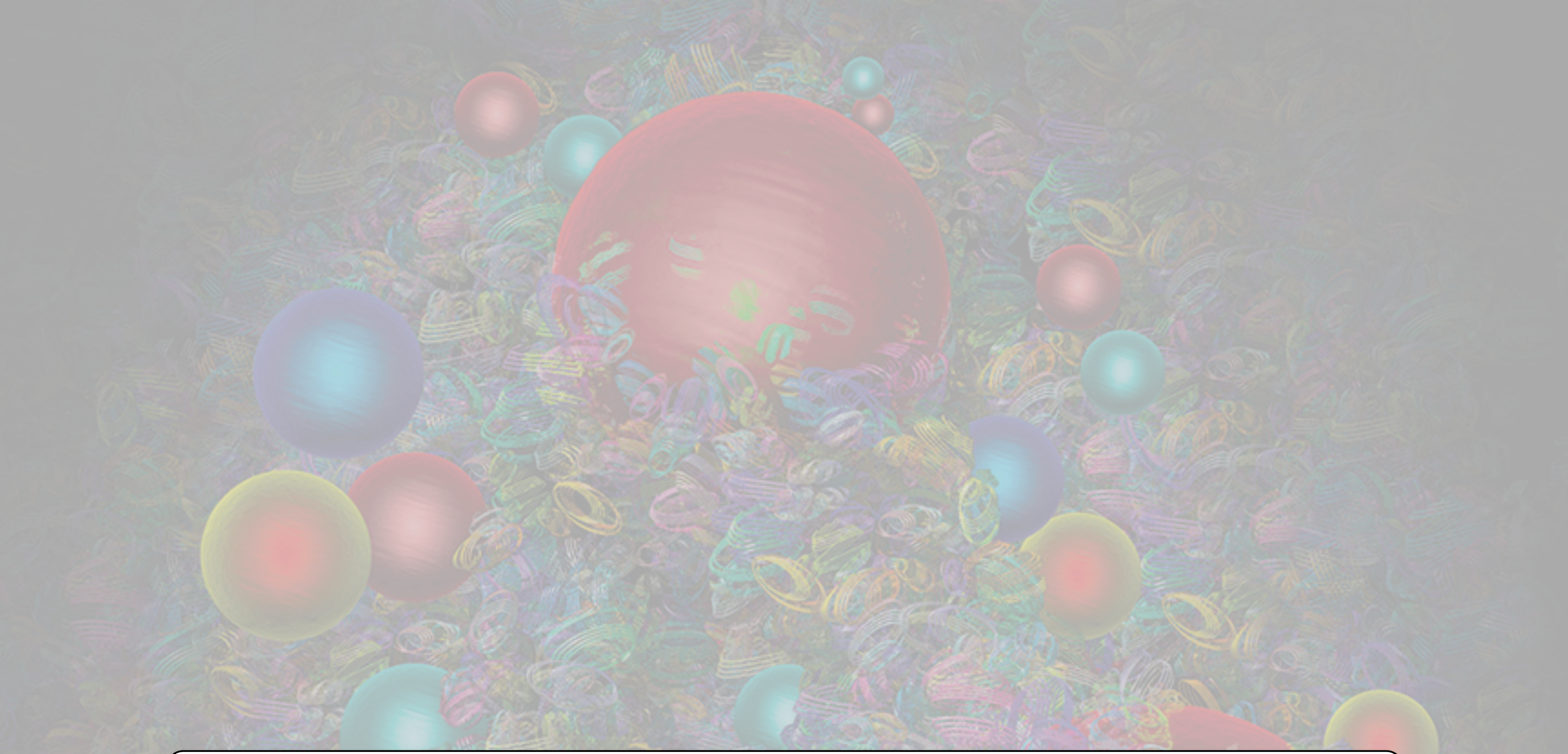
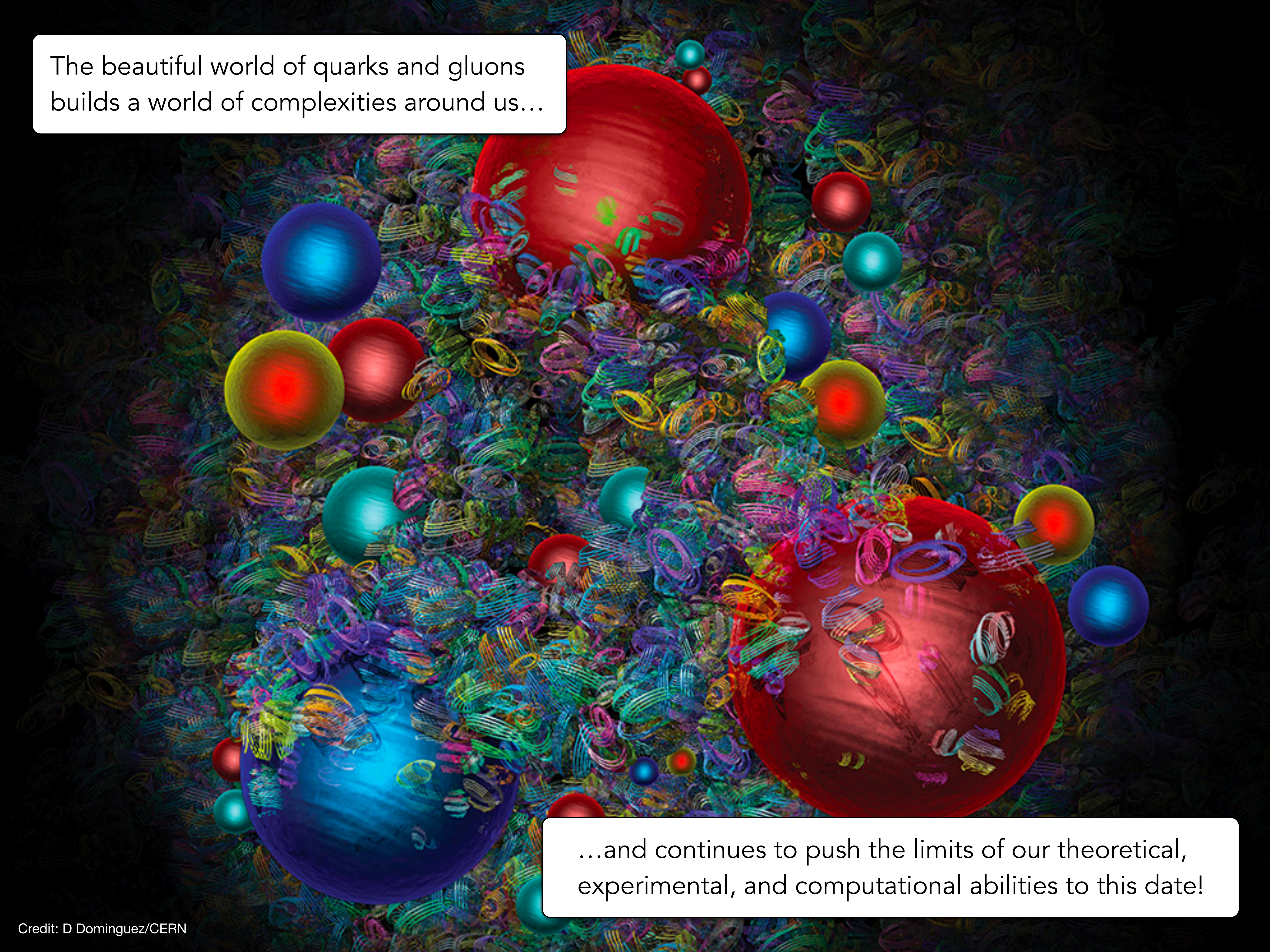


[Remote] Talk @ the UK Annual Theory Meeting
Durham University, UK
Dec 13-15, 2022

Quantum Simulations for Field Theories

Zohreh Davoudi
University of Maryland, College Park

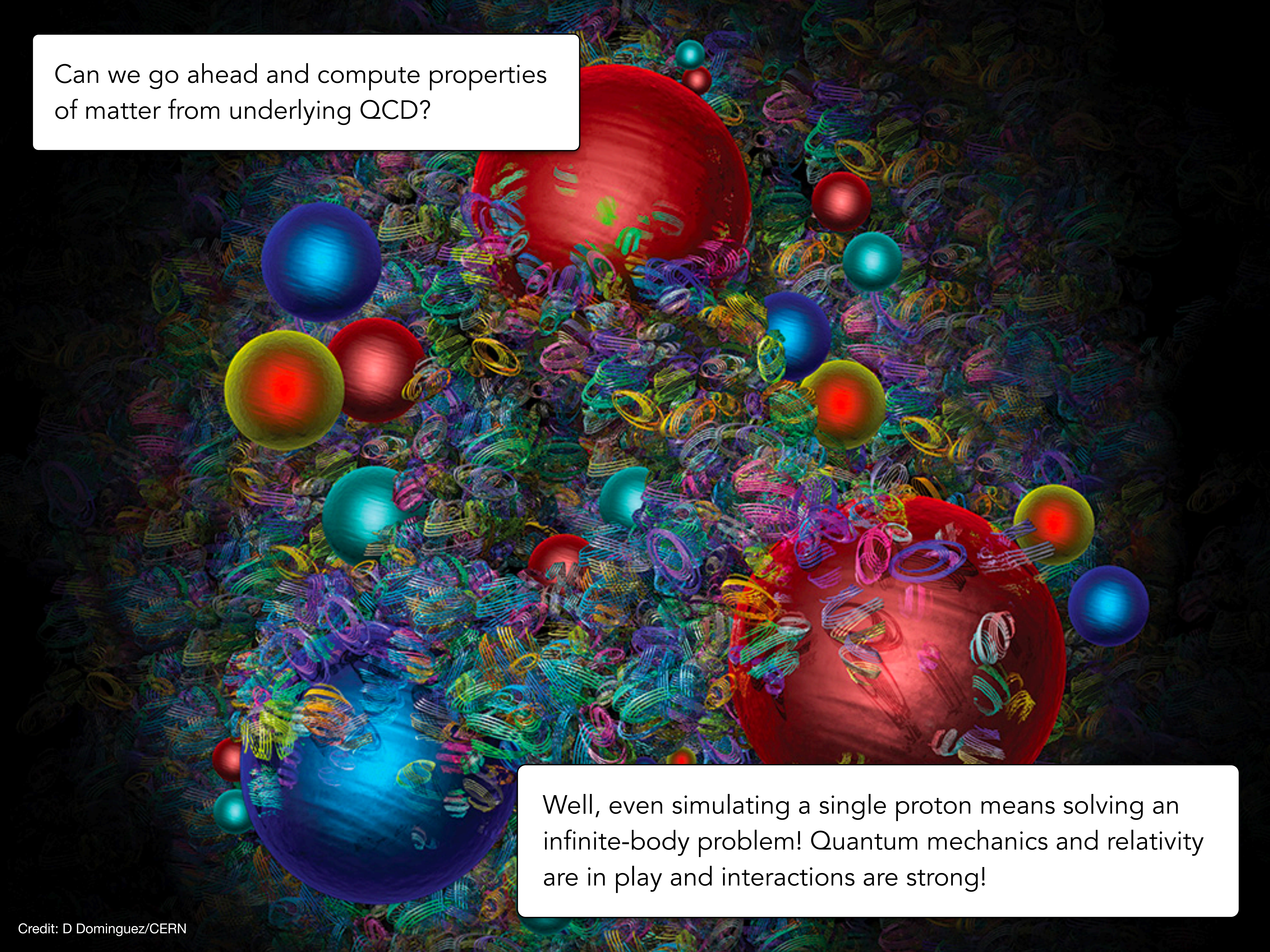


The beautiful world of quarks and gluons builds a world of complexities around us…

…and continues to push the limits of our theoretical, experimental, and computational abilities to this date!

Credit: D Dominguez/CERN

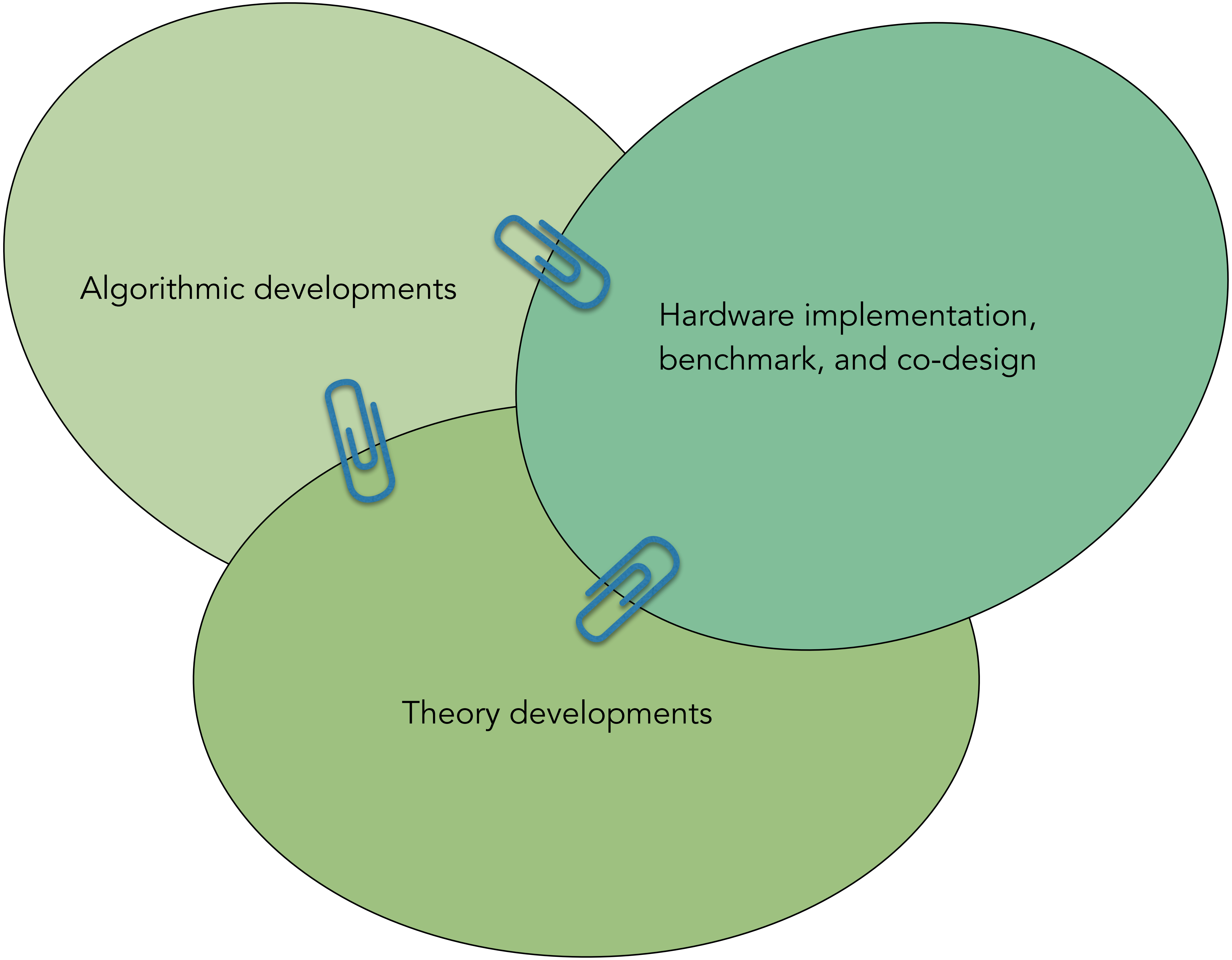
Can we go ahead and compute properties of matter from underlying QCD?



Well, even simulating a single proton means solving an infinite-body problem! Quantum mechanics and relativity are in play and interactions are strong!

Credit: D Dominguez/CERN

LATTICE QCD: A MULTI-PRONG PROGRAM THAT SIMULATES QCD NON-PERTURBATIVELY



Algorithmic developments

Hardware implementation, benchmark, and co-design

Theory developments

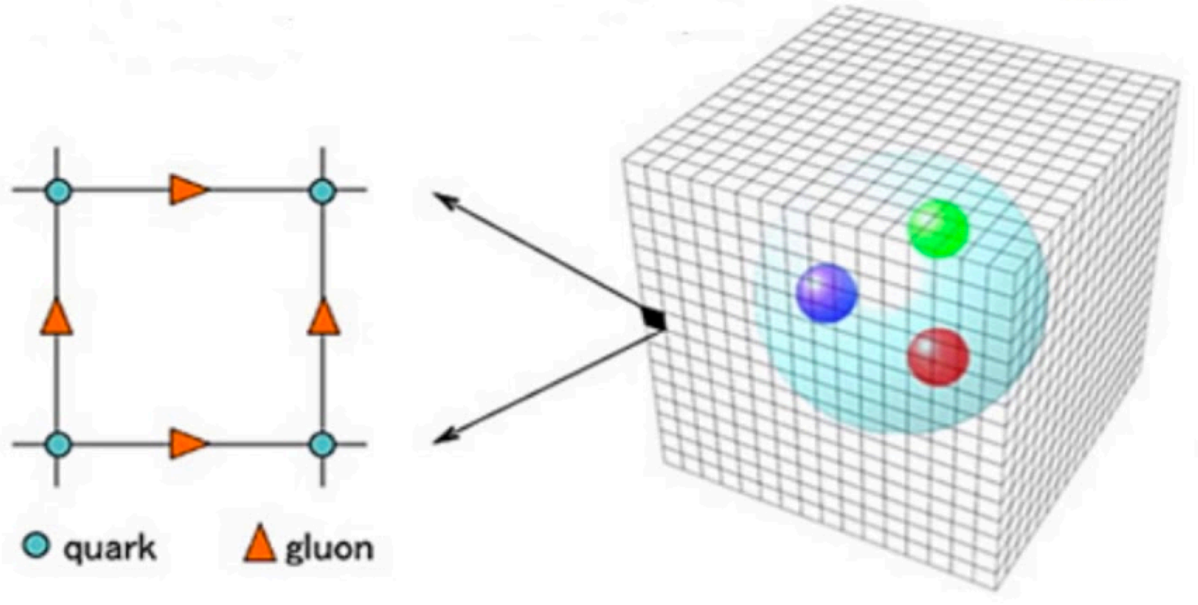
Theory developments

How to define QCD/QED on a finite grid?

How to preserve/recover symmetries,
e.g., gauge symmetry, chiral symmetry,
rotational symmetry.

How to take infinite-volume and continuum limits? How to quantify systematics?

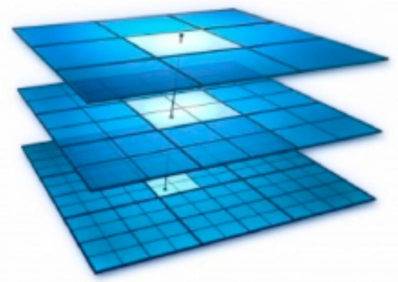
How to obtain scattering amplitudes and decay rates?



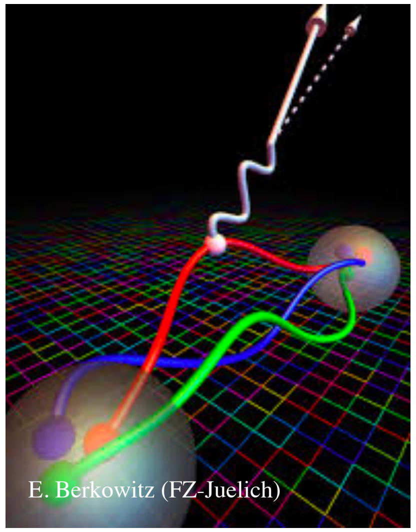
Theory developments

Algorithmic developments

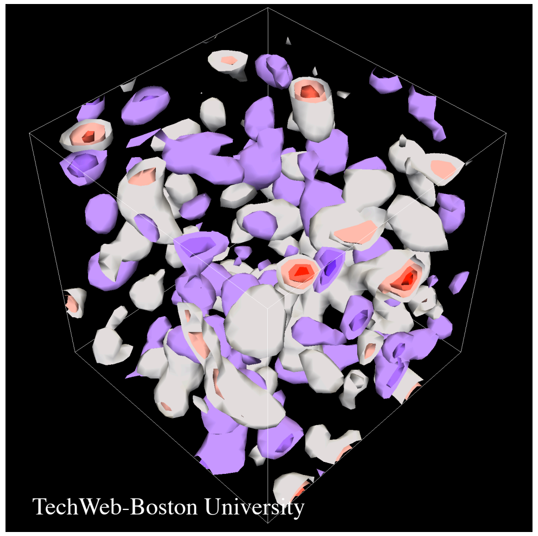
Algorithmic developments



e.g. How to solve **optimally** ?
A.x=b



E. Berkowitz (FZ-Juelich)



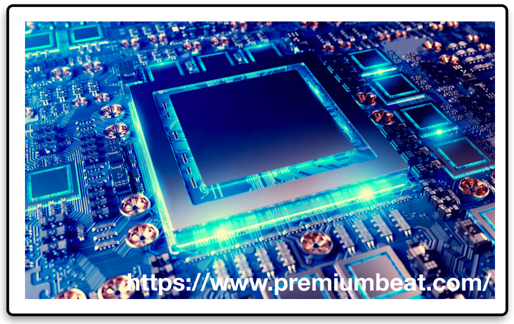
TechWeb-Boston University

How to importance sample vacuum gauge configurations?

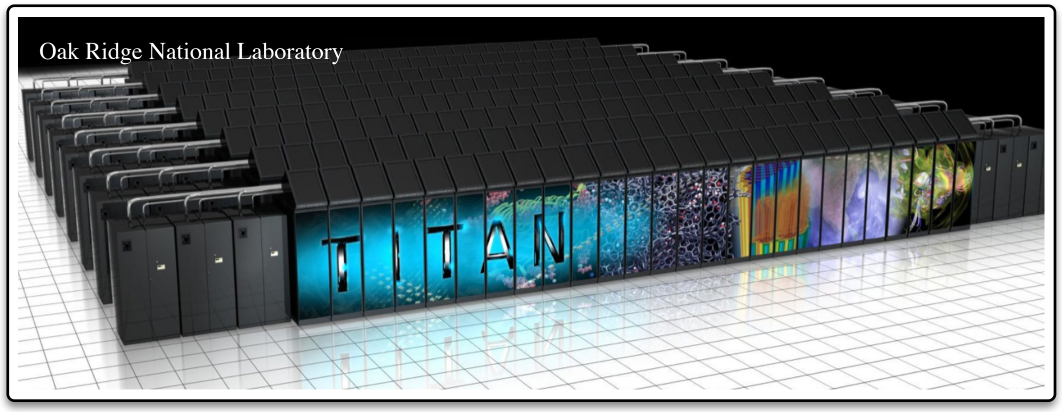
How to evaluate quark propagators (invert large matrices)?

How to contract quarks and form correlation functions efficiently?

Implementation, benchmark, and co-design


https://www.premiumbeat.com/


equinox.com


Oak Ridge National Laboratory

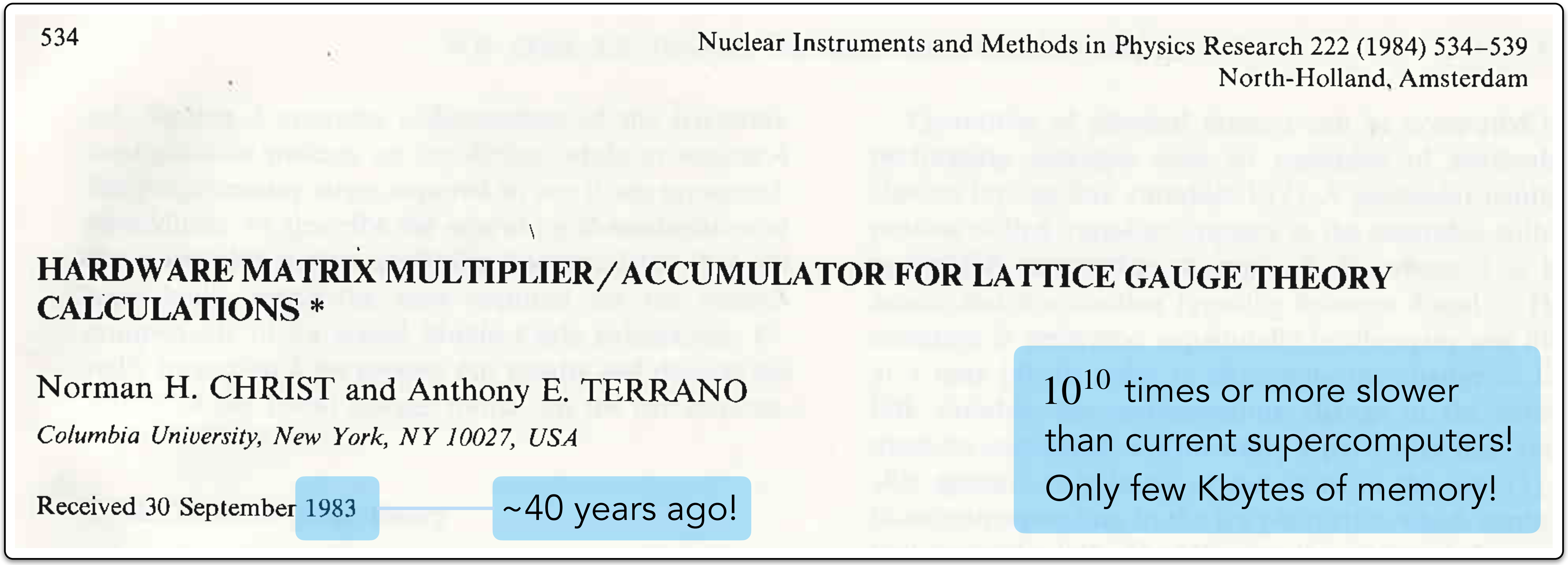
Implementation, benchmark, and co-design

Which tasks can be parallelized and which tasks are done in series?

What are the memory requirements and what kind of node connectivity is required?

Can we take advantage of GPUs? Which parts of the computations are more suitable for given architecture?

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 *

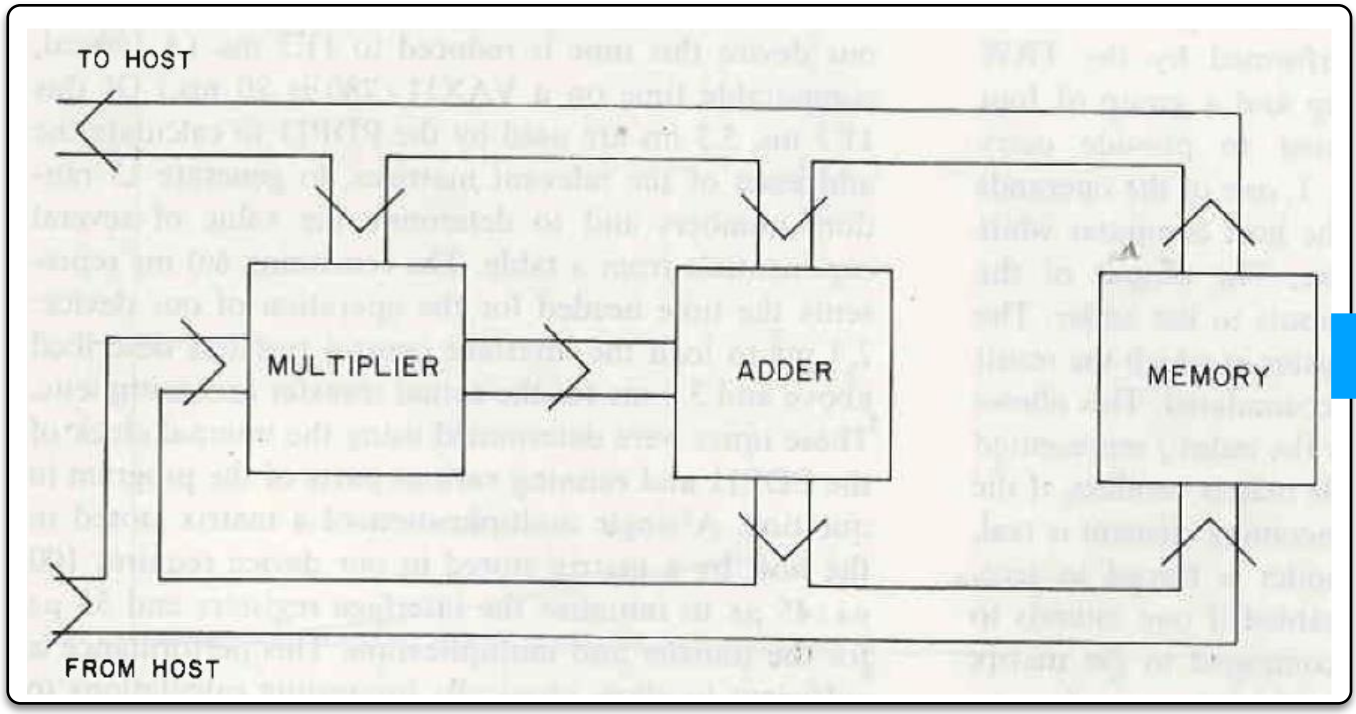
Norman H. CHRIST and Anthony E. TERRANO

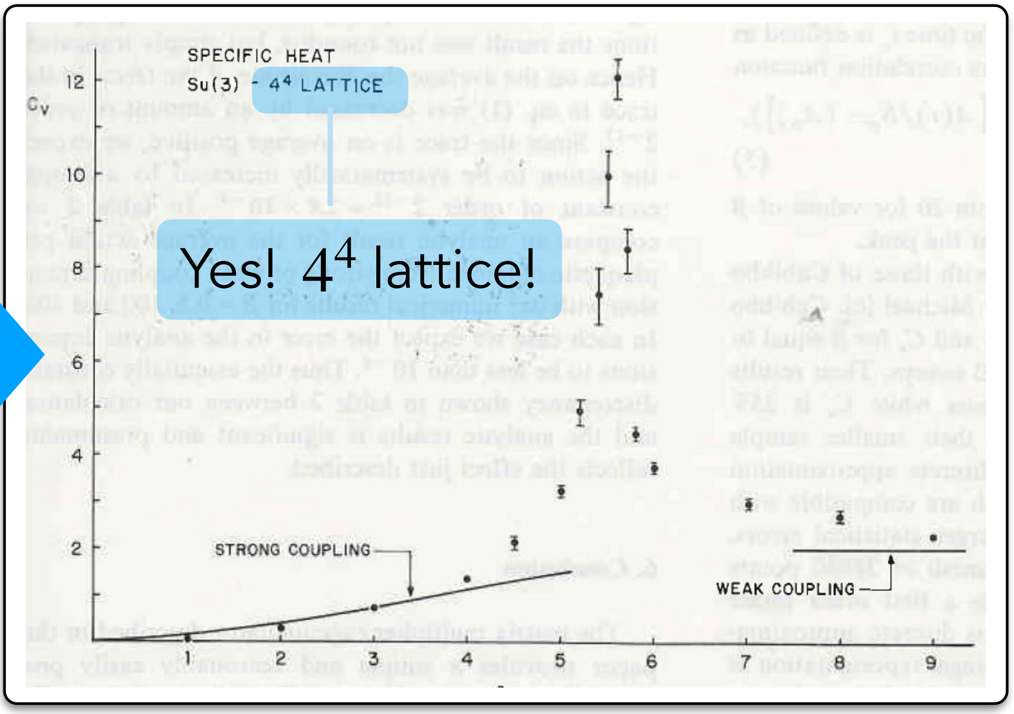
Columbia University, New York, NY 10027, USA

Received 30 September 1983

~40 years ago!

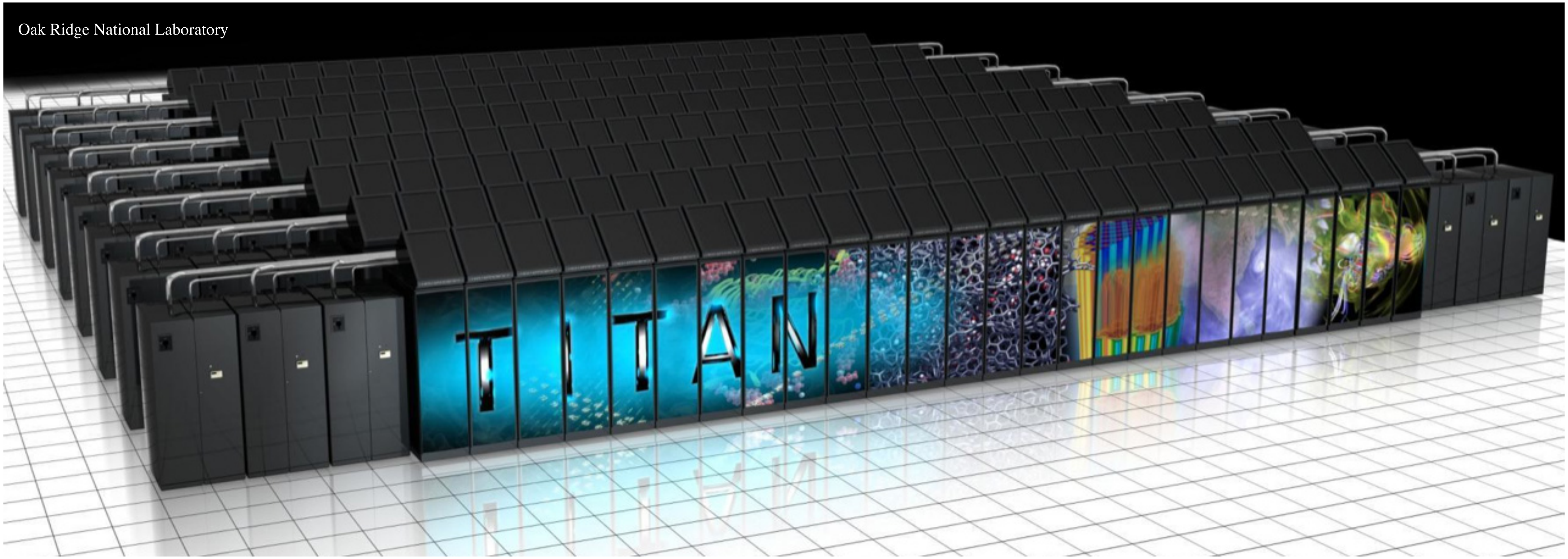
10^{10} times or more slower than current supercomputers!
Only few Kbytes of memory!





Yes! 4^4 lattice!

PUTTING ALL THESE HEROIC THEORY, ALGORITHM, AND CO-DESIGN EFFORTS TO WORK AND HAVING ACCESS TO HUNDREDS OF MILLION CPU HOURS ON THE LARGEST SUPERCOMPUTERS IN THE WORLD…

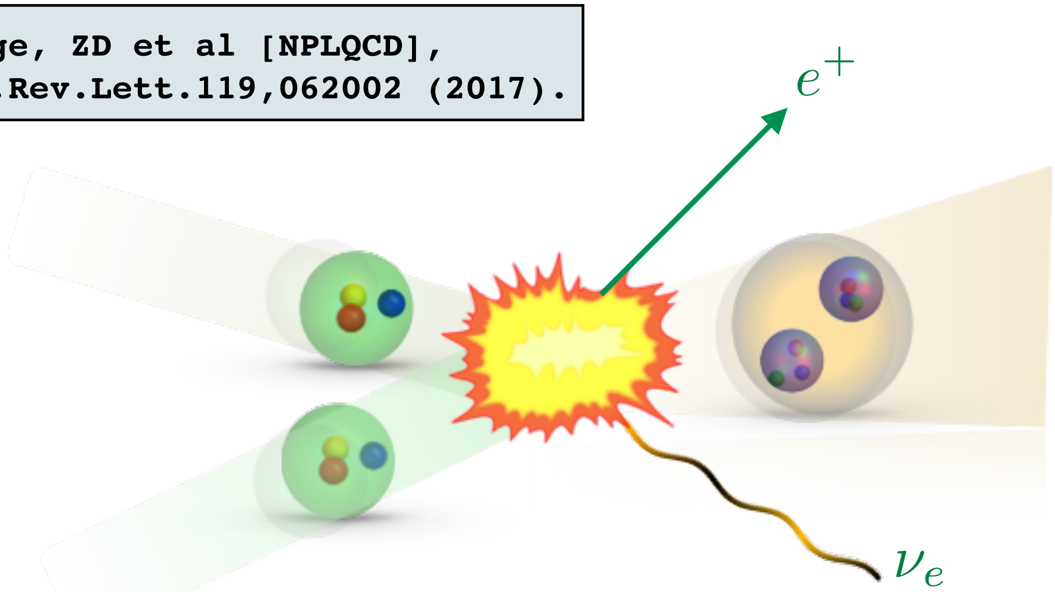


Titan supercomputer, Oak Ridge National Laboratory, USA

HAS LED TO TENS OF SUCCESS EXAMPLES
BUT LET ME TELL YOU ABOUT ONE…

pp fusion cross section

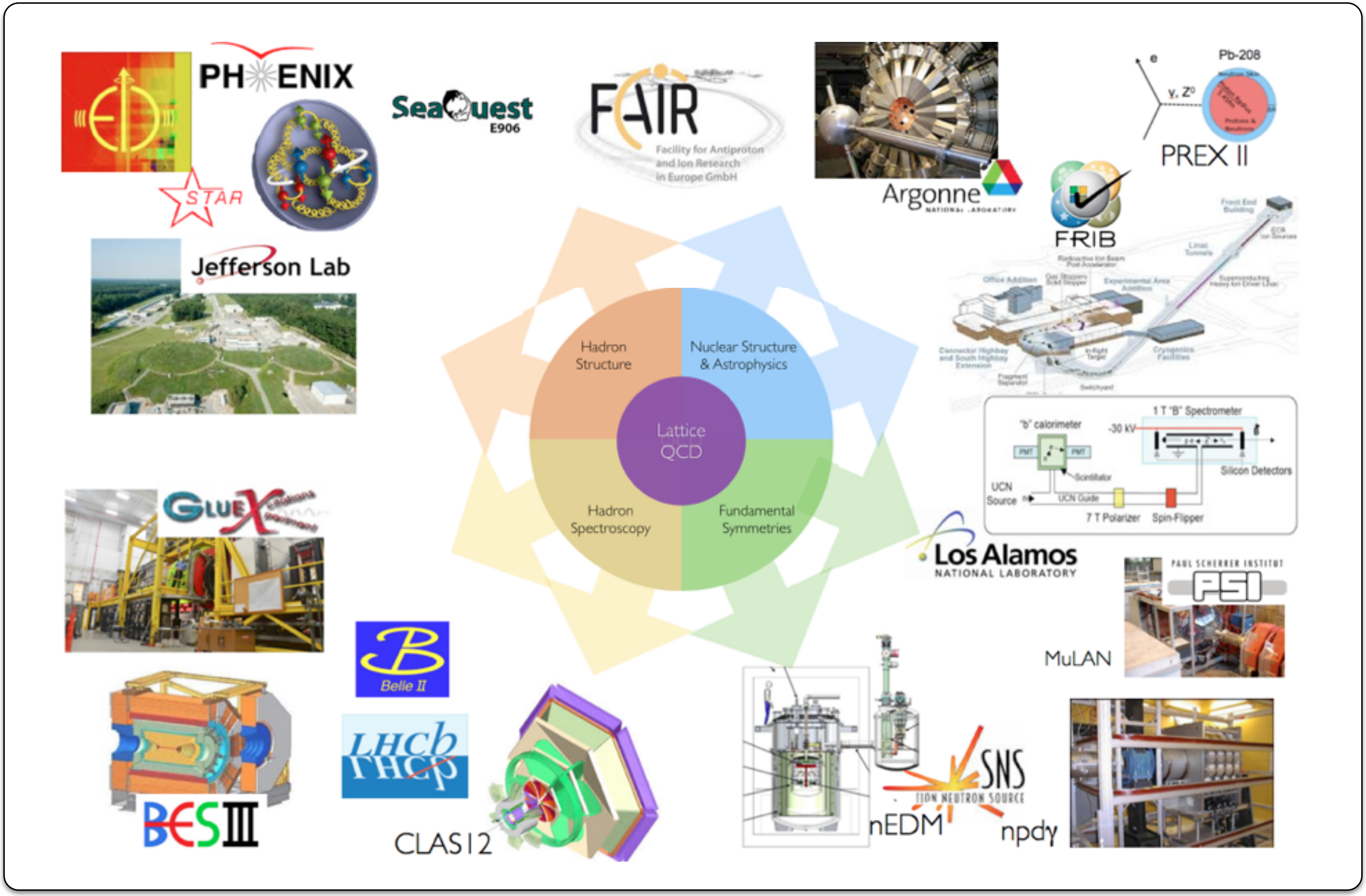
`Savage, ZD et al [NPLQCD],`
`Phys.Rev.Lett.119,062002 (2017).`



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

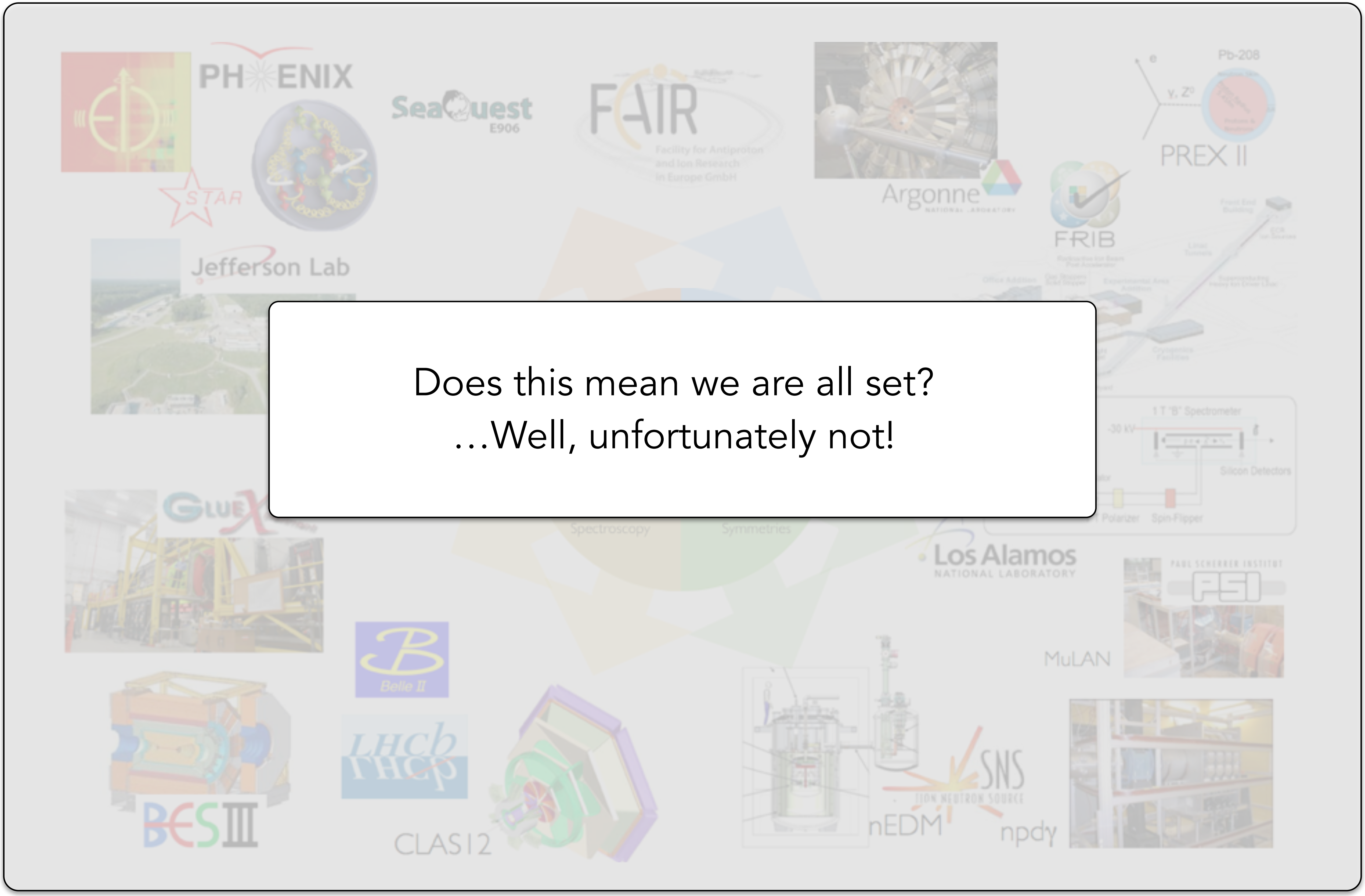
`ZD, Detmold, Orginos, Parreño, Savage,`
`Shanahan, Wagman, *Phys.Rept.*900,1-74 (2021).`

LATTICE QCD IS SUPPORTING A MULTI-BILLION DOLLAR EXPERIMENTAL PROGRAM!



Slide content courtesy of Martin Savage.

LATTICE QCD IS SUPPORTING A MULTI-BILLION DOLLAR EXPERIMENTAL PROGRAM!



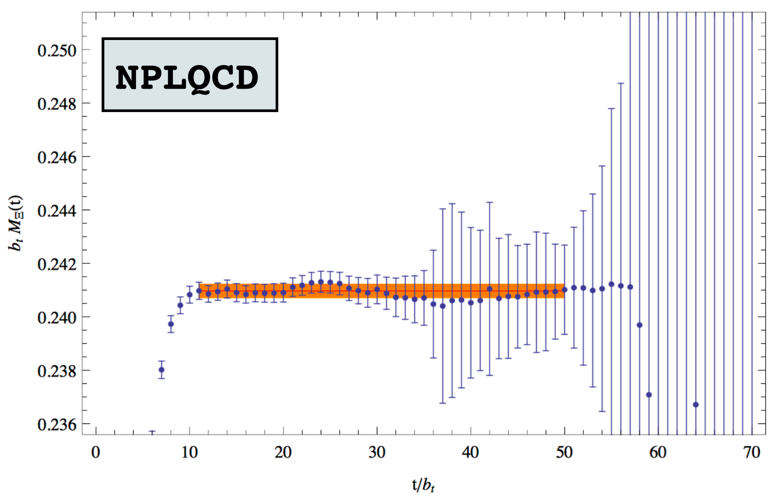
Does this mean we are all set?

…Well, unfortunately not!

Slide content courtesy of Martin Savage.

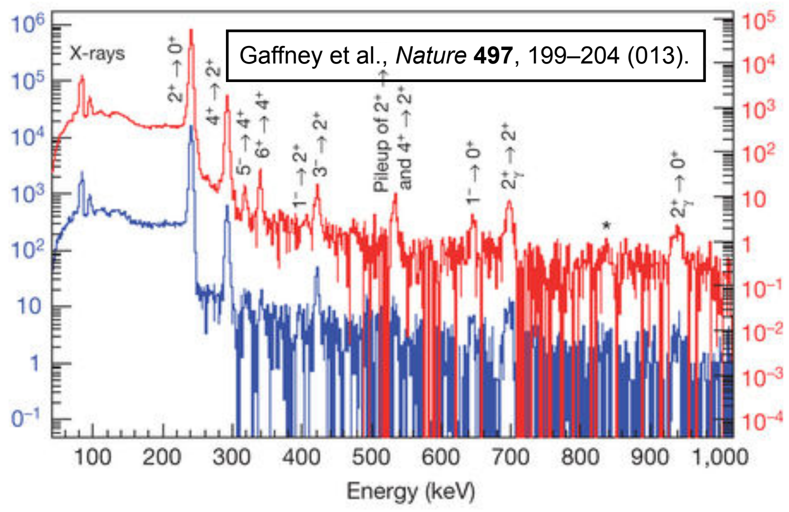
THREE FEATURES MAKE LATTICE QCD CALCULATIONS OF NUCLEI HARD:

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



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

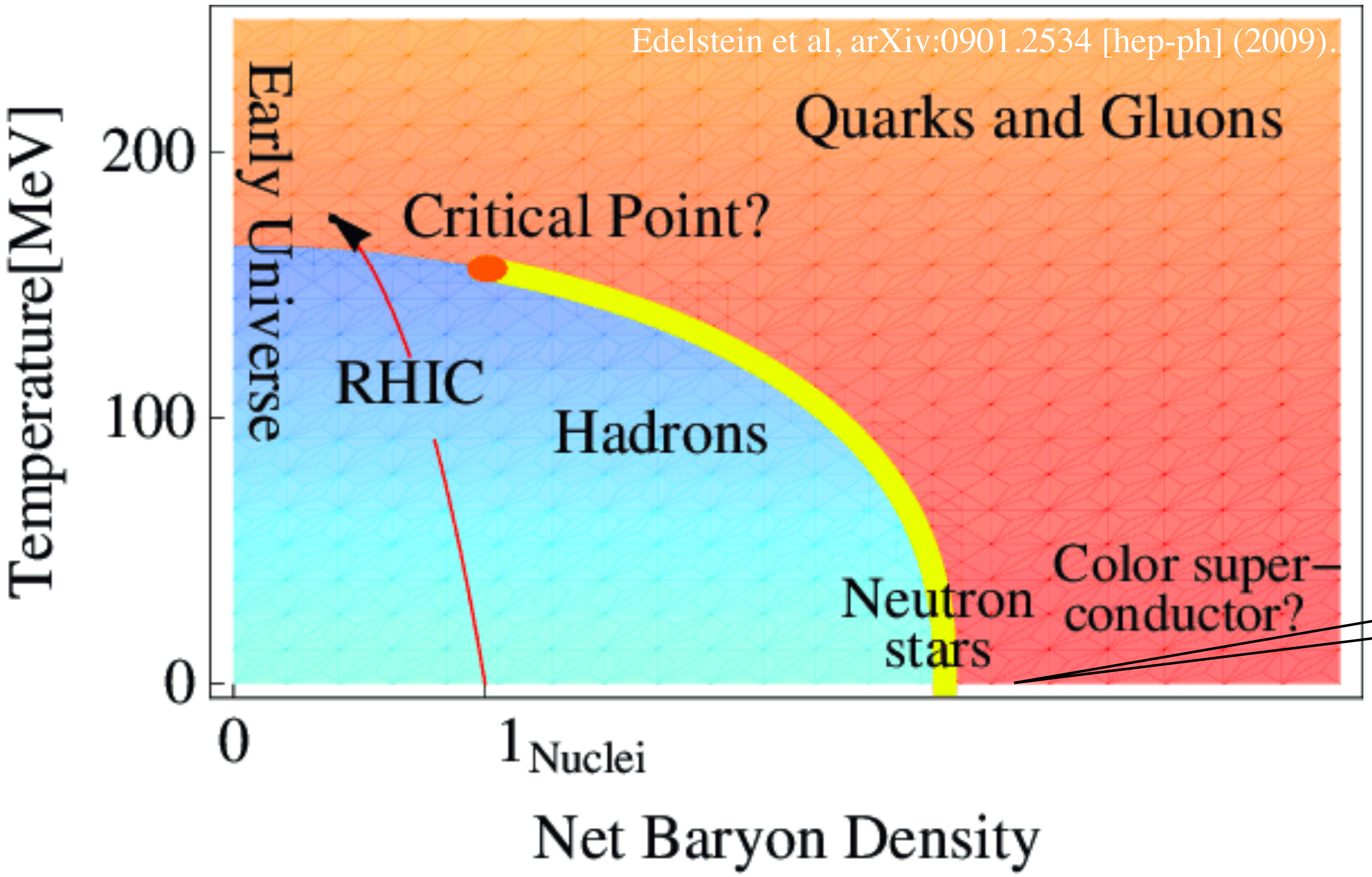
iii) Excitation energies of nuclei are much smaller than the QCD scale.

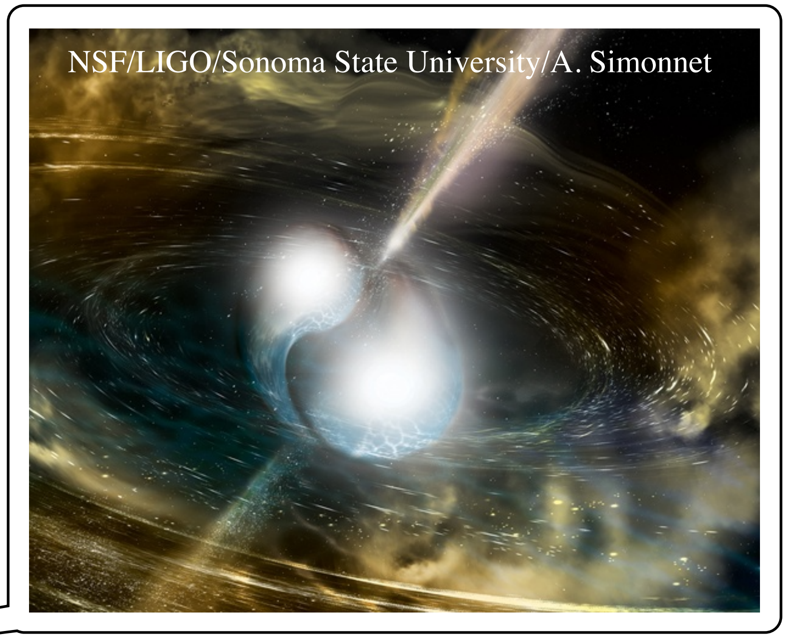


Gaffney et al., *Nature* **497**, 199–204 (013).

ADDITIONALLY THE SIGN PROBLEM FORBIDS:

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





Path integral formulation:

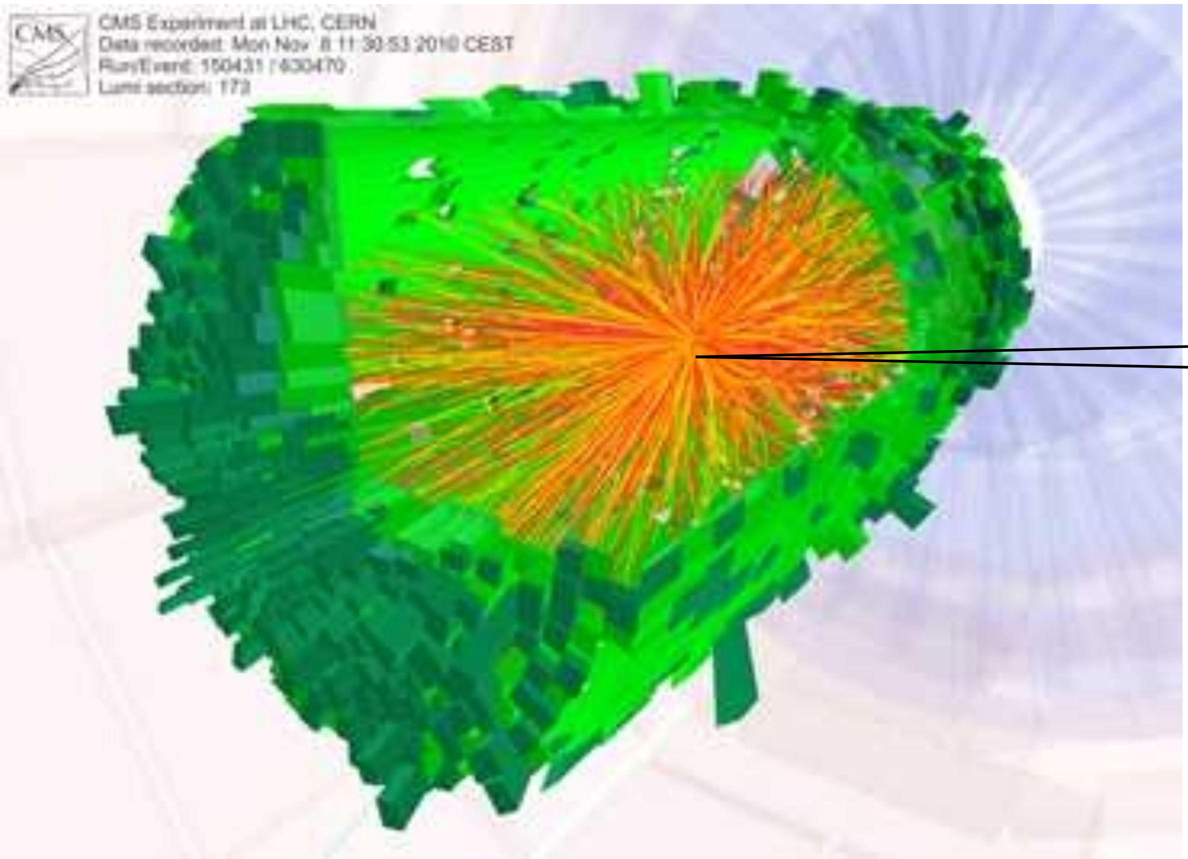
$$\boxed{e^{-S[U,q,\bar{q}]}}$$

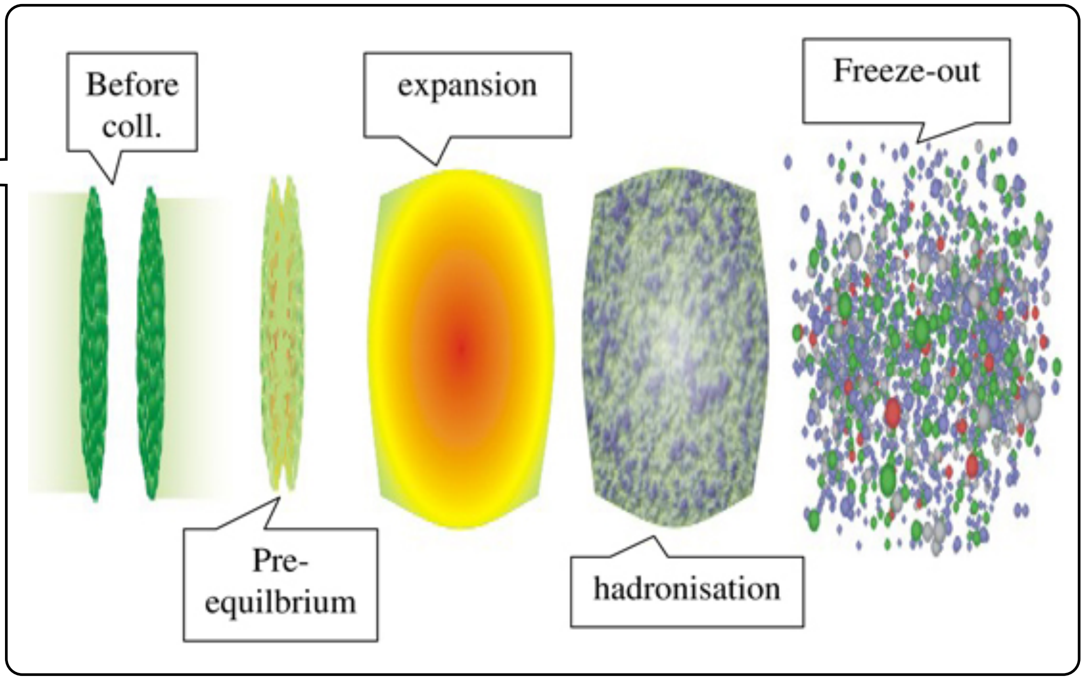
with a complex action:

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

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.

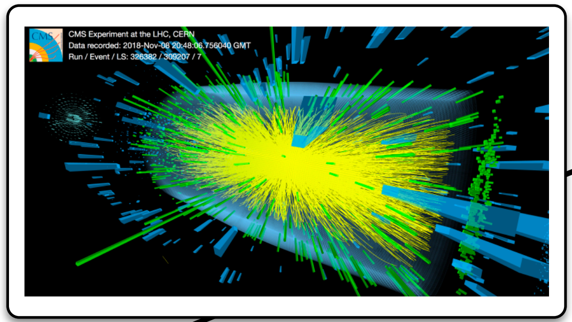
Path integral formulation:

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

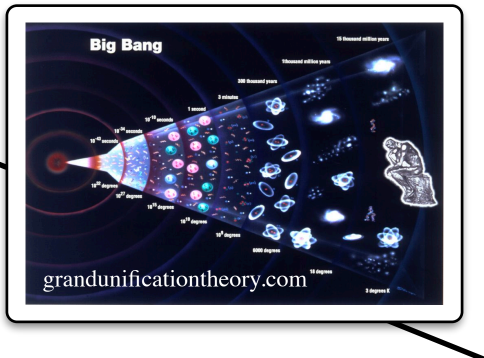
Hamiltonian evolution:

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

PLUS MANY INTRACTABLE QUESTIONS IN HIGH ENERGY PHYSICS AS WELL…



Collider phenomenology



grandunificationtheory.com

Cosmology and early universe

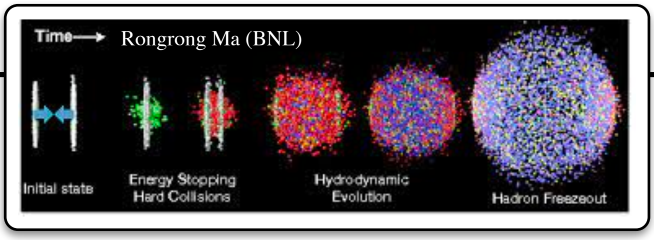
NASA/CXC/U.Texas

Neutrino (astro)physics

Quantum gravity

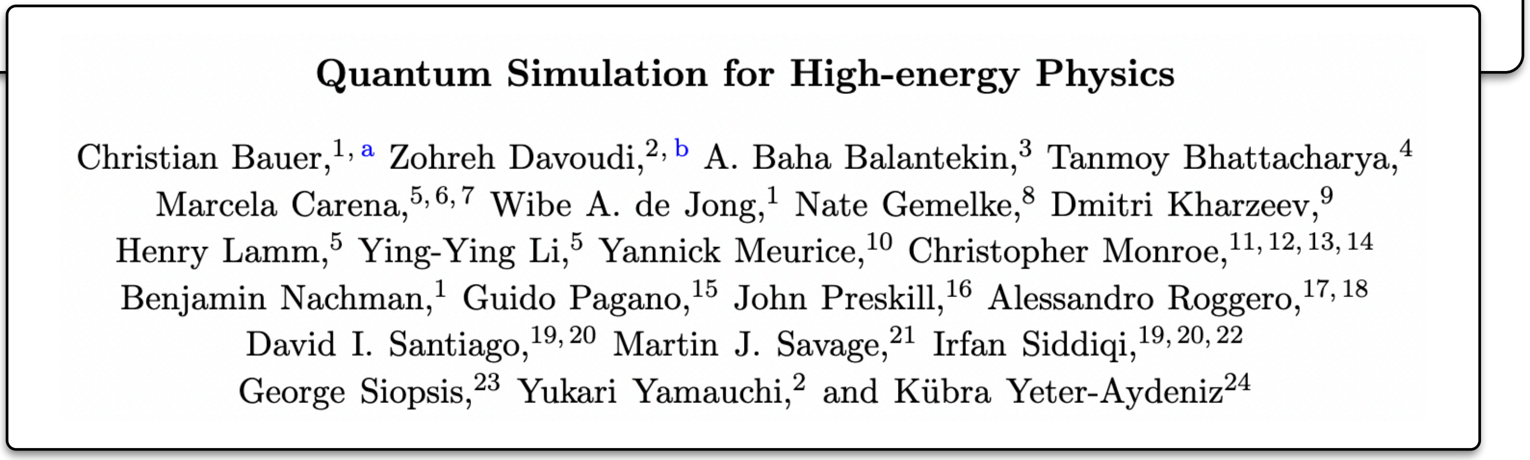
vchal/Shutterstock.com

Matter in and out of equilibrium



Rongrong Ma (BNL)

Bauer, ZD, et al,
arXiv:2204.03381 [quant-ph].



Quantum Simulation for High-energy Physics

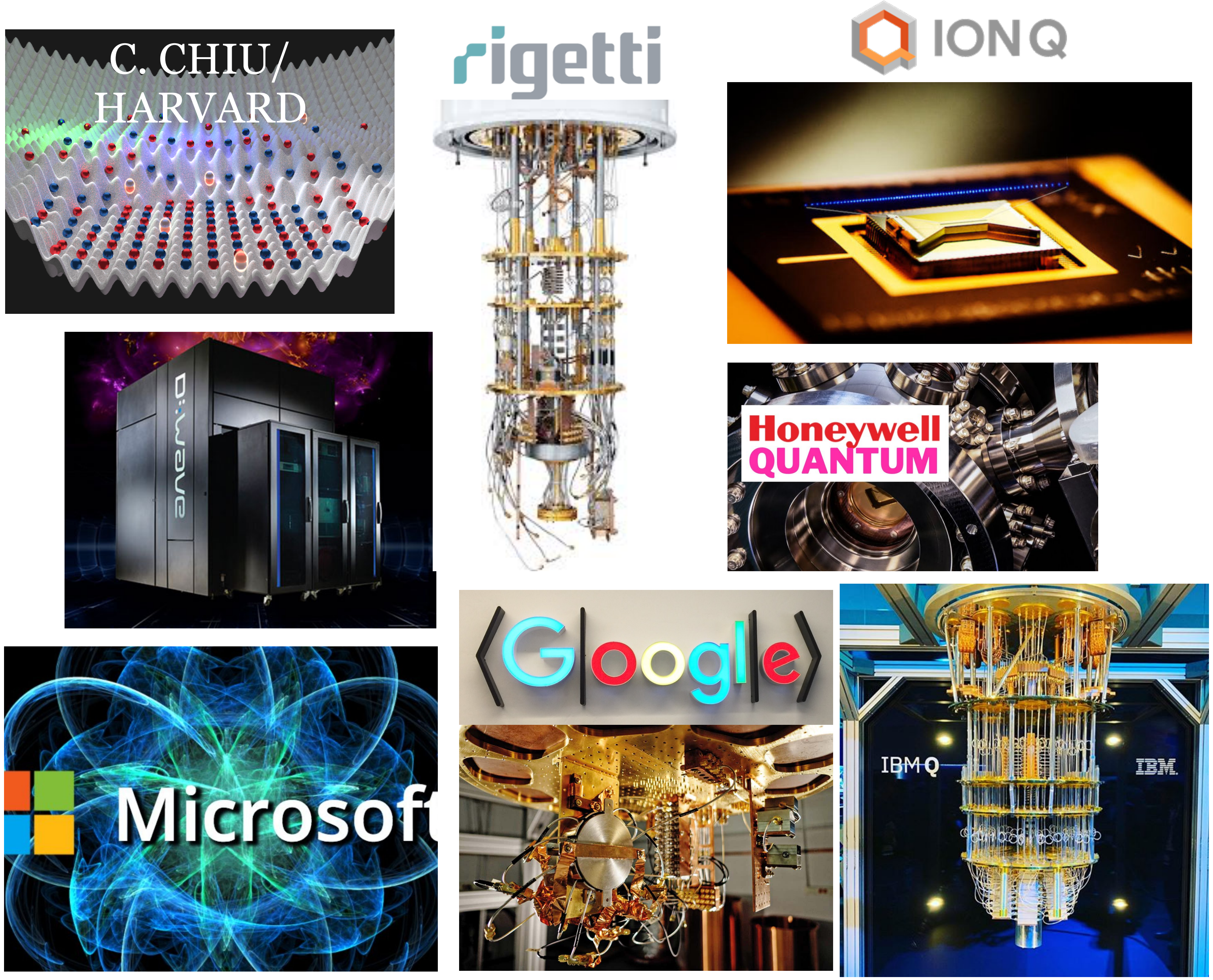
Christian Bauer,[1, a] Zohreh Davoudi,[2, b] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4]
Marcela Carena,[5, 6, 7] Wibe A. de Jong,[1] Nate Gemelke,[8] Dmitri Kharzeev,[9]
Henry Lamm,[5] Ying-Ying Li,[5] Yannick Meurice,[10] Christopher Monroe,[11, 12, 13, 14]
Benjamin Nachman,[1] Guido Pagano,[15] John Preskill,[16] Alessandro Roggero,[17, 18]
David I. Santiago,[19, 20] Martin J. Savage,[21] Irfan Siddiqi,[19, 20, 22]
George Siopsis,[23] Yukari Yamauchi,[2] and Kübra Yeter-Aydeniz[24]

An opportunity to explore new paradigms and new technologies:
Turning to quantum simulation

https://www.pechakucha.com/

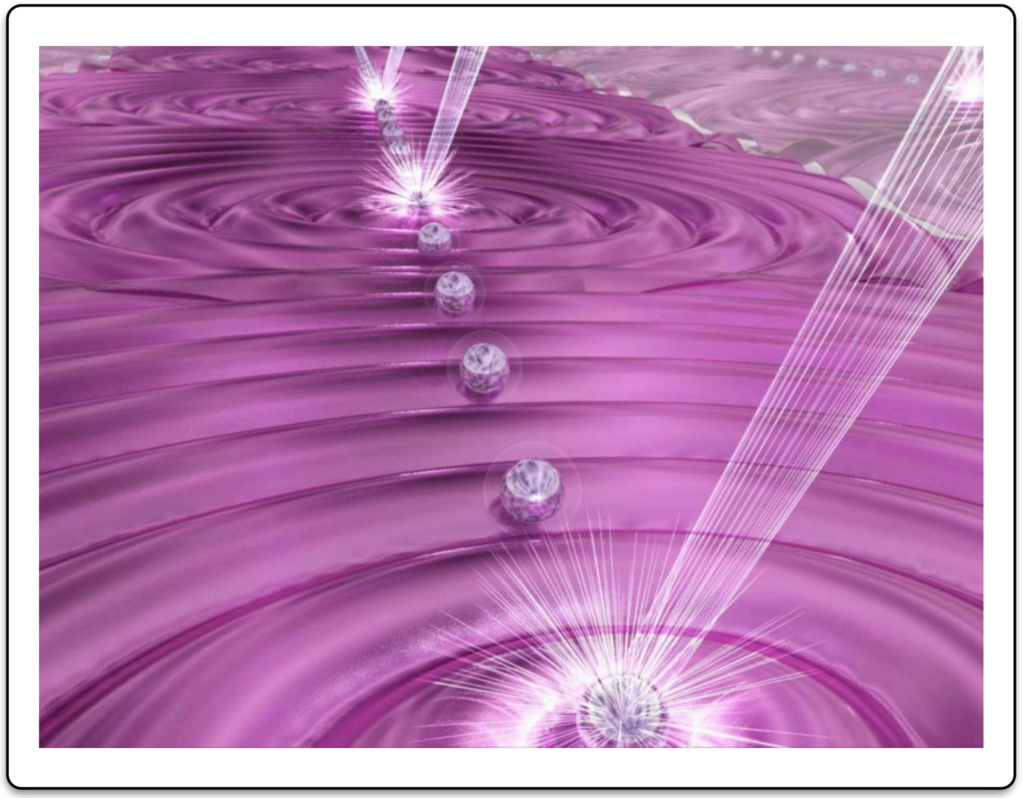
A RANGE OF QUANTUM SIMULATORS WITH VARING CAPACITY AND CAPABILITY IS AVAILABLE!

- 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 systems (cavity quantum electrodynamics)



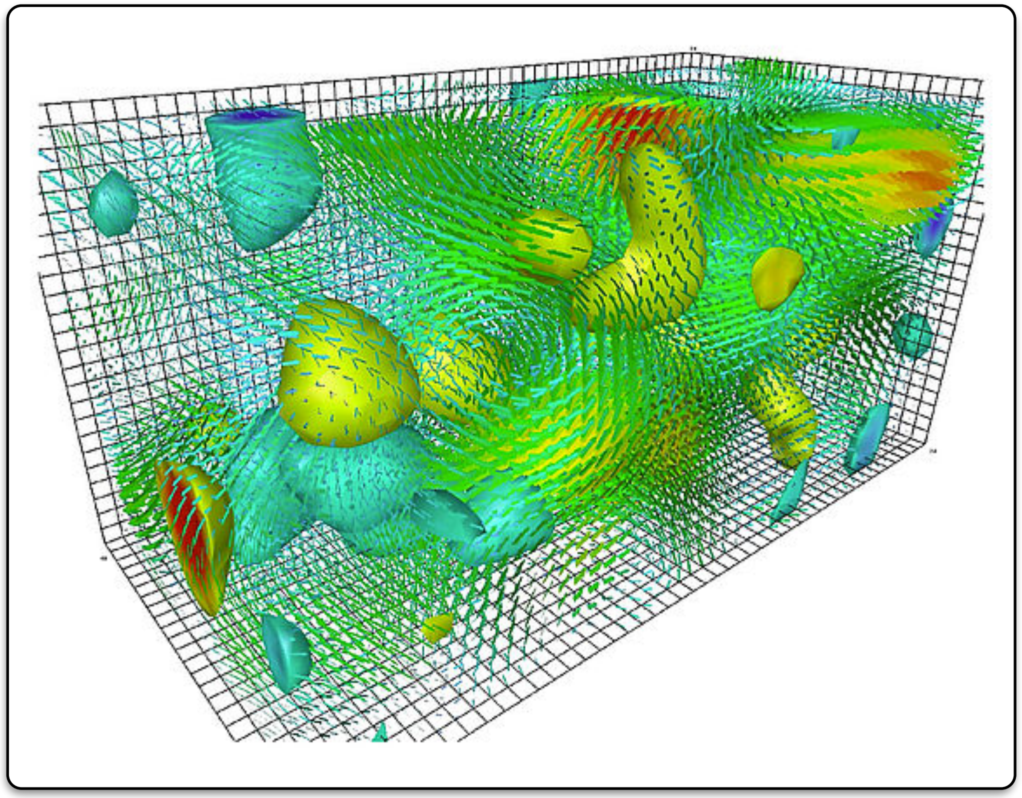
QUANTUM SIMULATION OF QCD?

A controlled quantum system



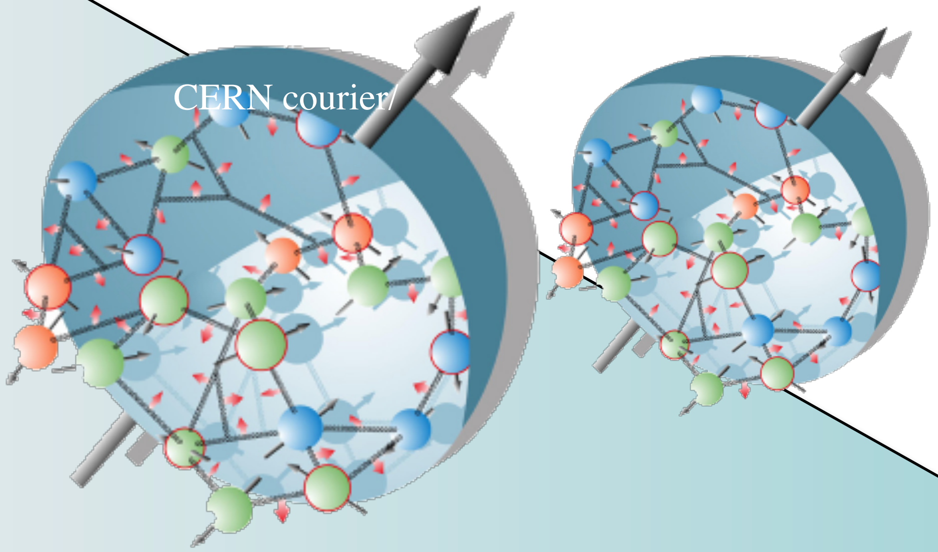
CREDIT: EMILY EDWARDS, UNIVERSITY OF MARYLAND

Strong-interaction physics



COPY RIGHT: UNIVERSITY OF ADELAIDE

DIFFERENT FROM QUANTUM-CHEMISTRY SIMULATIONS

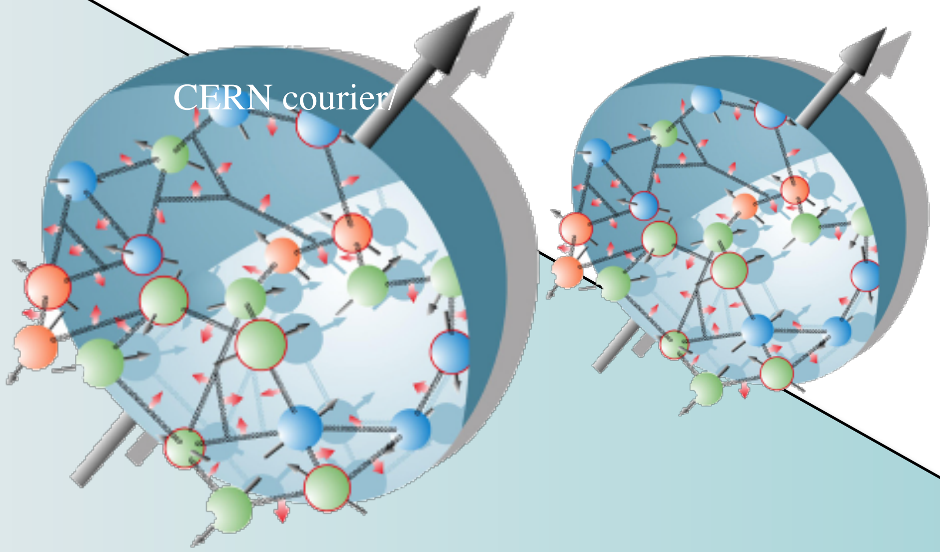


CERN courier/

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.

DIFFERENT FROM QUANTUM-CHEMISTRY SIMULATIONS



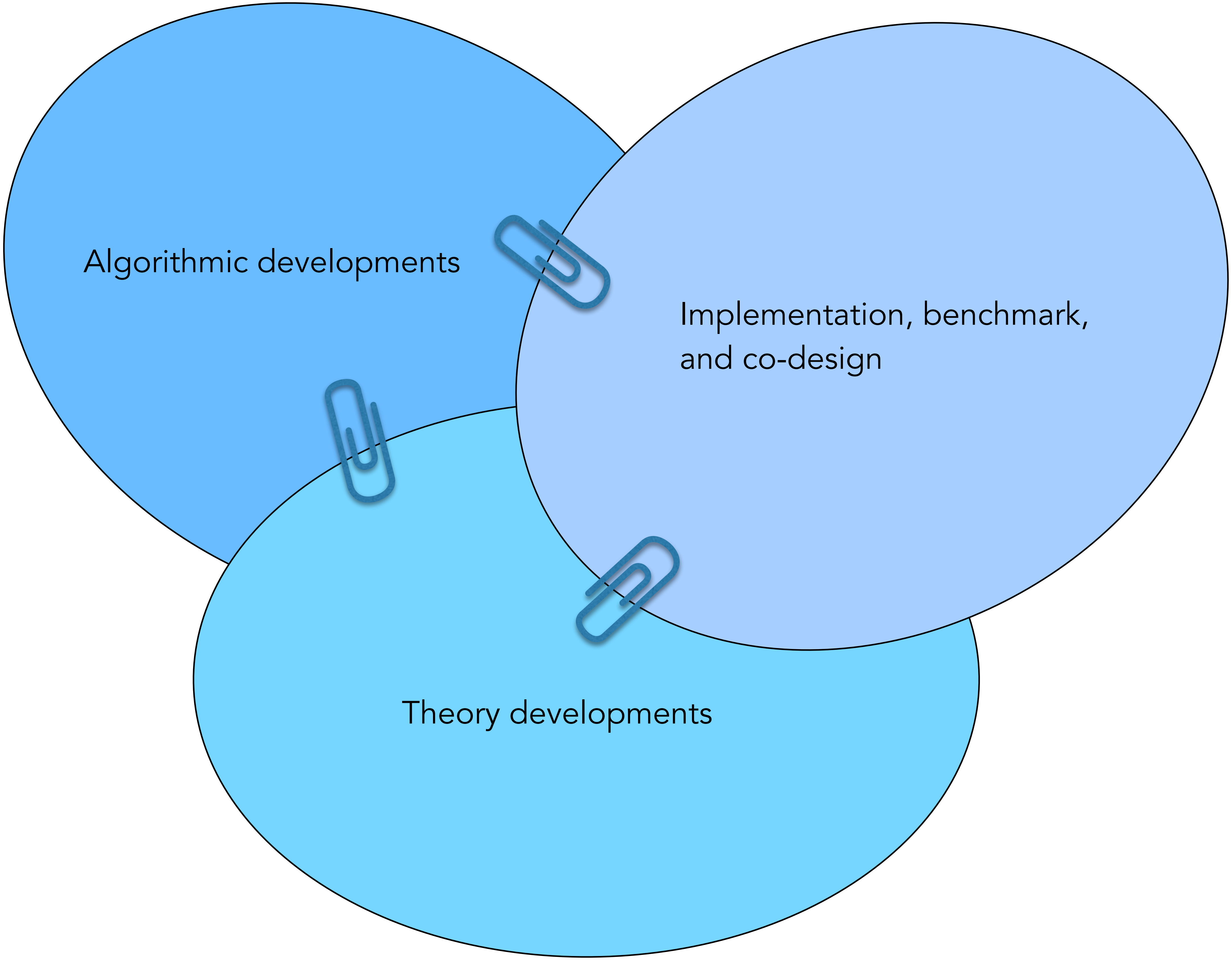
CERN courier/

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



Algorithmic developments

Implementation, benchmark, and co-design

Theory developments

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

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

Hamiltonian formalism maybe more natural than the path integral formalism for quantum simulation/computation:

Kogut and Susskind formulation:

$$H_{\mathrm{QCD}} = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_{\langle xy\rangle}\left(L_{xy}^2 + R_{xy}^2\right) - \frac{1}{4g^2}\sum_{\square}\mathrm{Tr}\left(U_\square + U_\square^\dagger\right).$$

Fermion hopping term

Fermion mass

Energy of color electric field

Energy of color magnetic field

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

Hamiltonian formalism maybe more natural than the path integral formalism for quantum simulation/computation:

Kogut and Susskind formulation:

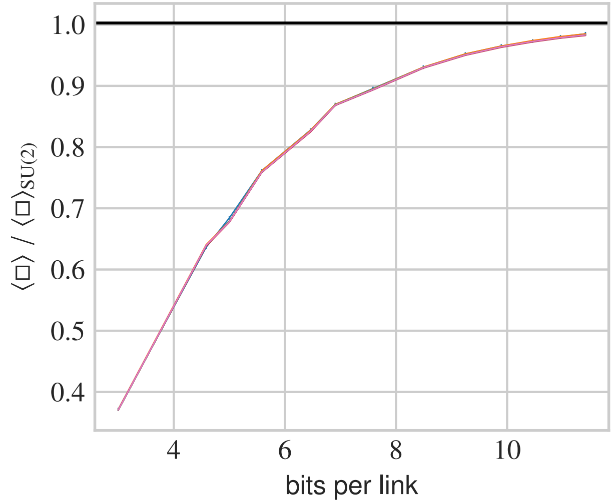
An infinite-dimensional Hilbert space!

$$H_{\text{QCD}} = \underbrace{-t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right)}_{\text{Fermion hopping term}} + \underbrace{m\sum_x s_x\psi_x^\dagger\psi_x}_{\text{Fermion mass}} + \underbrace{\frac{g^2}{2}\sum_{\langle xy\rangle}\left(L_{xy}^2 + R_{xy}^2\right)}_{\text{Energy of color electric field}} - \underbrace{\frac{1}{4g^2}\sum_{\Box}\mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right)}_{\text{Energy of color magnetic field}}.$$

Tong, Albert, McClean, Preskill, and Su (2021).

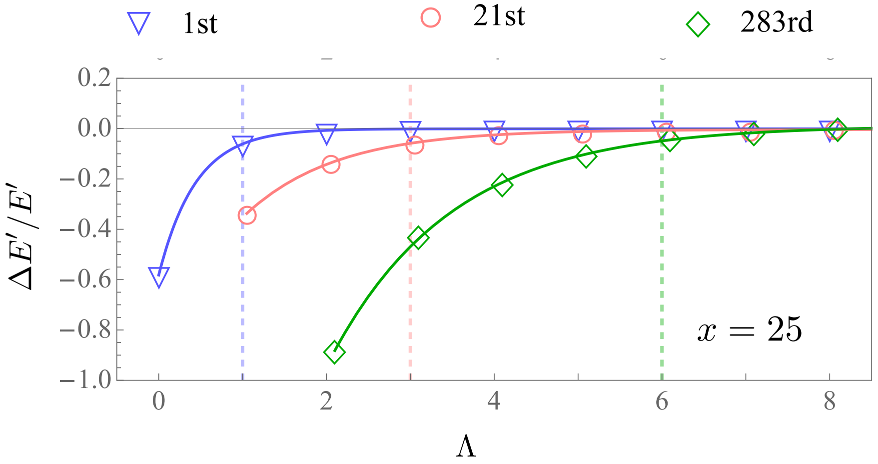
Gauge-field truncation

SU(2) pure gauge in 3+1 D
in group element basis



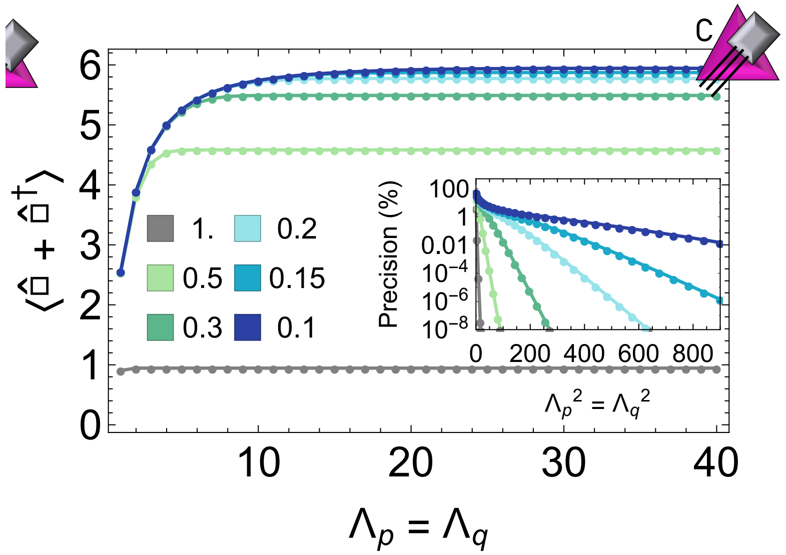
Hackett et al, Phys. Rev. A 99, 062341 (2019)

SU(2) with matter in 1+1 D
in electric-field basis



ZD, Raychowdhury, and Shaw, arXiv:2009.11802 [hep-lat]

SU(3) pure gauge in 2+1 D
in local-irreps basis



Ciavarella, Klco, and Savage, arXiv:2101.10227 [quant-ph]

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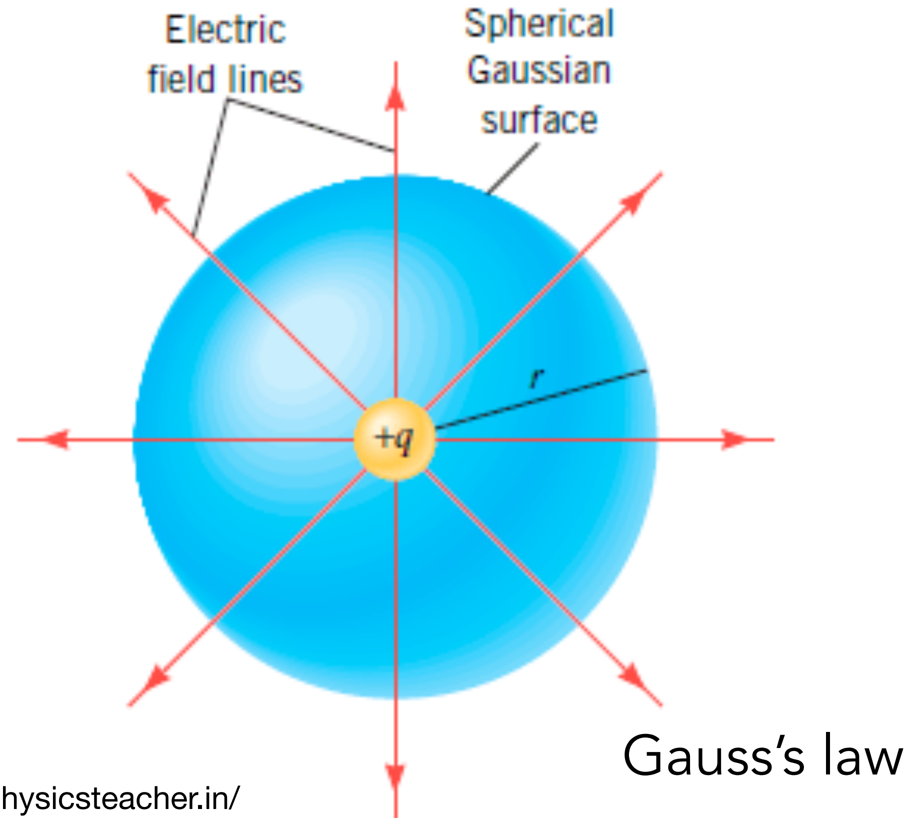
Generator of infinitesimal gauge transformation

$$G_x^a = \psi_x^{i\dagger}\lambda_{ij}^a\psi_x^j + \sum_k \left(L^a_{x,x+\hat{k}} + R^a_{x-\hat{k},x}\right) \Longrightarrow G_x^i|\psi(\{q_x^{(i)}\})\rangle = q_x^{(i)}|\psi(\{q_x^{(i)}\})\rangle$$



Gauss's law

https://physicsteacher.in/

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

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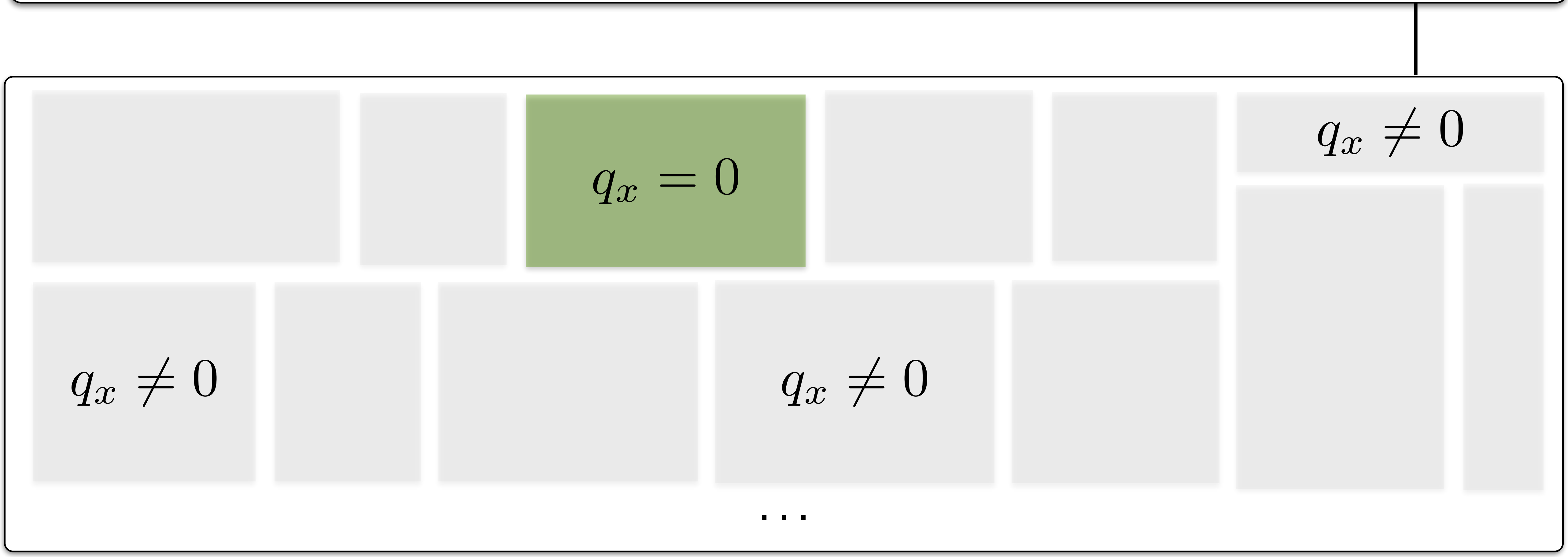
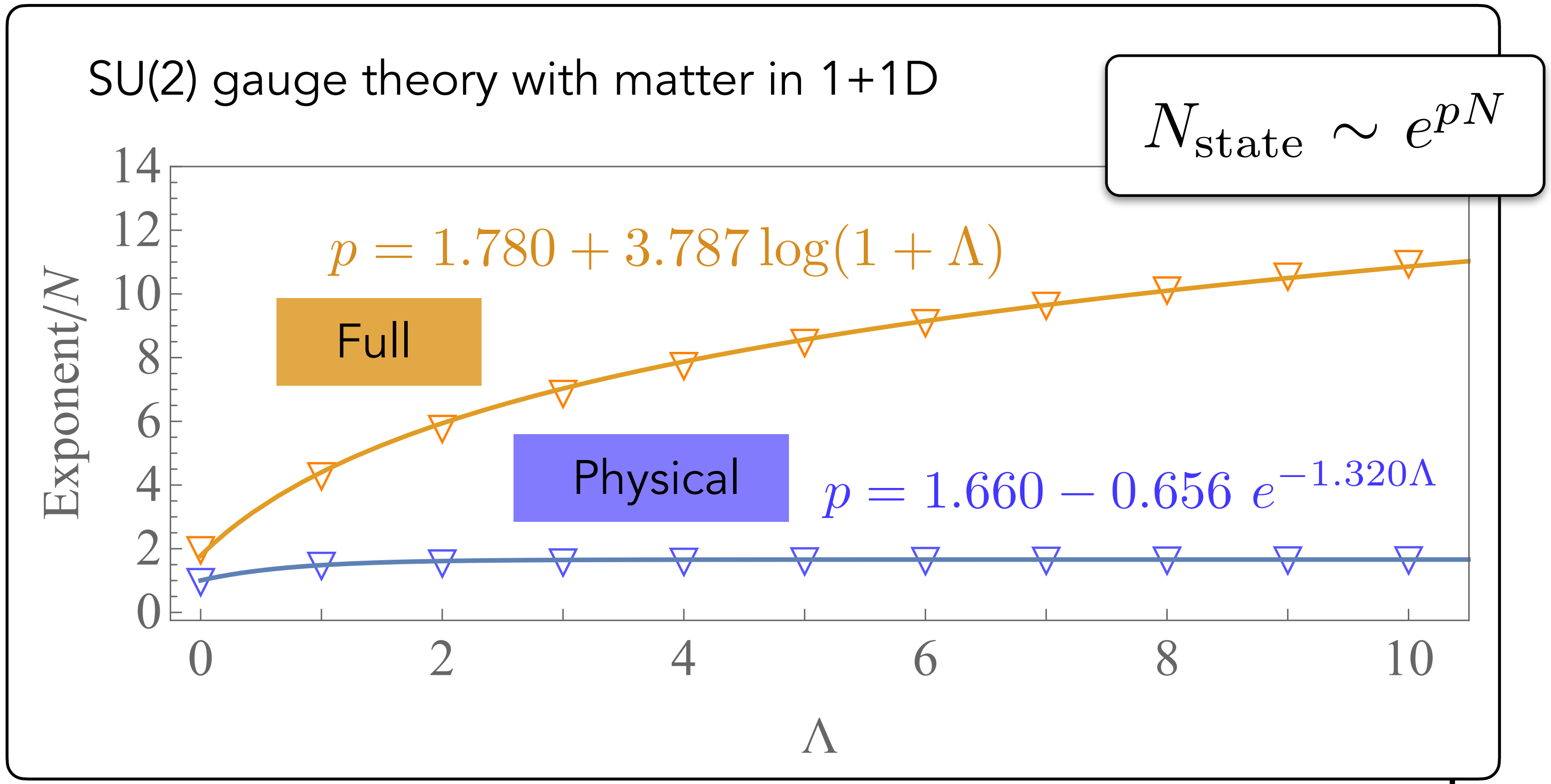
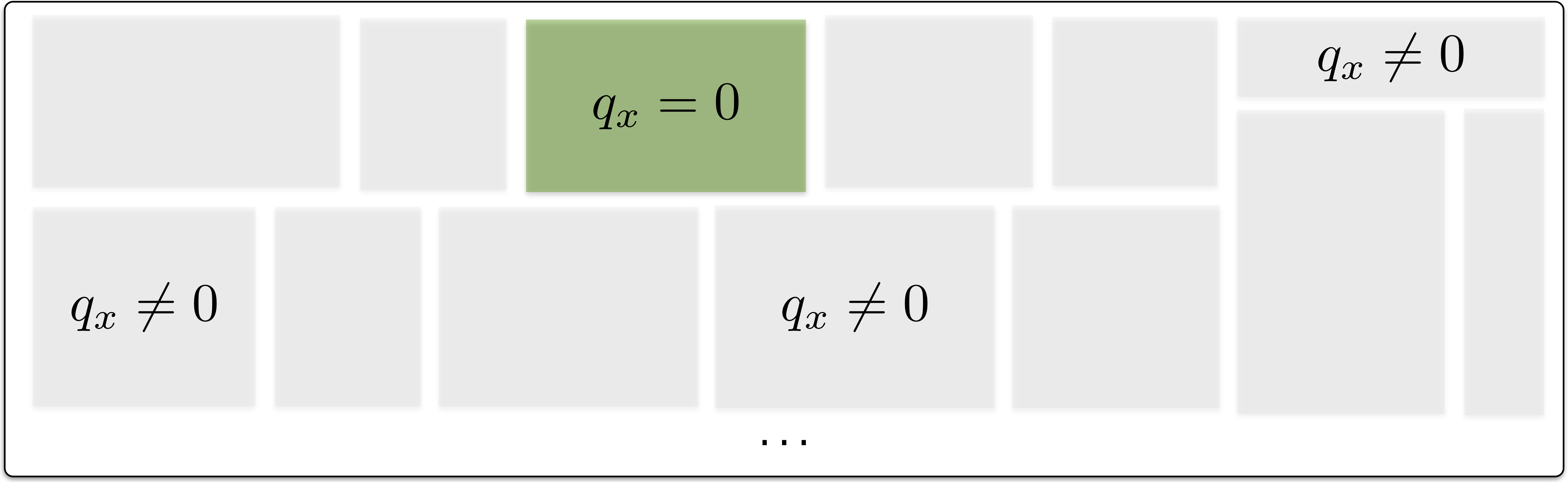


QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS


SU(2) gauge theory with matter in 1+1D

$N_{\text{state}} \sim e^{pN}$

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


$q_x = 0$

$q_x \neq 0$

$q_x \neq 0$

$q_x \neq 0$

…

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

Prepotential formulation
Mathur, Raychowdhury et al

Loop-String-Hadron basis
Raychowdhury and
Stryker, ZD, Shaw

Link models
Chandrasekharan, Wiese 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.; Ortega at 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; 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.

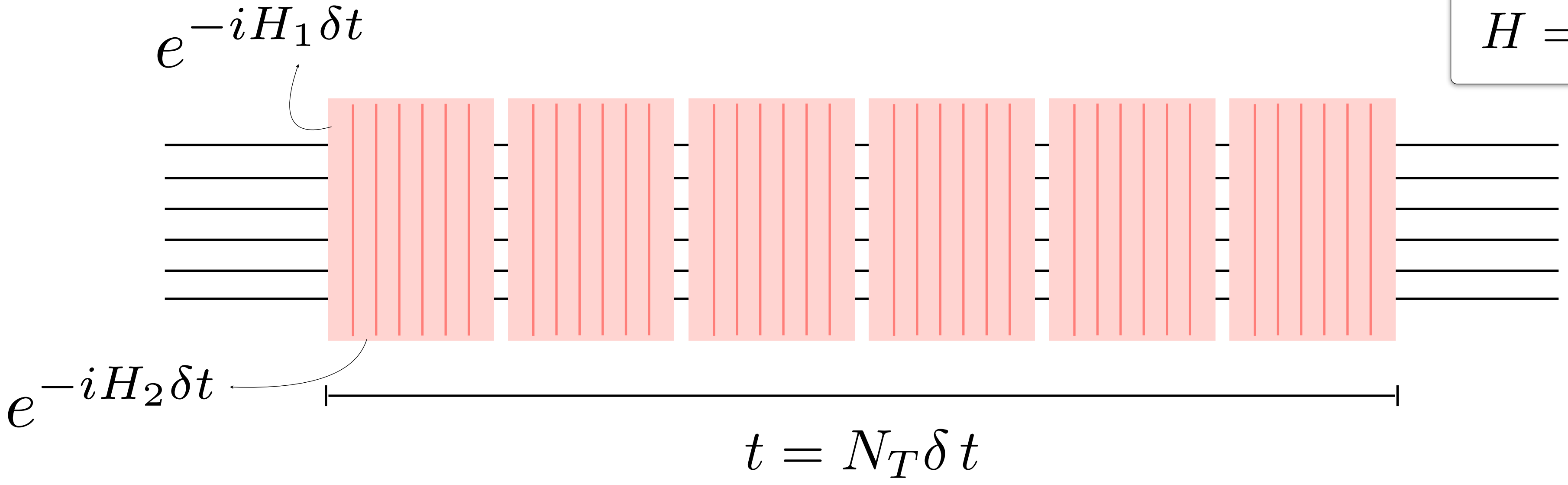
Lots of interesting ideas using **analog simulators** will not be covered here.

Algorithmic developments
[Digital]

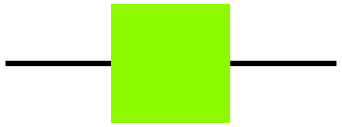
- Near- and far-term algorithms with bounded errors and resource requirement for gauge theories?
- Can given formulation/encoding reduce qubit and gate resources?
- Should we develop gauge-invariant simulation algorithms?
- How do we do state preparation and compute observables like scattering amplitudes?

Digital

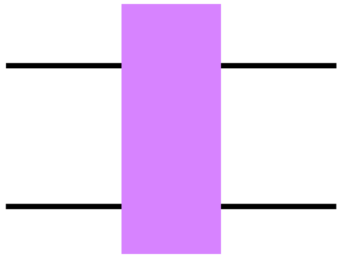
$H = H_1 + H_2 + \cdots$



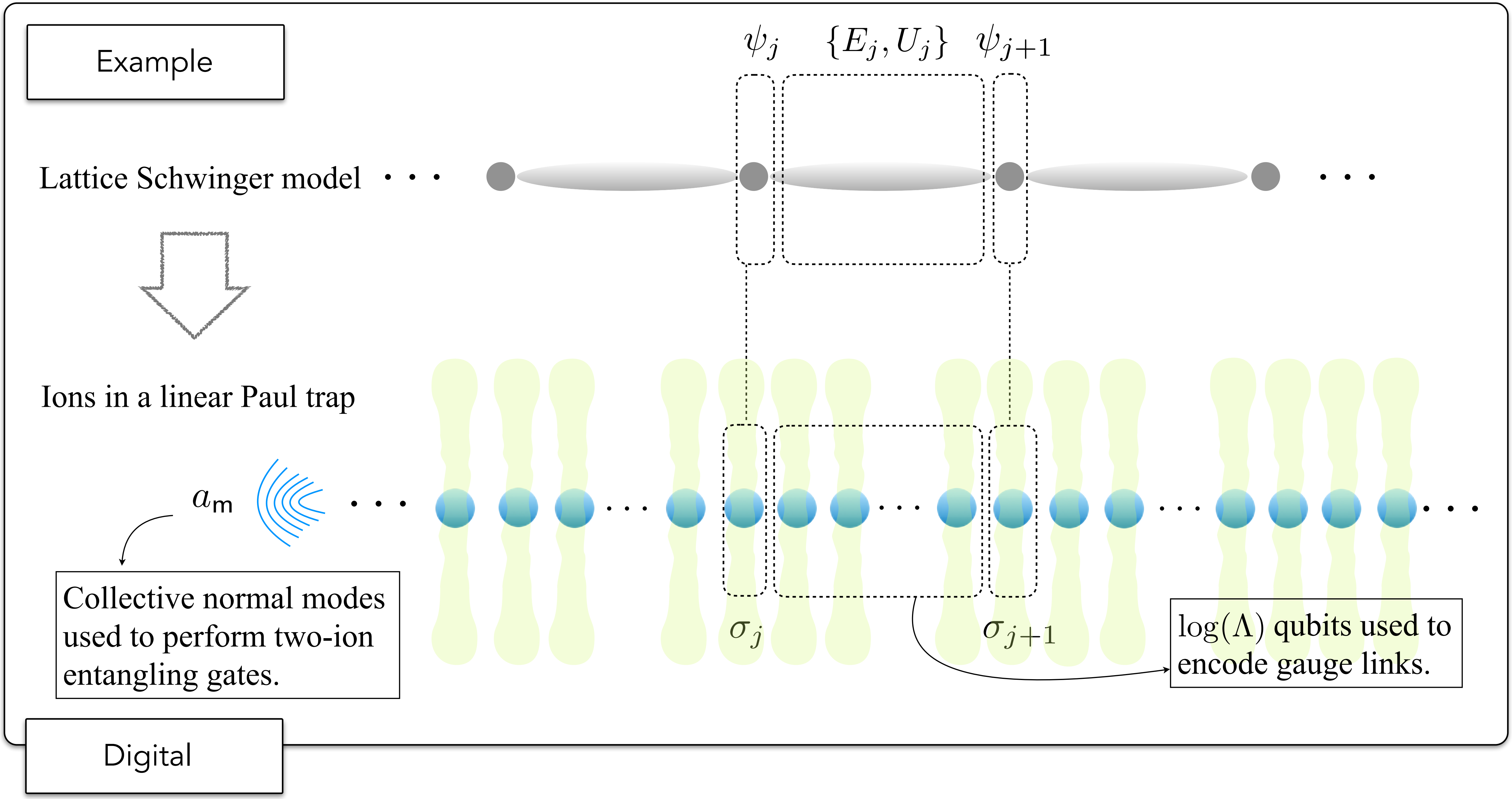
Single-qubit gates



Two-qubit entangling gate



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



Example

Lattice Schwinger model

Ions in a linear Paul trap

Collective normal modes used to perform two-ion entangling gates.

log(Λ) qubits used to encode gauge links.

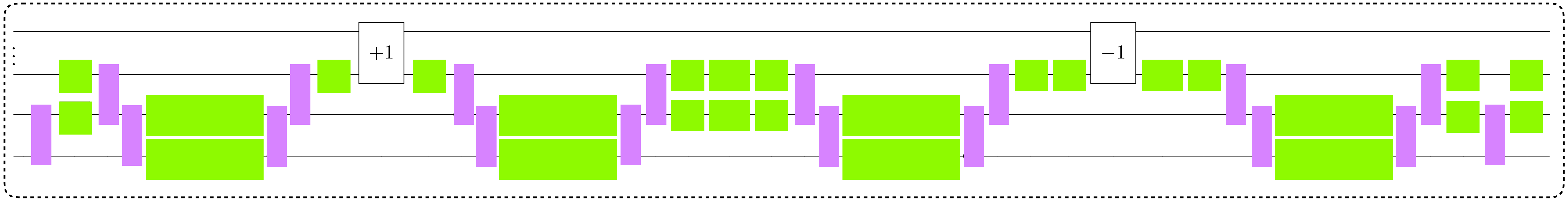
Digital

$$H = -ix \sum_{n=1}^{N-1} \left[\psi_n^\dagger U_n \psi_{n+1} - \mathrm{h.c.}\right] + \sum_{n=1}^{N-1} E_n^2 + \mu \sum_{n=1}^{N} (-1)^n \psi_n^\dagger \psi_n$$

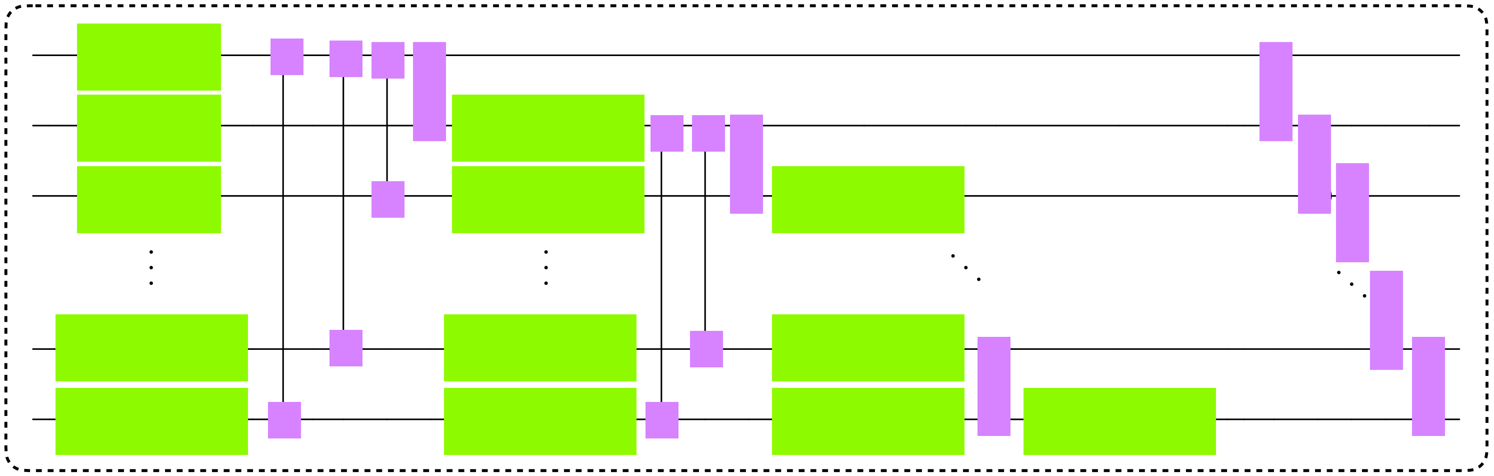
`Interesting algorithmic progress for SU(2), and SU(3) theories can be found in: Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021), arXiv:2101.10227 [quant-ph]. Kan and Nam, arXiv:2107.12769 [quant-ph].`

Circuit and recourse analysis

`Shaw, Lougovski, Stryker, Wiebe, Quantum 4, 306 (2020).`



Sample gauge-fermion interaction block



Part of electric field interactions acting on gauge DOF registers

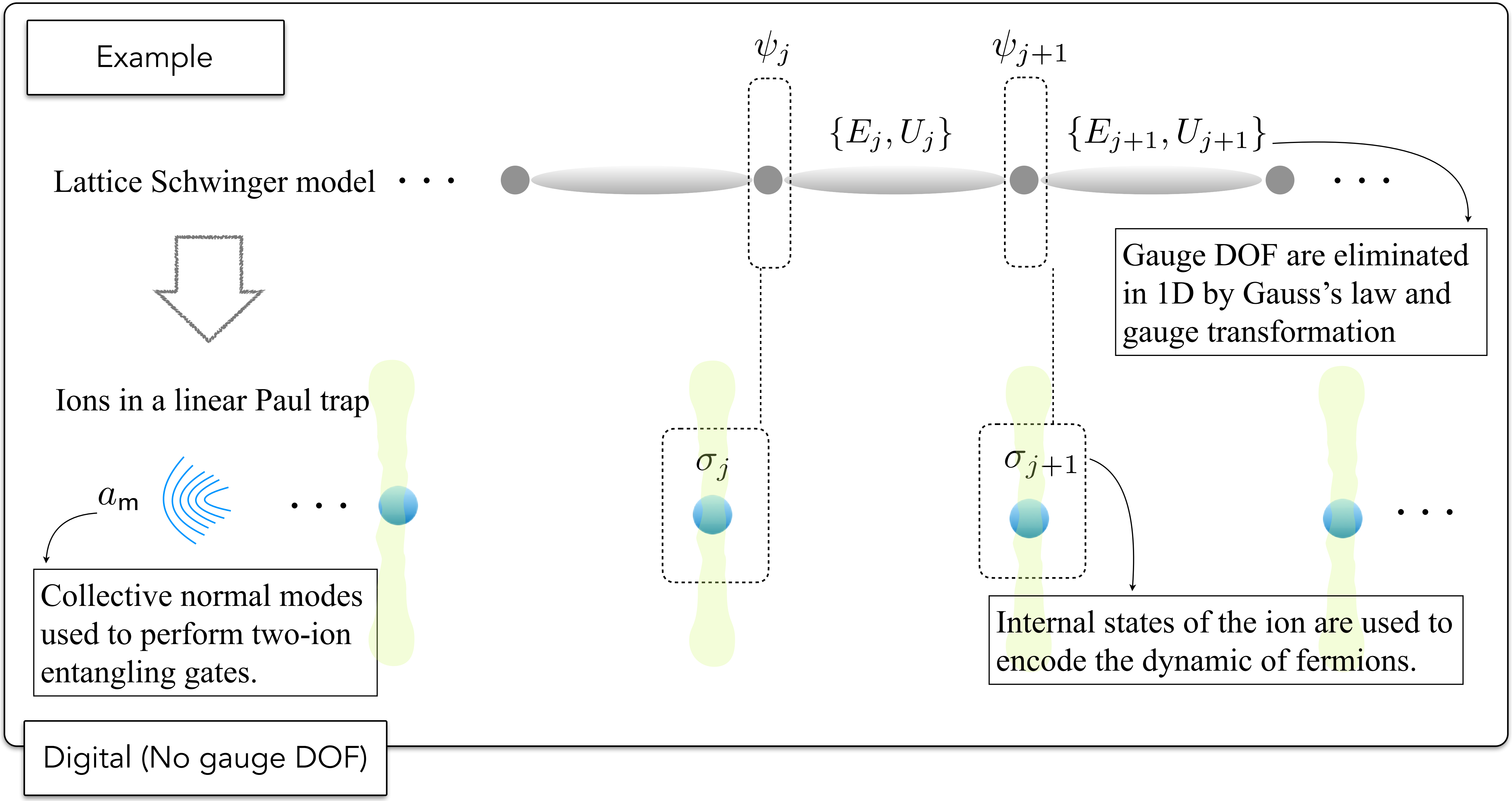
Near term cost

	$\delta_g = 10^{-3}$		$\delta_g = 10^{-4}$		$\delta_g = 10^{-5}$		$\delta_g = 10^{-6}$		$\delta_g = 10^{-7}$	
	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT
$x = 10^{-2}$	—	7.3e4	—	1.6e5	—	3.4e5	—	7.3e5	5.6e-2	1.6e6
$x = 10^{-1}$	—	1.6e4	—	3.5e4	—	7.5e4	5.9e-2	1.6e5	2.7e-3	3.5e5
$x = 1$	—	4.6e3	—	9.9e3	1.0e-1	2.1e4	4.7e-3	4.6e4	2.2e-4	9.9e4
$x = 10^{2}$	—	2.8e3	8.3e-1	6.1e3	3.8e-2	1.3e4	1.8e-3	2.8e4	8.2e-5	6.0e4

$$H = -ix \sum_{n=1}^{N-1} \left[\psi_n^\dagger U_n \psi_{n+1} - \text{h.c.}\right] + \sum_{n=1}^{N-1} E_n^2 + \mu \sum_{n=1}^{N} (-1)^n \psi_n^\dagger \psi_n$$

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?



Example

Lattice Schwinger model

Gauge DOF are eliminated in 1D by Gauss's law and gauge transformation

Ions in a linear Paul trap

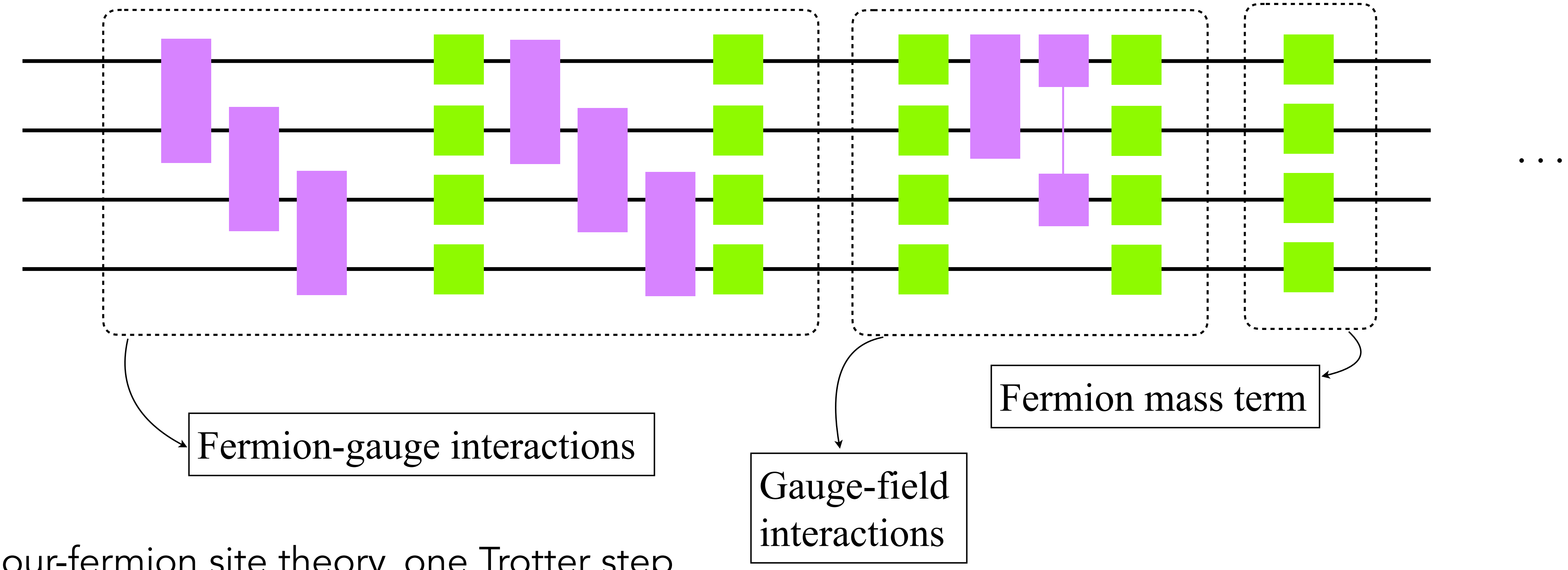
Collective normal modes used to perform two-ion entangling gates.

Internal states of the ion are used to encode the dynamic of fermions.

Digital (No gauge DOF)

$$H = x\sum_{n=1}^{N-1}\left[\sigma_+^{(n)}\sigma_-^{(n+1)} + \sigma_+^{(n+1)}\sigma_-^{(n)}\right] + \sum_{n=1}^{N-1}\left[\epsilon_0 + \frac{1}{2}\sum_{m=1}^{n}\left(\sigma_z^{(m)} + (-1)^m\right)\right]^2 + \frac{\mu}{2}\sum_{n=1}^{N}(-1)^n\sigma_z^{(n)}$$

Associated quantum circuit for Trotterized evolution:



Fermion-gauge interactions

Gauge-field interactions

Fermion mass term

Four-fermion site theory, one Trotter step

$$H = x \sum_{n=1}^{N-1} \left[\sigma_+^{(n)} \sigma_-^{(n+1)} + \sigma_+^{(n+1)} \sigma_-^{(n)} \right] + \sum_{n=1}^{N-1} \left[\epsilon_0 + \frac{1}{2} \sum_{m=1}^{n} \left(\sigma_z^{(m)} + (-1)^m \right) \right]^2 + \frac{\mu}{2} \sum_{n=1}^{N} (-1)^n \sigma_z^{(n)}$$

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

INSTITUTE for NUCLEAR THEORY

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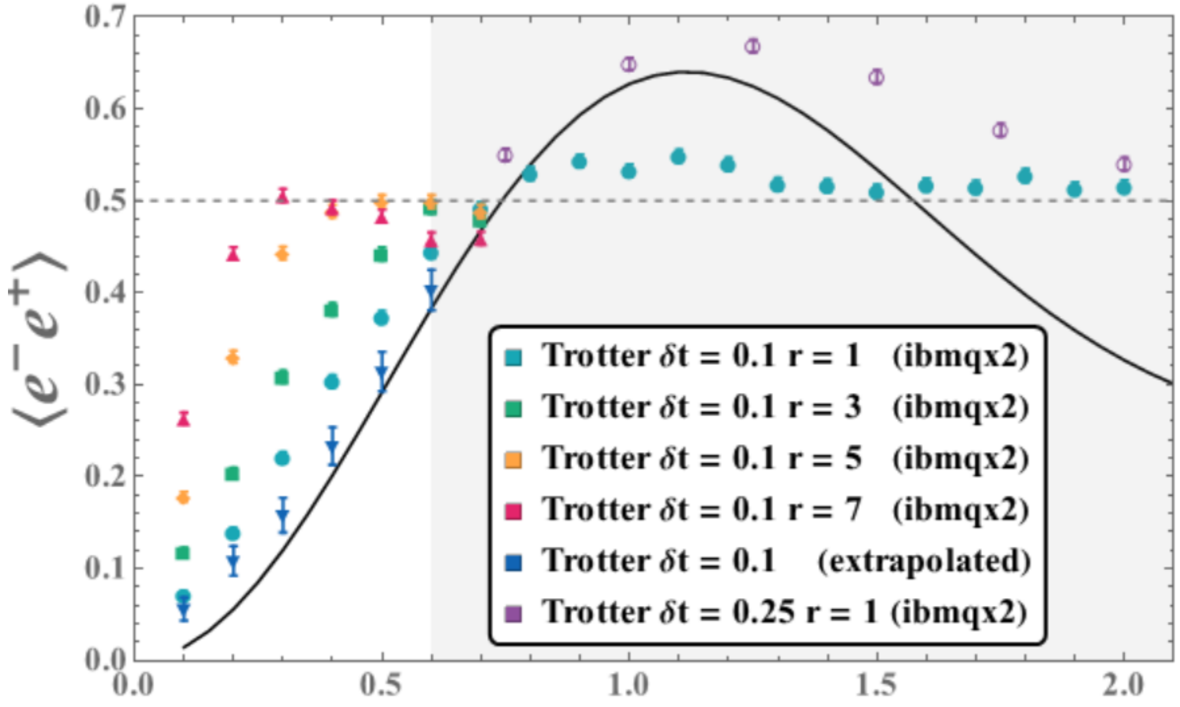
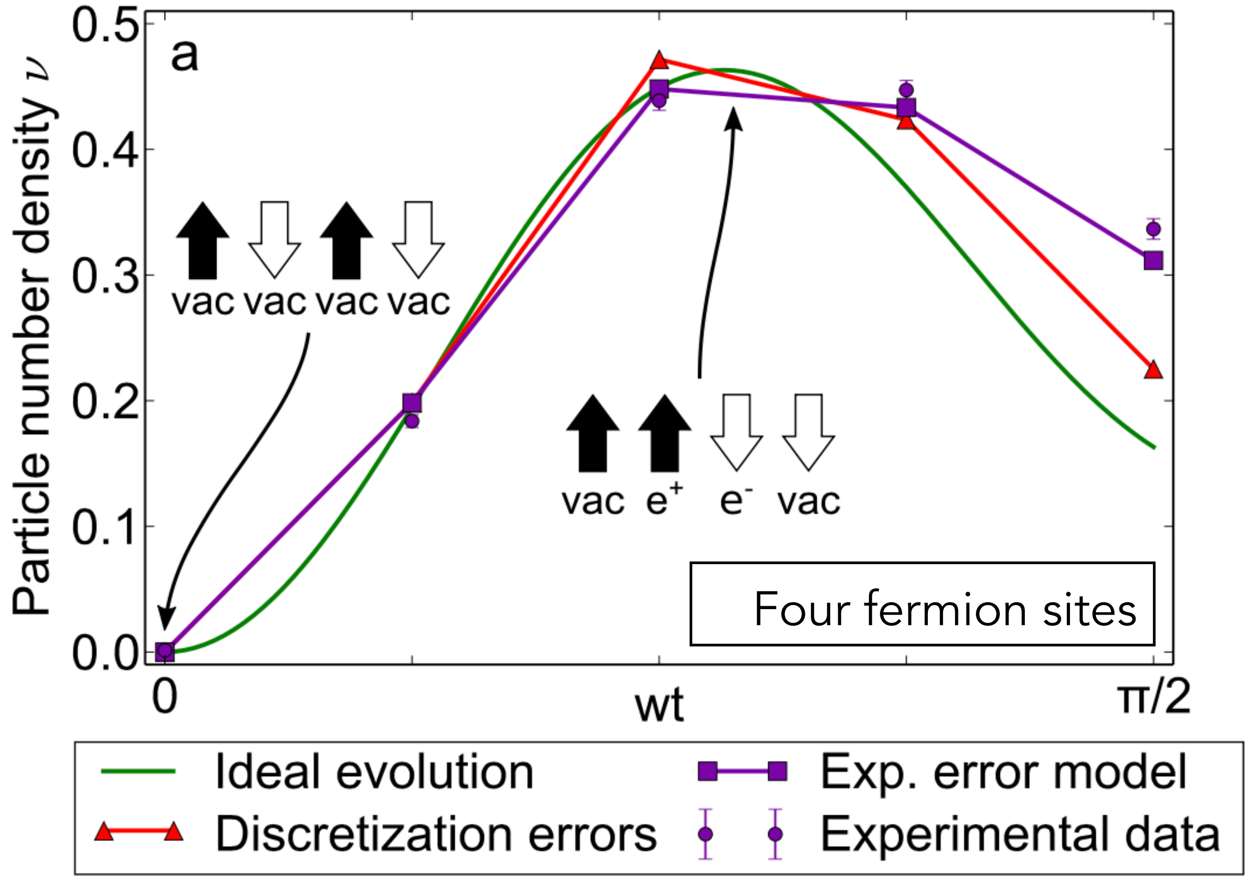
IBM



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

universität innsbruck

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



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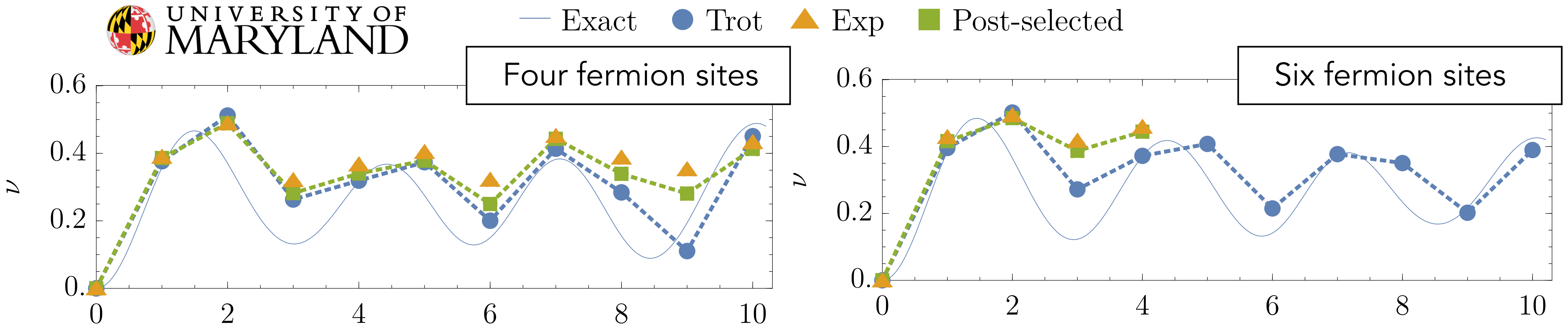
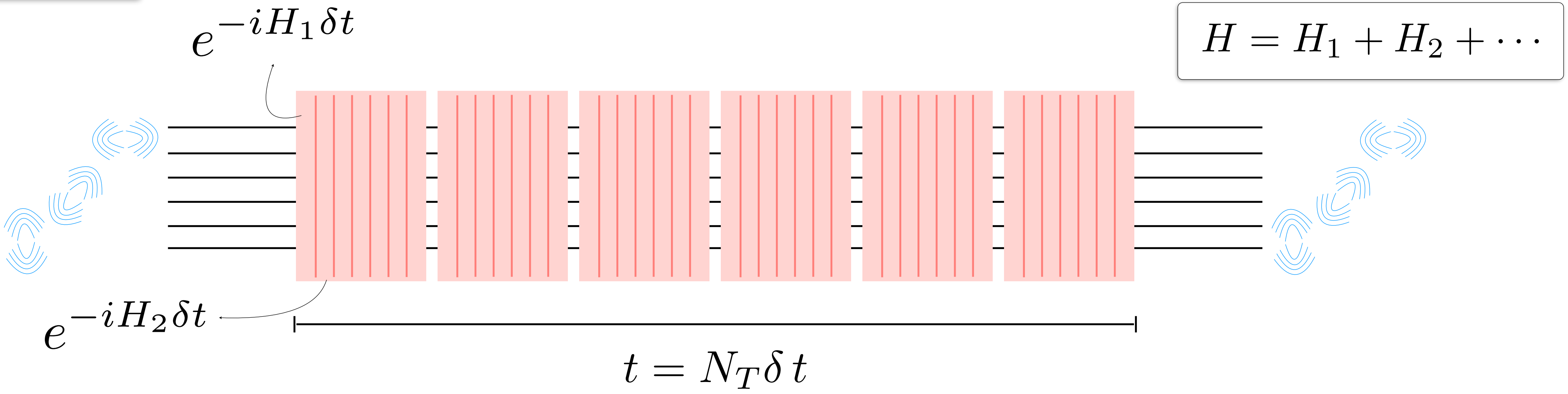


80 entangling gates!

90 entangling gates!

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

Analog-Digital



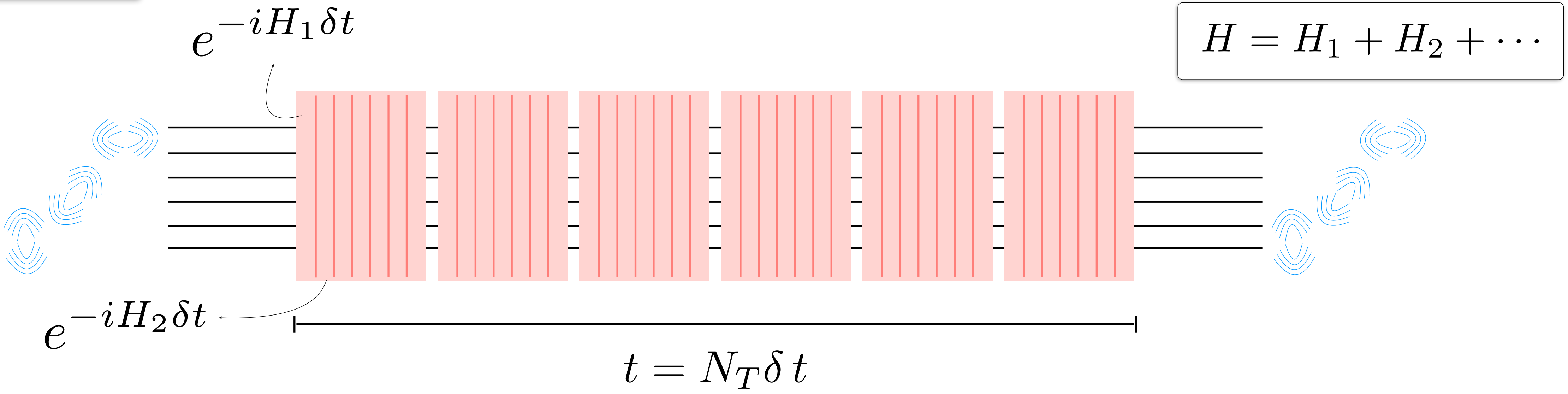
$e^{-iH_1\delta t}$

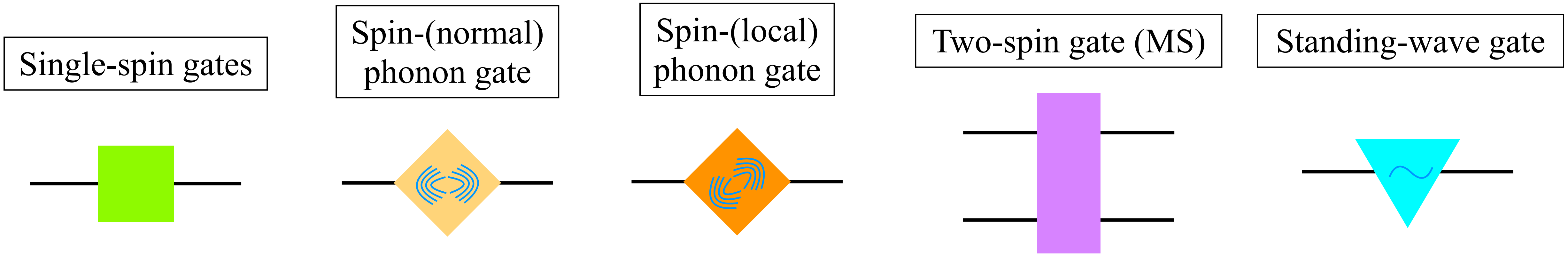
$H = H_1 + H_2 + \cdots$

$e^{-iH_2\delta t}$

$t = N_T\delta t$

Analog-Digital





Single-spin gates

Spin-(normal) phonon gate

Spin-(local) phonon gate

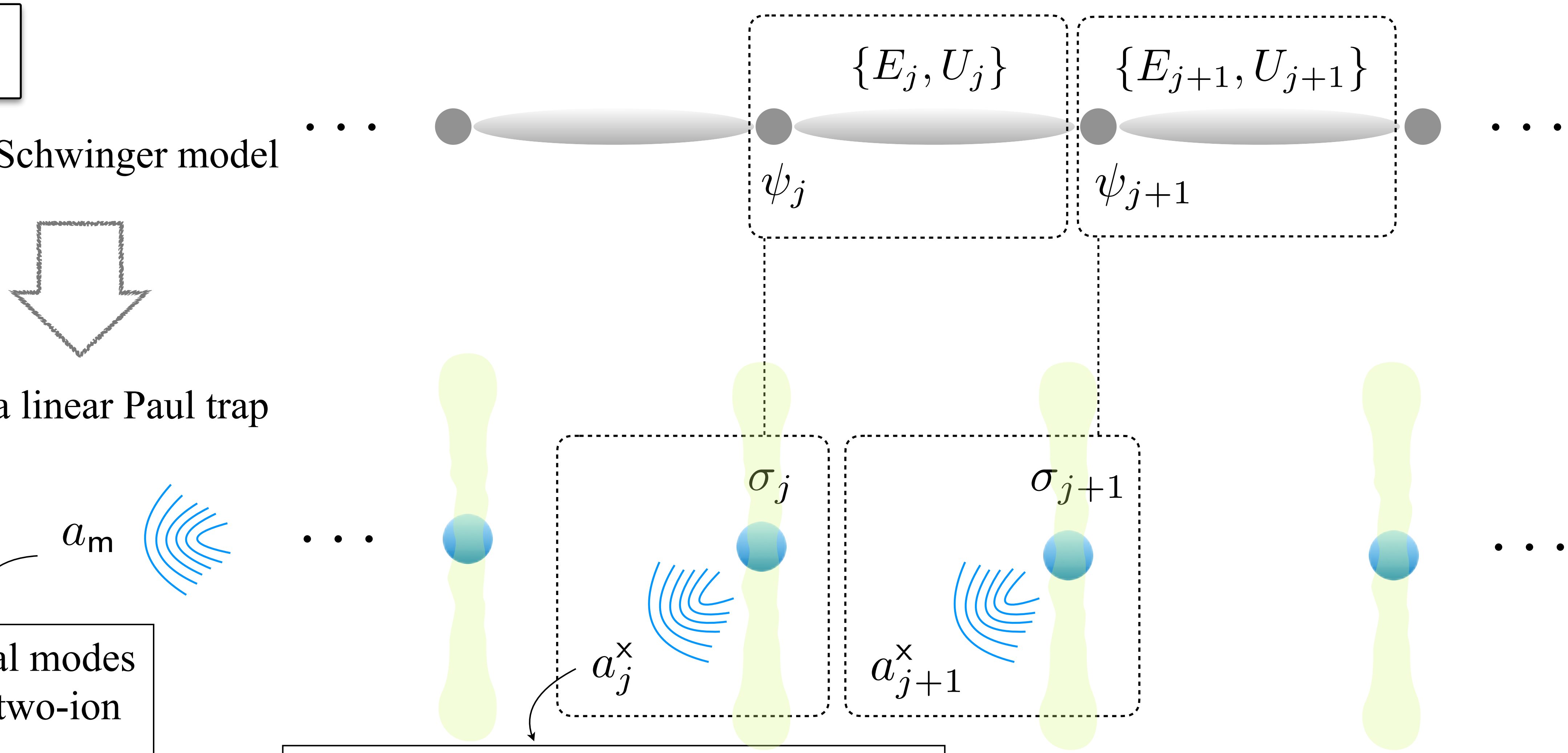
Two-spin gate (MS)

Standing-wave gate

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

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

Example



Lattice Schwinger model

Ions in a linear Paul trap

Collective normal modes used to perform two-ion entangling gates.

Local transverse modes used to encode the dynamic of the gauge fields.

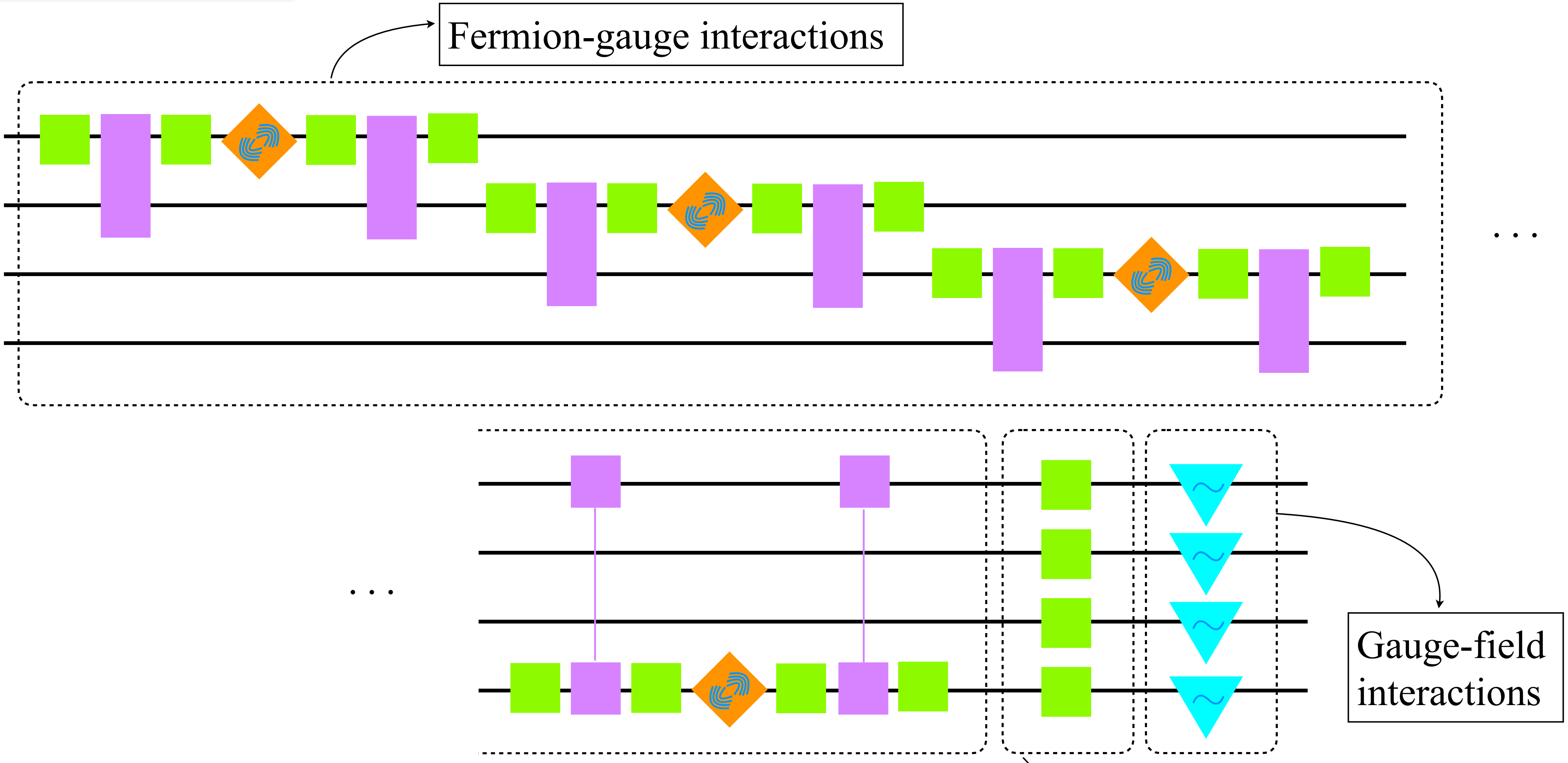
Analog-Digital

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) for analog-digital approaches to other interacting fermion-boson theories.

$$H = -ix \sum_{n=1}^{N-1} \left[\psi_n^\dagger U_n \psi_{n+1} - \mathrm{h.c.}\right] + \sum_{n=1}^{N-1} E_n^2 + \mu \sum_{n=1}^{N} (-1)^n \psi_n^\dagger \psi_n$$

Analog-Digital



Fermion-gauge interactions

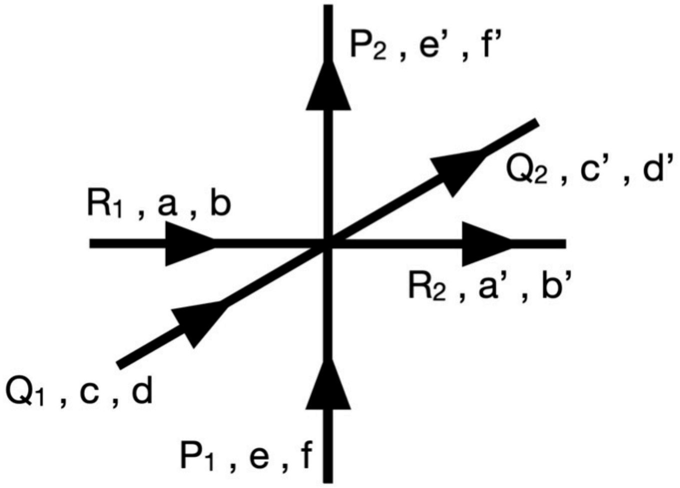
Gauge-field interactions

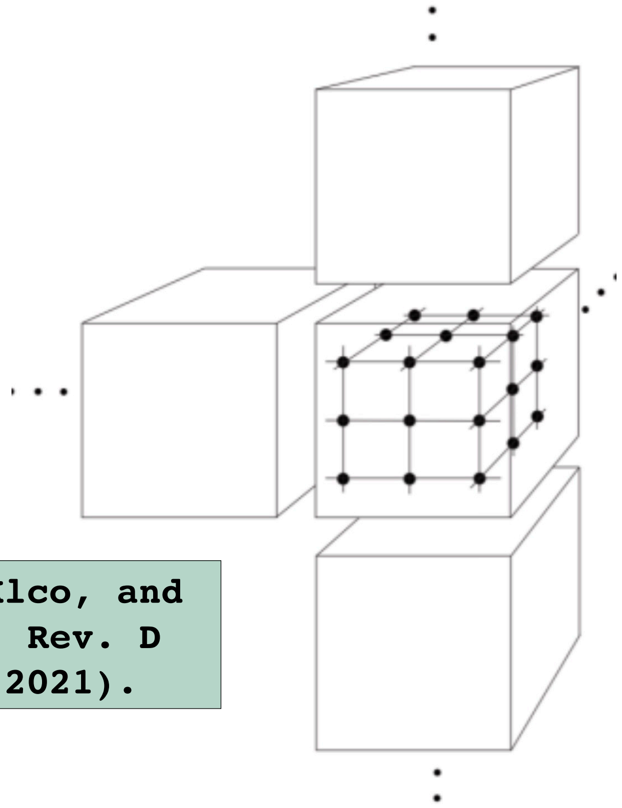
Fermion mass term

ZD, Linke, Pagano, Phys. Rev. Research 3, 043072 (2021), arXiv:2104.09346 [quant-ph].

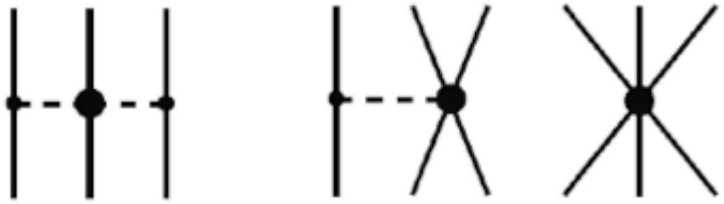
$$H = -ix \sum_{n=1}^{N-1} \left[\psi_n^\dagger U_n \psi_{n+1} - \text{h.c.}\right] + \sum_{n=1}^{N-1} E_n^2 + \mu \sum_{n=1}^{N} (-1)^n \psi_n^\dagger \psi_n$$

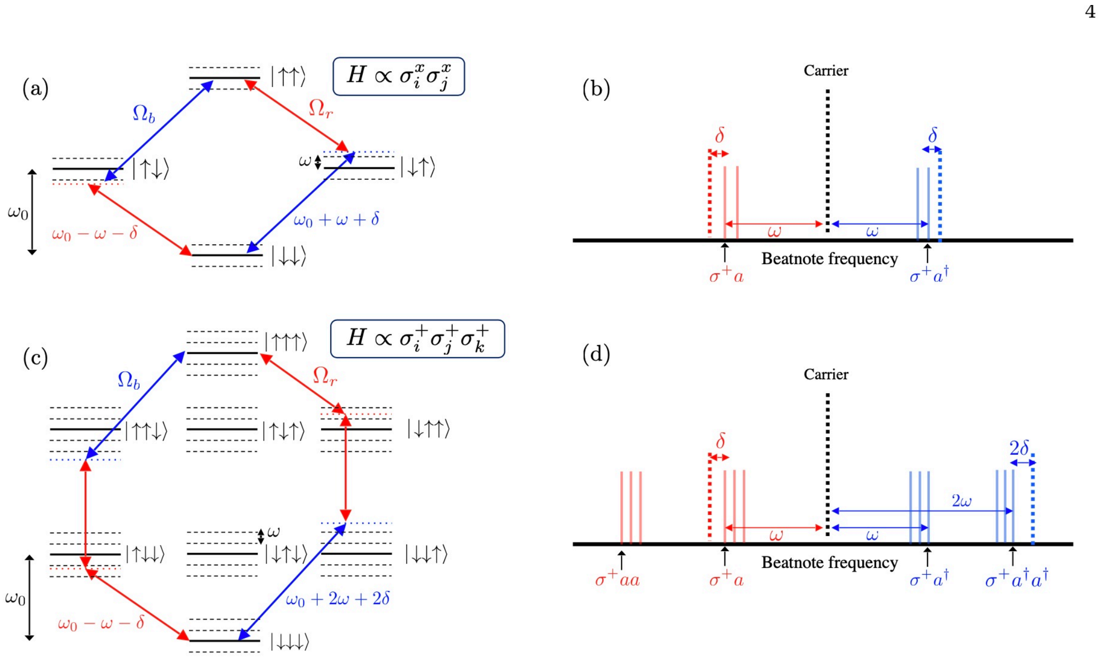
More co-design examples: Multi-dimensional local Hilbert spaces and multi-mode interactions

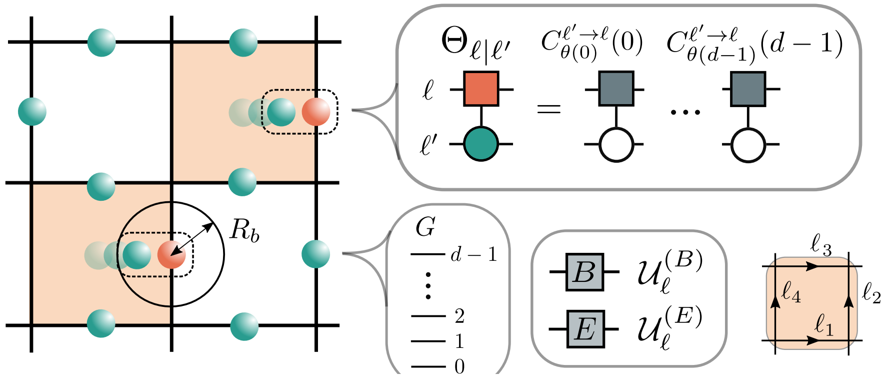




Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).





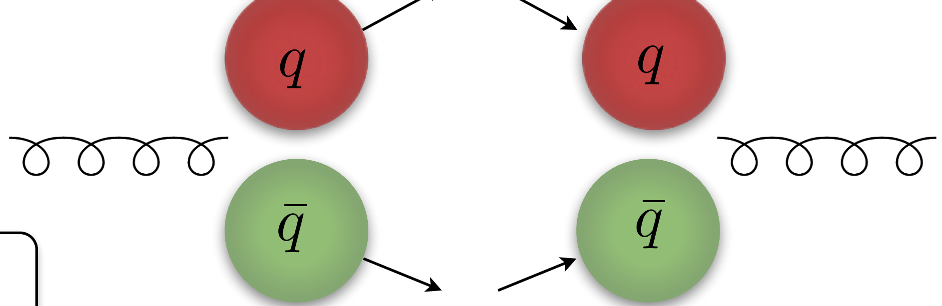


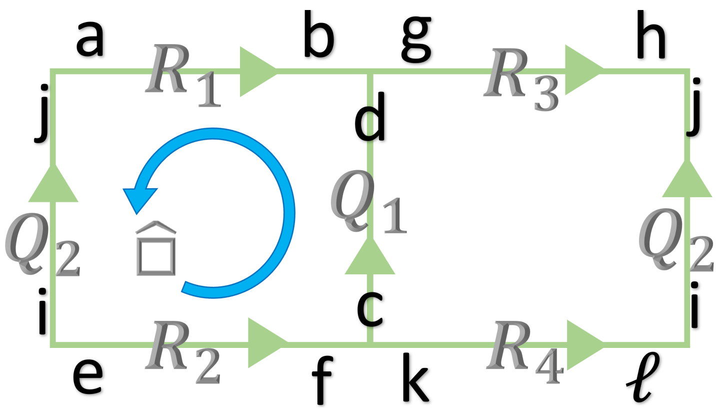
González-Cuadra, Zache, Carrasco, Kraus, Zoller, arXiv:2203.15541 [quant-ph].

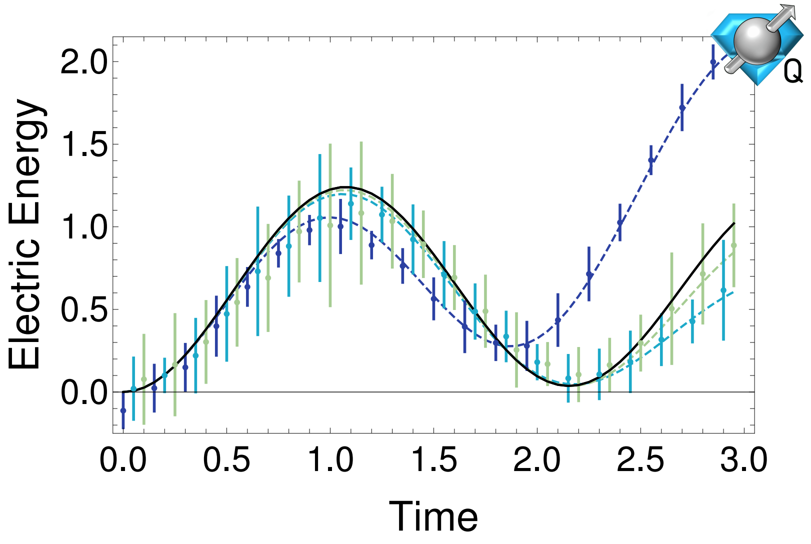
Andrade, ZD, Grass, Hafezi, Pagano, Seif, arXiv:2108.01022 [quant-ph], Bermudez et al, Pays.Rev.A79, 060303 R (2009), Katz, Centina, Monroe, arXiv:2202.04230 [quant-ph].

Finally a few more examples showcasing progress in hardware implementation of a range of QCD-inspired problems…

DIGITAL COMPUTATIONS OF NON-ABELIAN LGTs



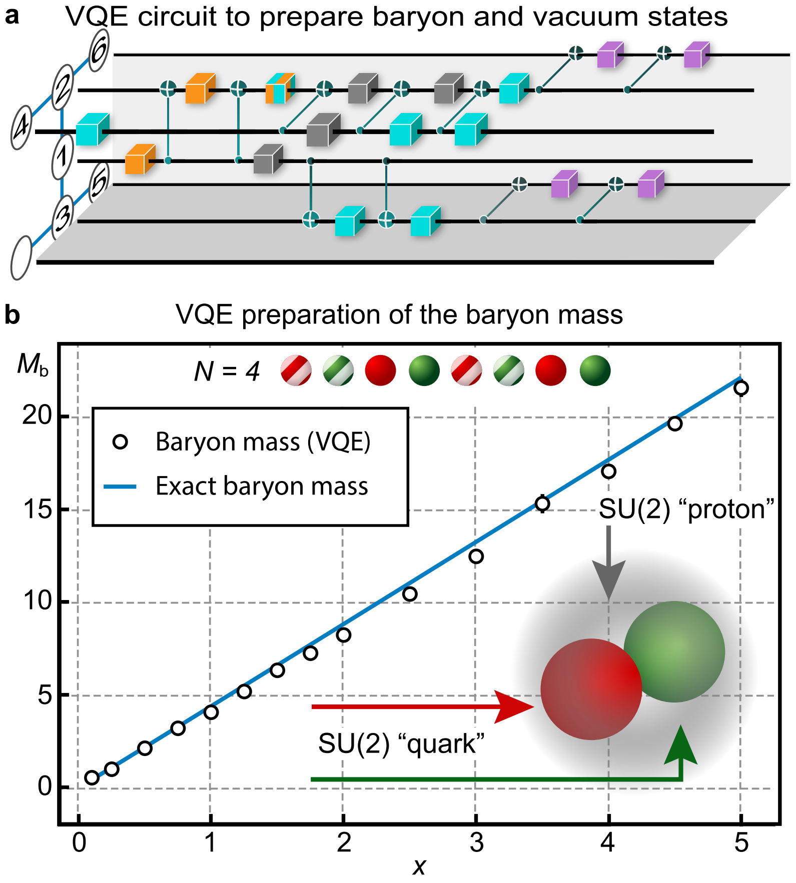




Real-time dynamic of pure SU(3) with global irrupts on IBM

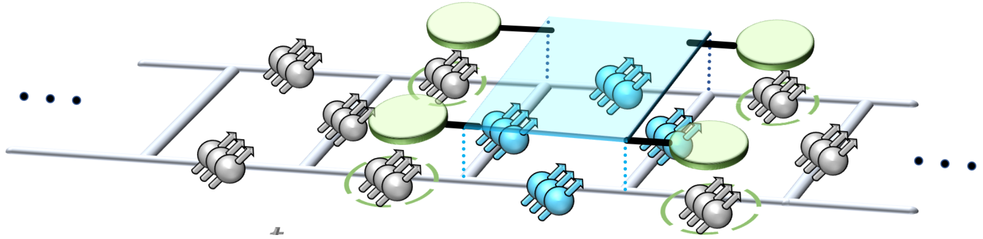
Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).

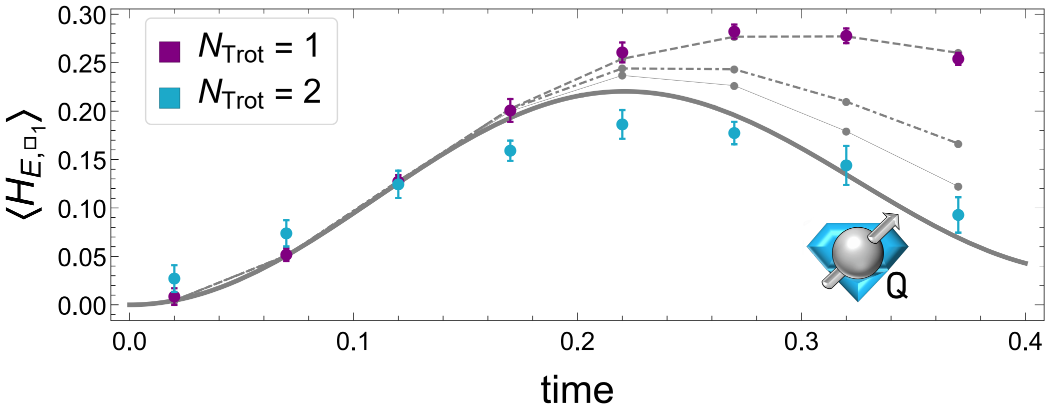
Low-lying spectrum of SU(2) with matter in 1+1 D on IBM



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

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



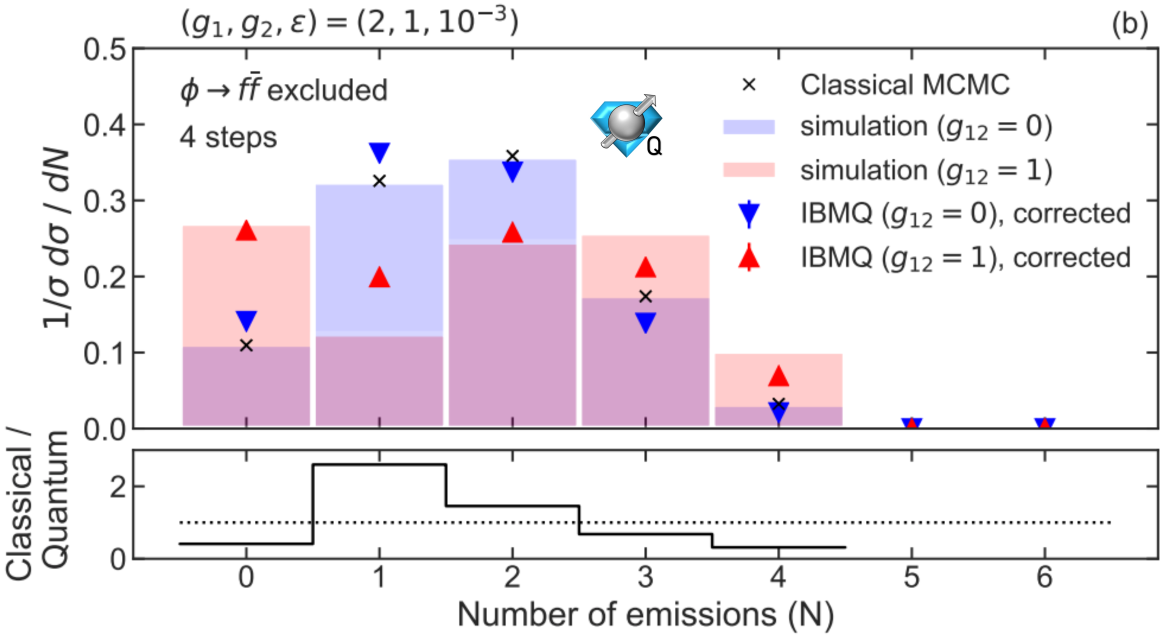


Klco, Savage, and Stryker, Phys. Rev. D 101, 074512 (2020).

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].

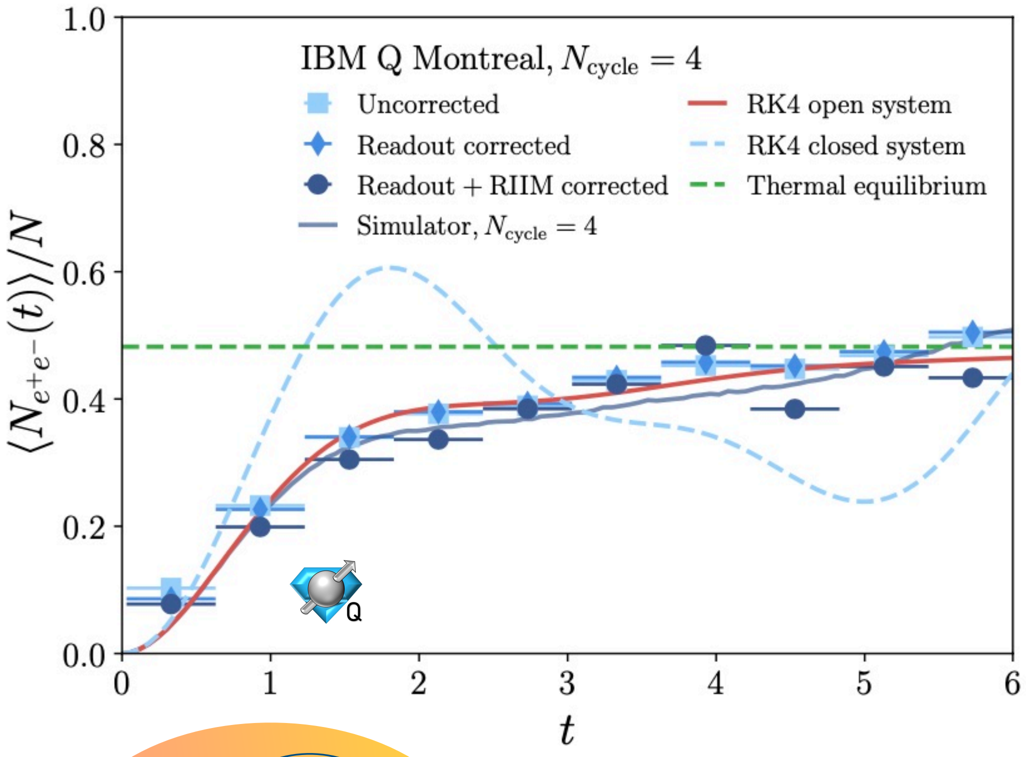
PARTON SHOWER ALGORITHMS AND HEAVY QUARKONIA MOTION IN QGP

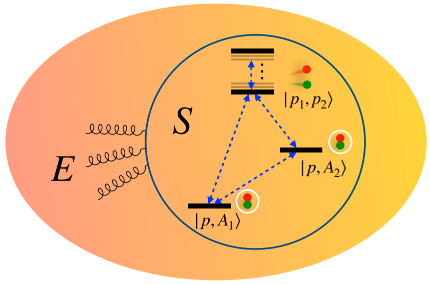
Nachman, Provasoli, and Bauer‡, *Phys. Rev. Lett.* 126 (2021) 6, 062001.



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

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).

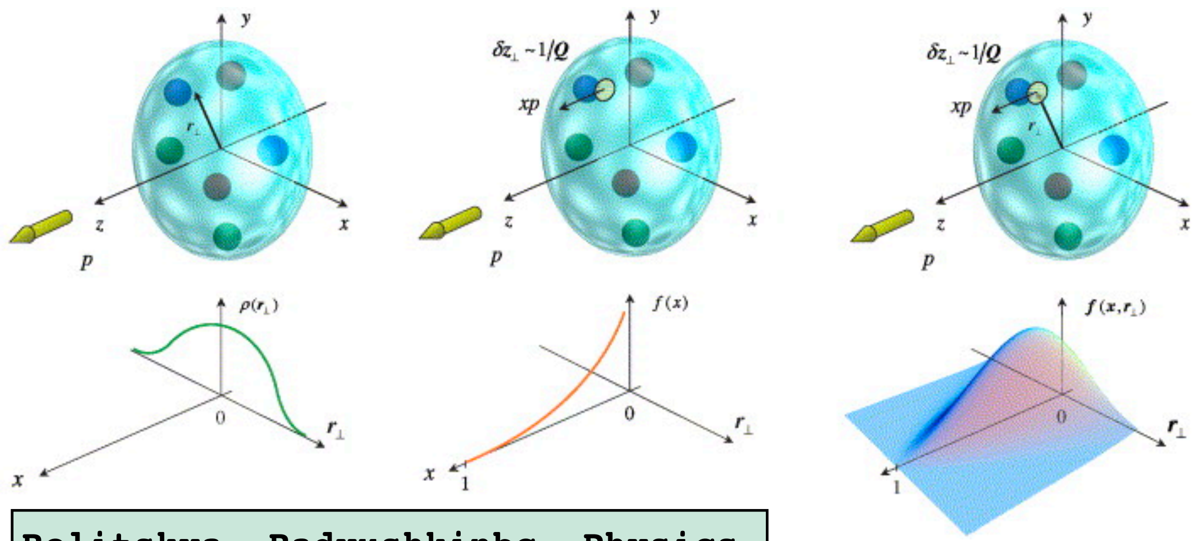




$q\bar{q}$ moving in medium

de Jong, Metcal, Mulligan, Ploskon, Ringer, and, Yao, *Phys.Rev.D* 104 (2021) 5, 051501.

PARTON DISTRIBUTION FUNCTIONS, DECAY AMPLITUDES



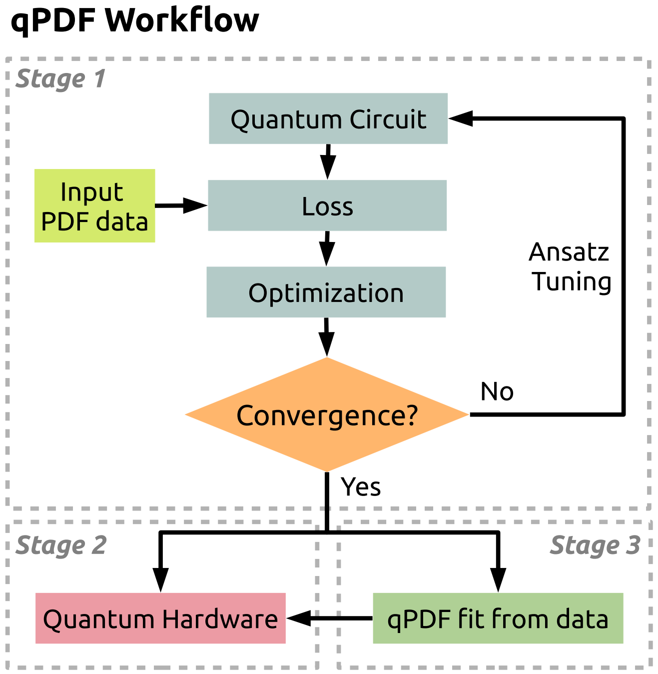
Belitskya, Radyushkinbc, Physics Reports 418 (2005), 1-387.

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…

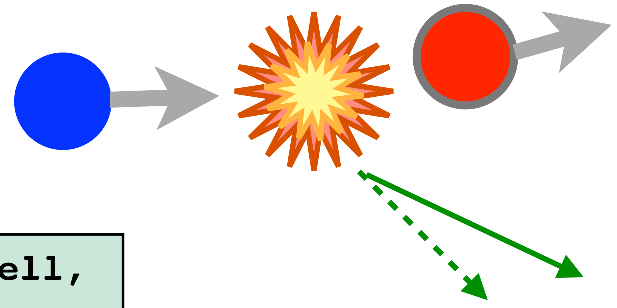
Perez-Salinas, Cruz-Martinez, Alhajri, and Carrazza , PRD 103, 034027 (2021), Qian, Basili, Pal, Luecke, and Vary, arXiv:2112.01927 (2021).



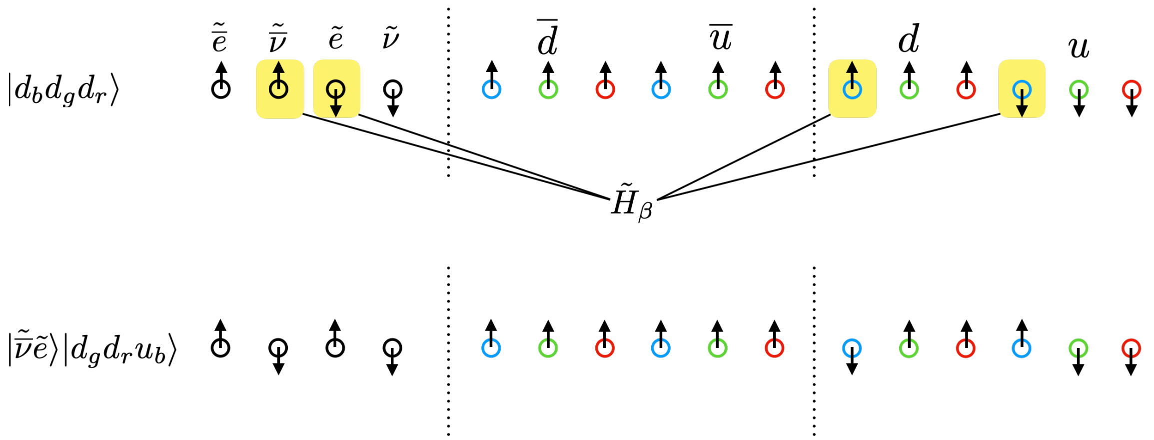
qPDF Workflow

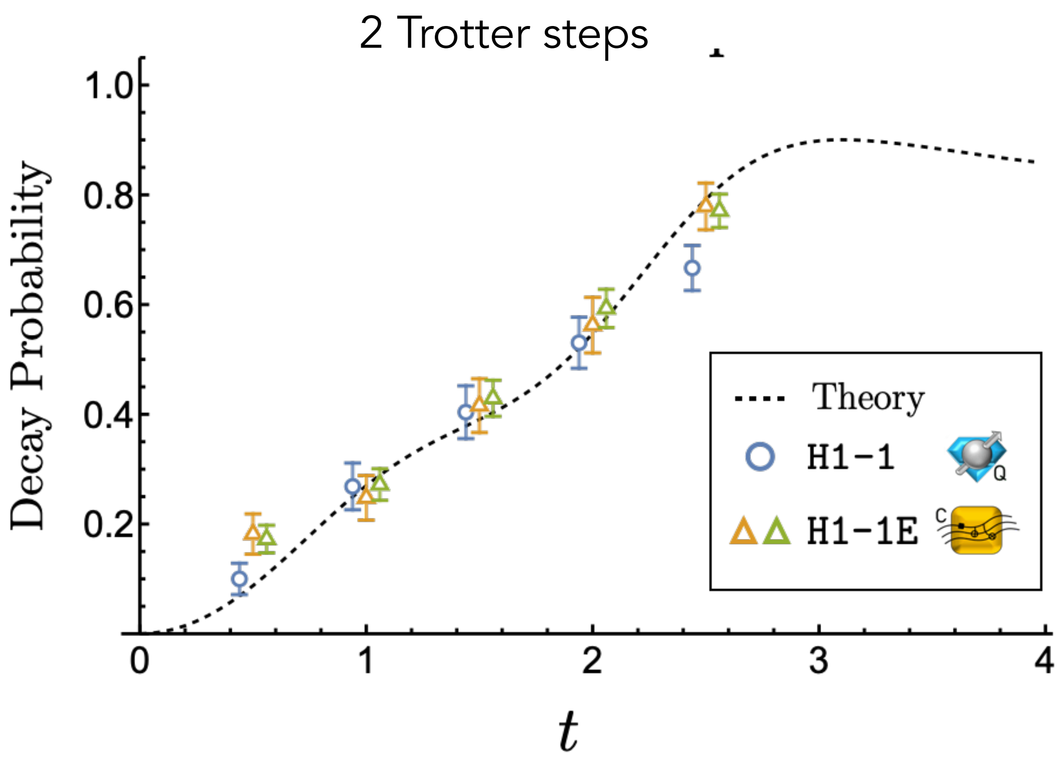
Stage 1
Quantum Circuit
Input PDF data
Loss
Optimization
Ansatz Tuning
Convergence?
No
Yes
Stage 2
Stage 3
Quantum Hardware
qPDF fit from data

Quantum computing β decay in 1+1 QCD

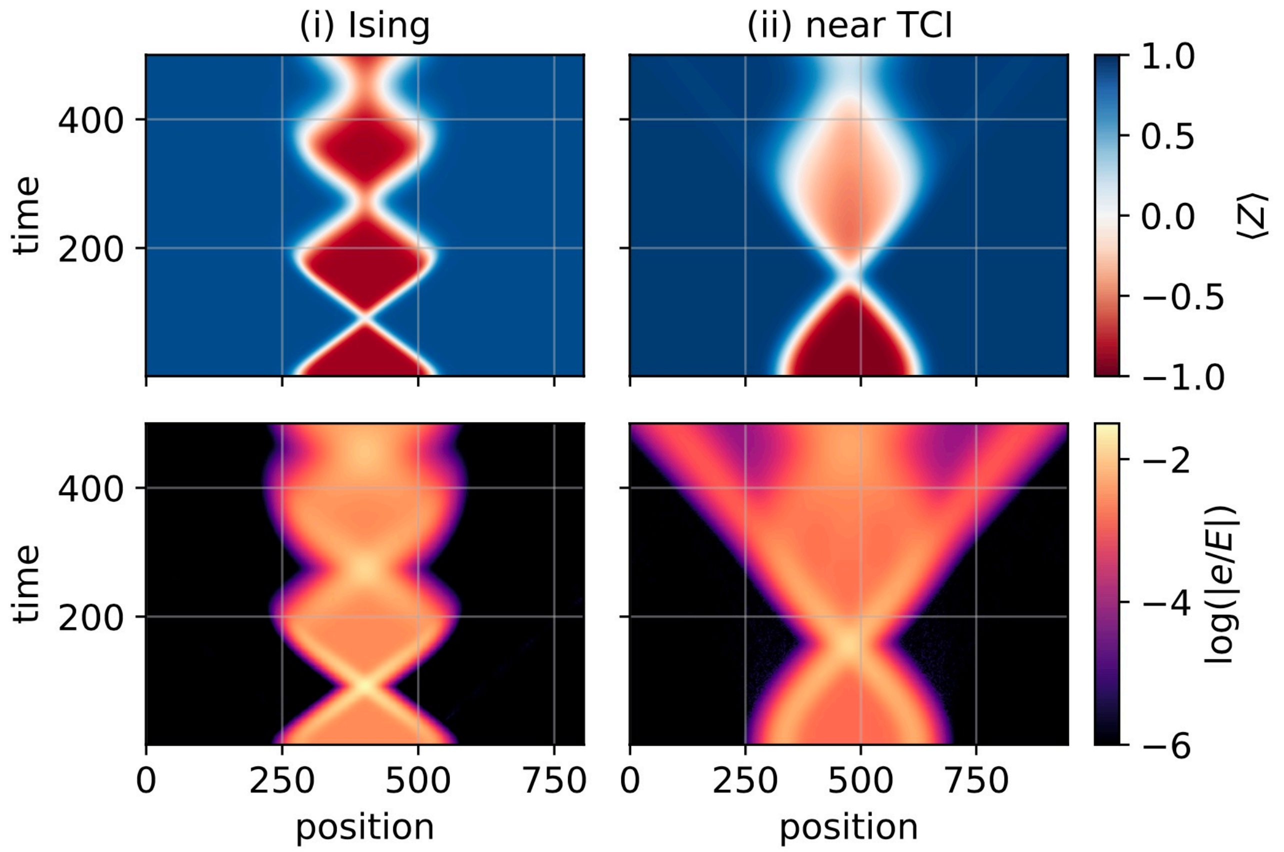


Farrell, Chernyshev, Powell, Zemlevskiy, Illa, and Savage, arXiv:2209.10781 [quant-ph].

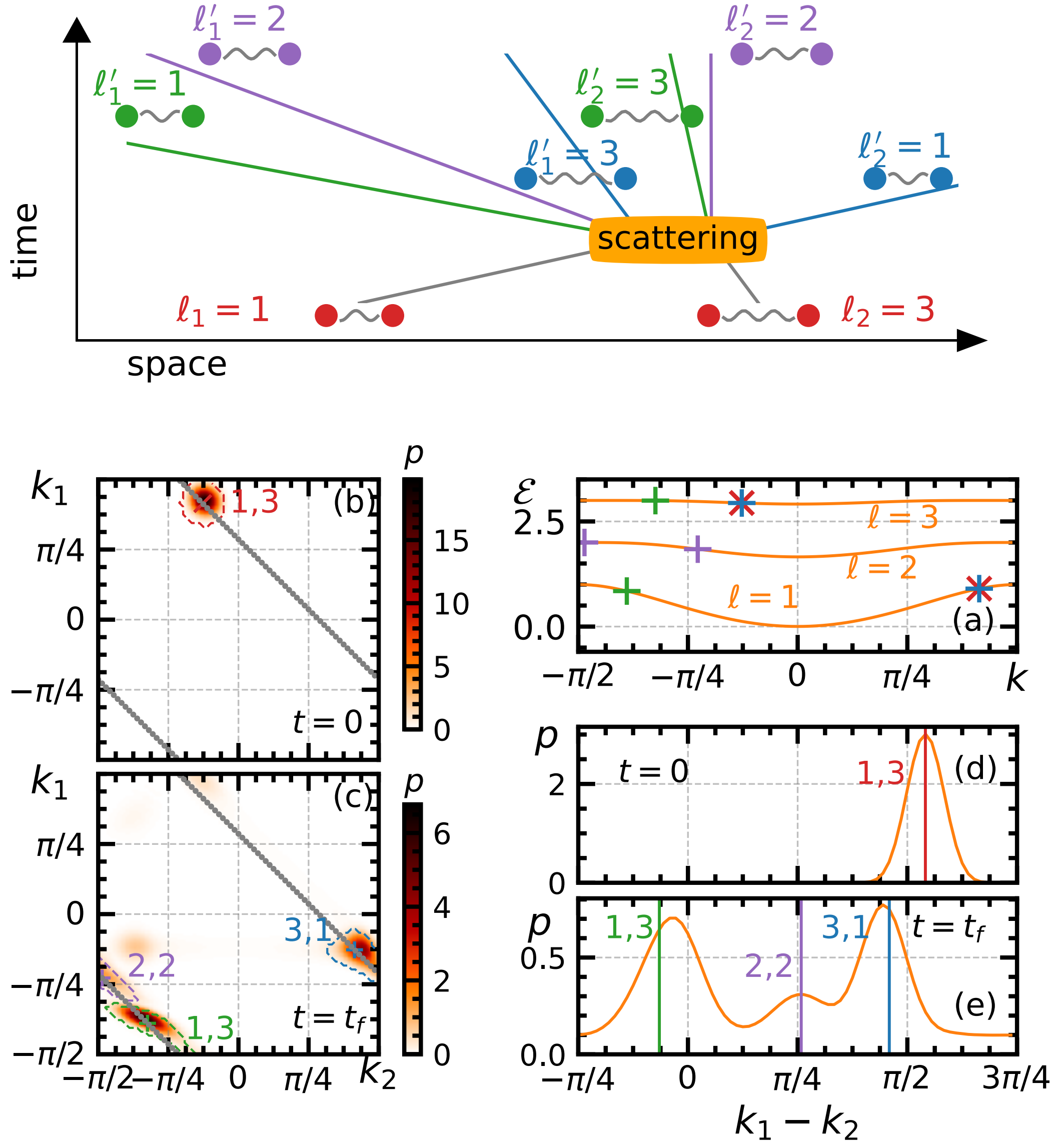




FIRST STEPS TOWARD SCATTERING IN SPIN SYSTEMS
— NUMERICAL SIMULATIONS —



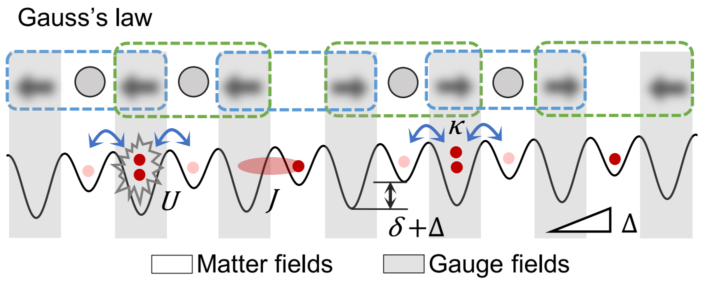
Ashley Milsted, Liu, John Preskill, and Vidal, PRX Quantum 3 (2022) 2, 020316.



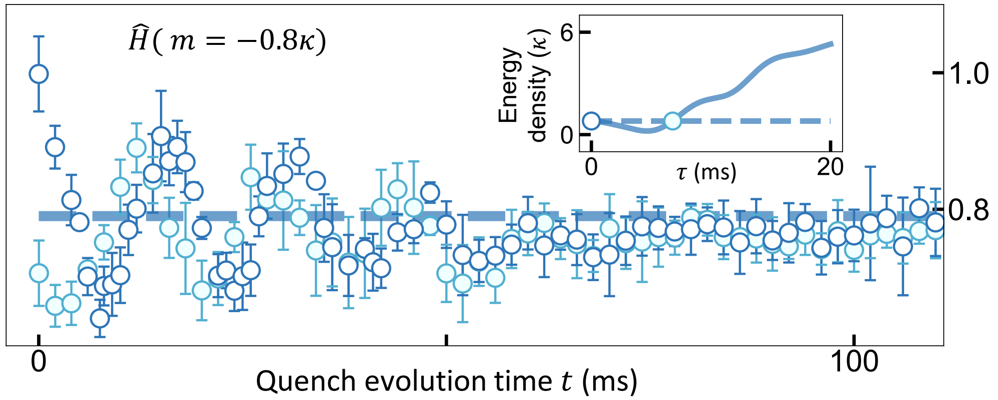
Surace, Lerose, New J. Phys. 23 (2021) 062001.

THERMALIZATION AND NON-EQUILIBRIUM PROPERTIES

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

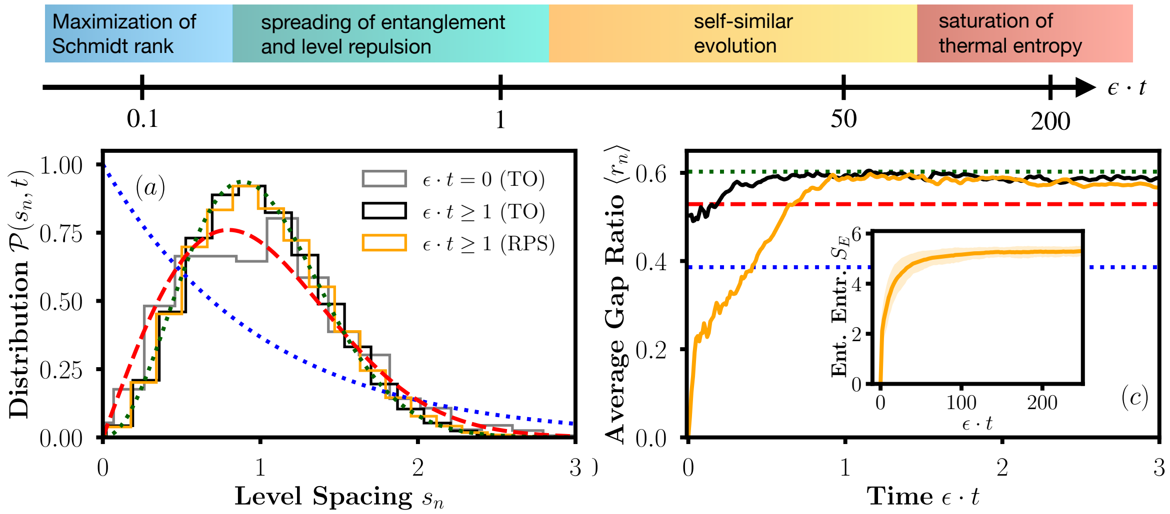


Zhou et al, *Science* 377 (2022) 6603.

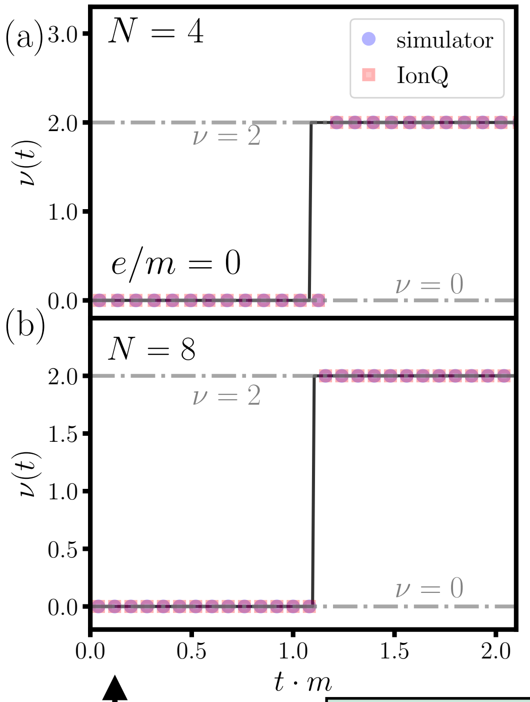


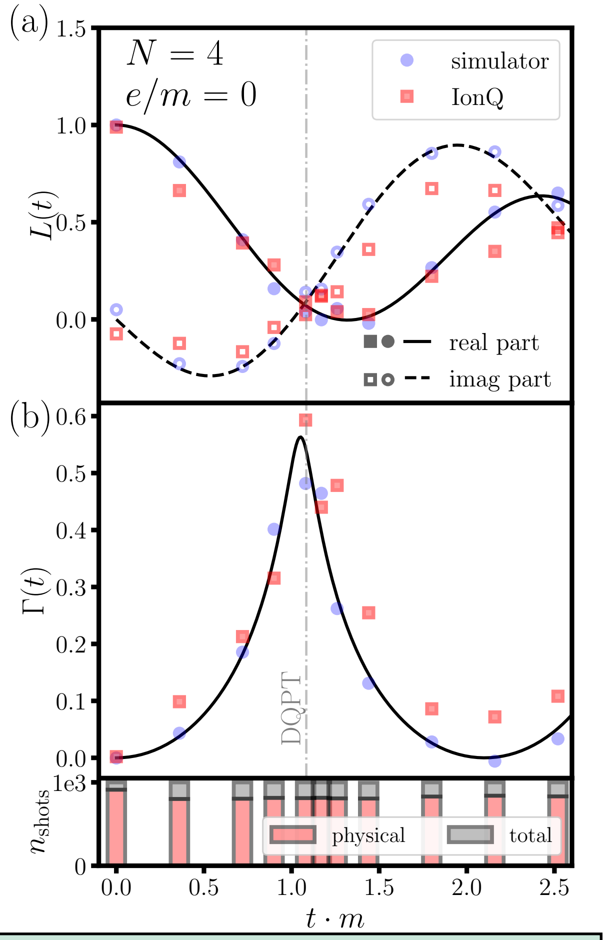
Stages of thermalization dynamics of Z2 LGT in 2+1 D from entanglement spectrum

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

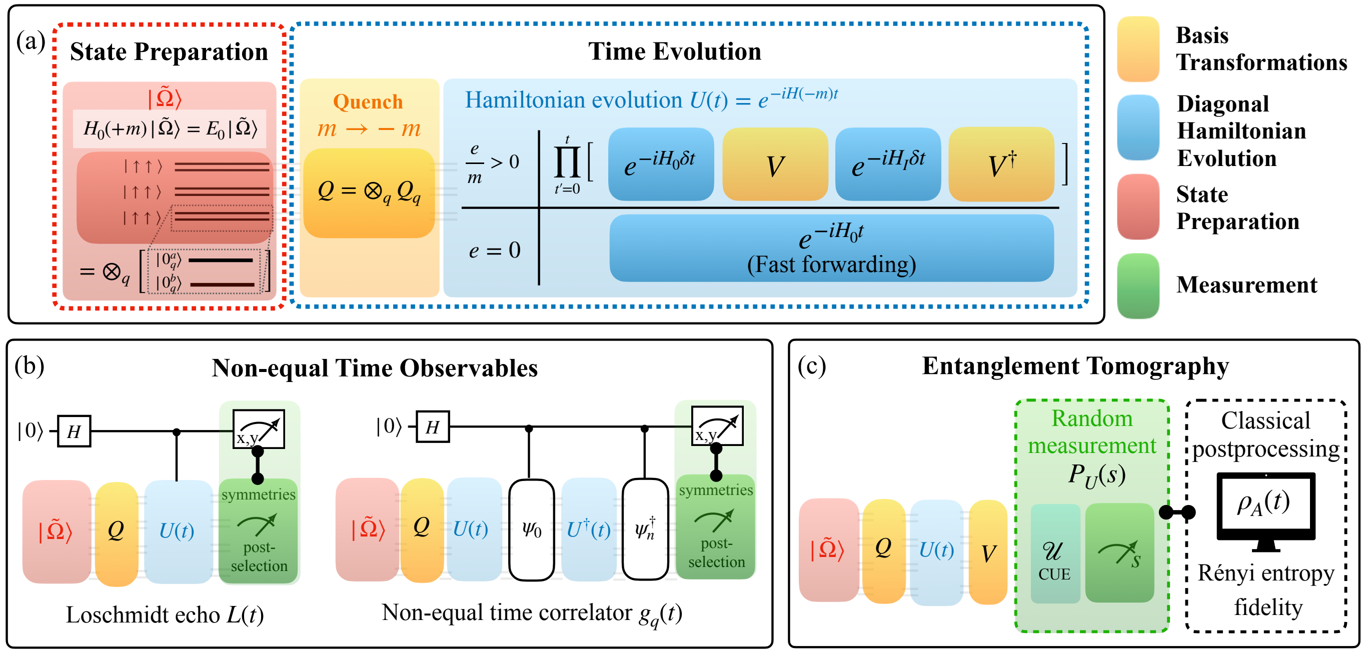


A dynamical phase transition and topological order in lattice Schwinger model with an IonQ quantum computer:



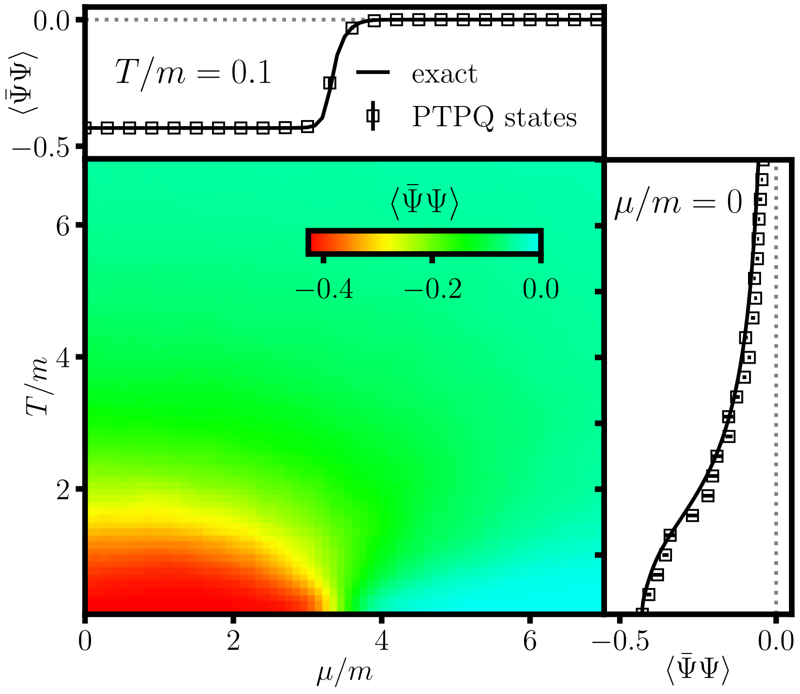


Mueller, Carolan, Connelly, Dumitrescu, ZD, Mueller, Yeter-Aydeniz, to be released (2022).



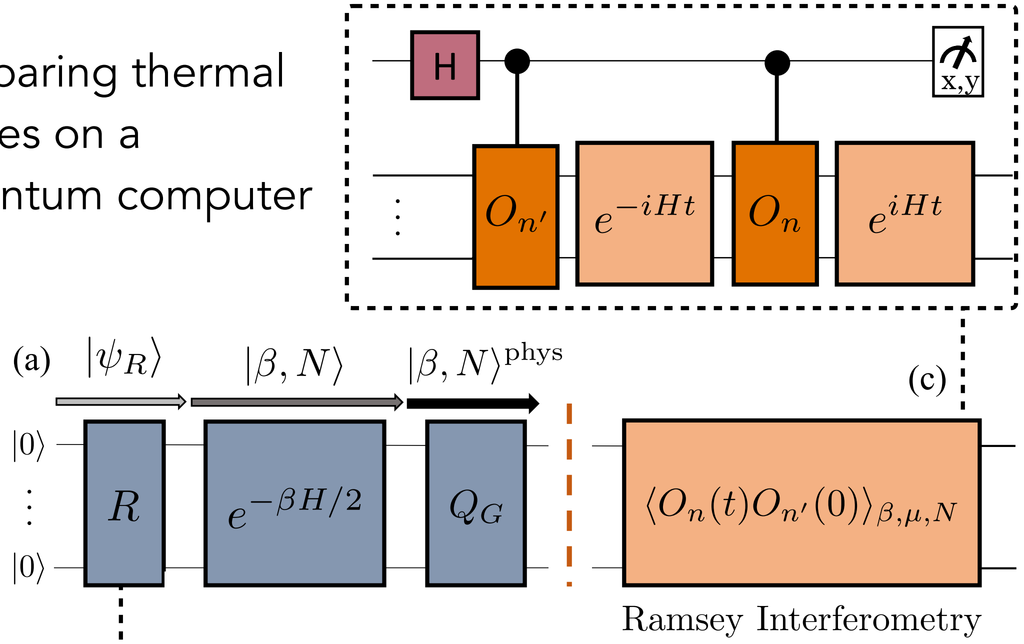
FINITE TEMPERATURE AND FINTIE DENSITY PHASE DIAGRAM

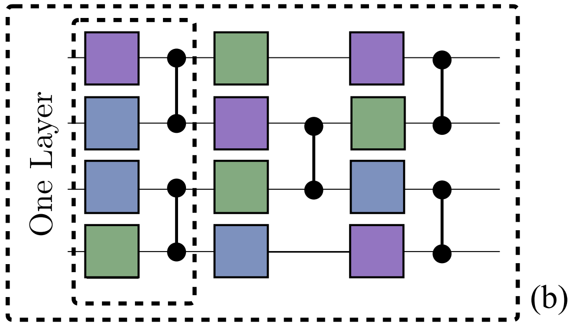
Toward Quantum Computing Phase Diagrams of Gauge Theories with Thermal Pure Quantum States, ZD, Mueller, Powers, arXiv:2208.13112 [hep-lat] (2022).



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

Preparing thermal states on a quantum computer

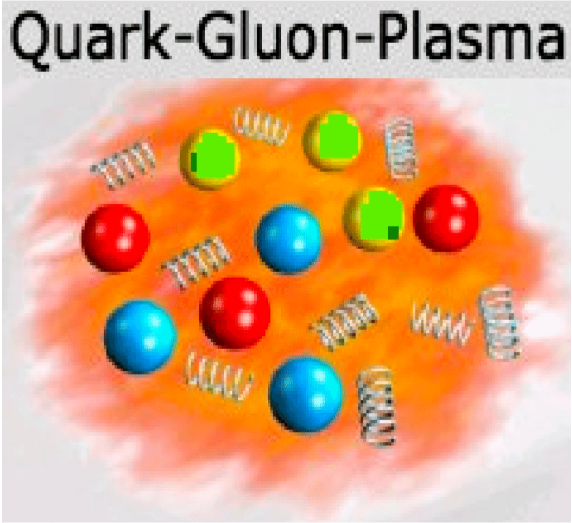




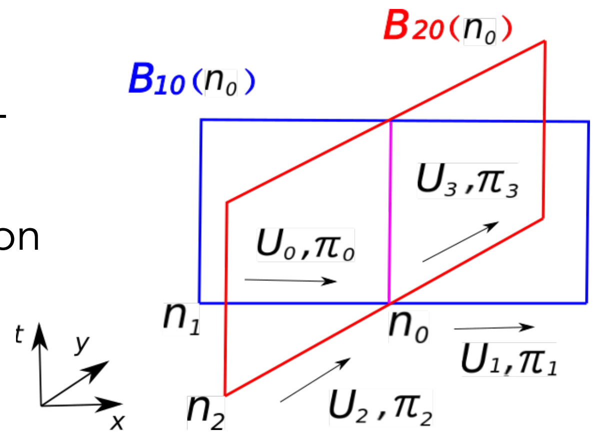
See also: Quantum Simulation of Chiral Phase Transitions, Czajkaa, Kang, Ma , Zhaoa, *JHEP* 08 (2022) 209.

Transport coefficients from real-time correlators of energy momentum tensor

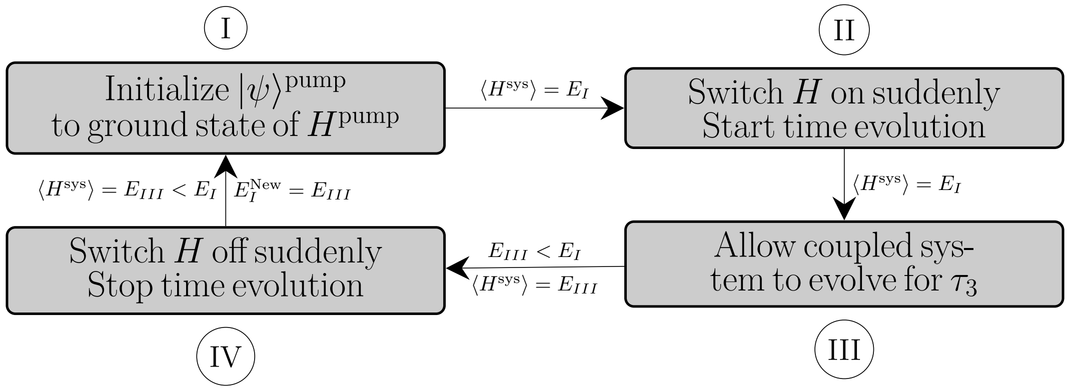
Cohen, Lamm, Lawrence, and Yamauchi, Phys. Rev. D 104, 094514 (2021).



How to define energy-momentum tensor in Hamiltonian formulation



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



Initialize $|\psi\rangle^{\text{pump}}$ to ground state of H^{pump}

$\langle H^{\text{sys}}\rangle = E_I$

Switch H on suddenly Start time evolution

$\langle H^{\text{sys}}\rangle = E_I$

Allow coupled system to evolve for τ_3

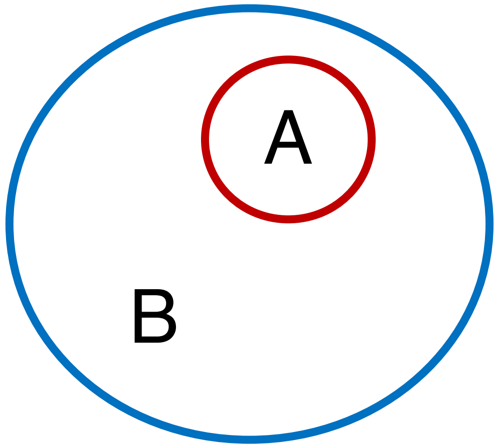
$E_{III} < E_I$ $\langle H^{\text{sys}}\rangle = E_{III}$

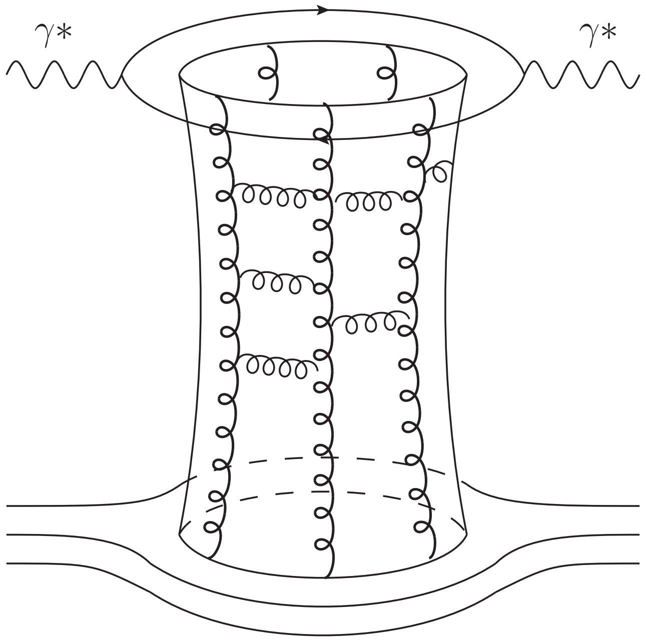
Switch H off suddenly Stop time evolution

$\langle H^{\text{sys}}\rangle = E_{III} < E_I$ $E_I^{\text{New}} = E_{III}$

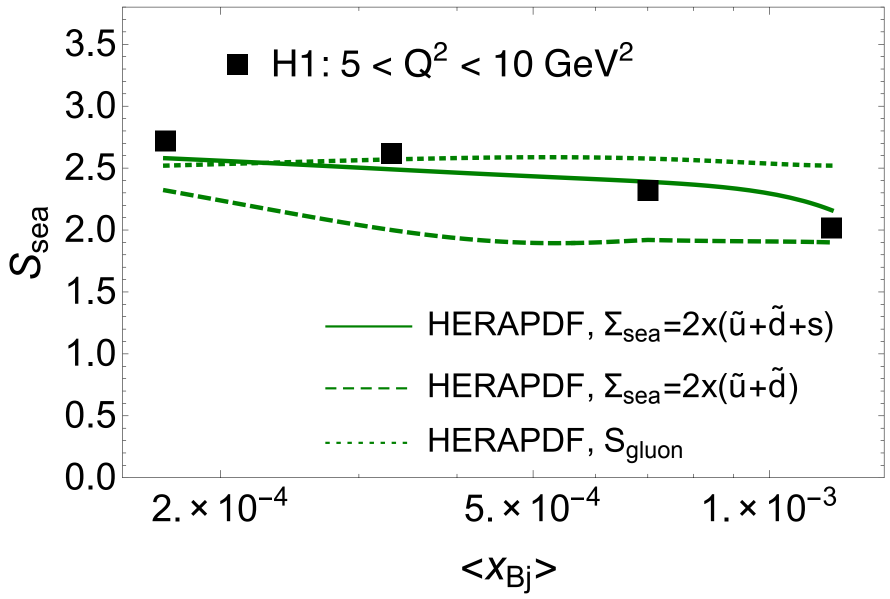
QUANTUM ENTANGLEMENT IN HIGH- AND LOW-ENERGY NUCLEAR PHYSICS

Deep inelastic scattering as a probe of entanglement?



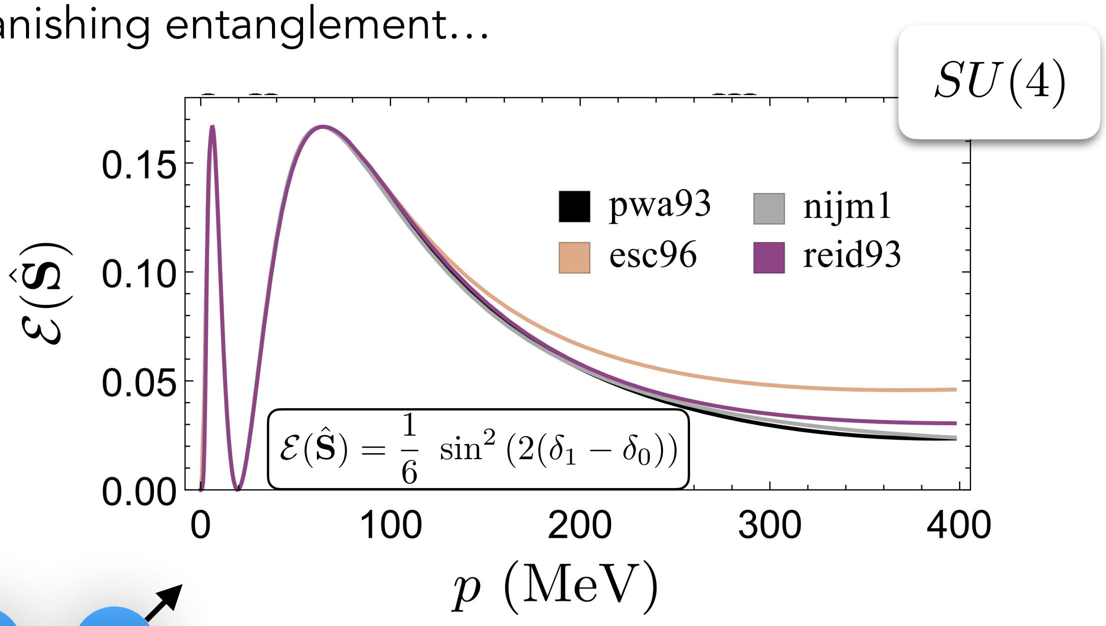


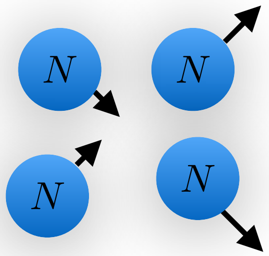
Entropy of hadrons derived from PDFs can be related to entanglement entropy.



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

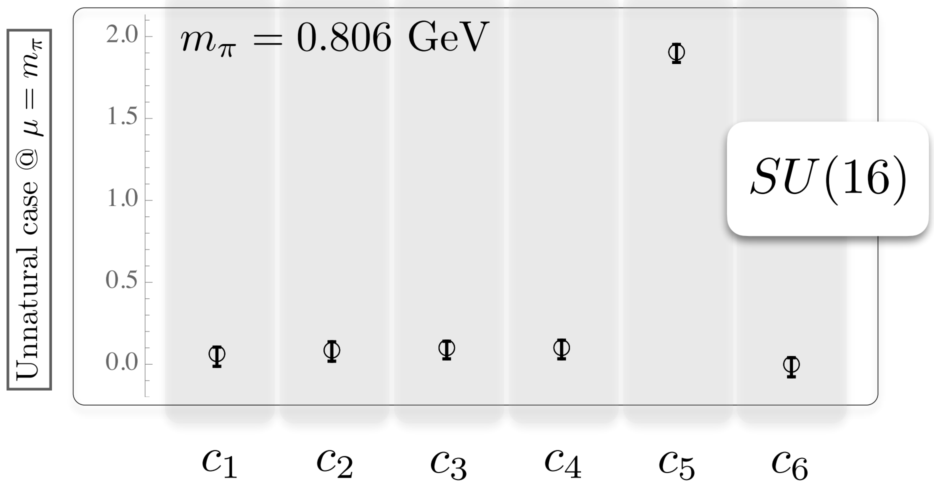
NN interactions at low energies are consistent with vanishing entanglement…

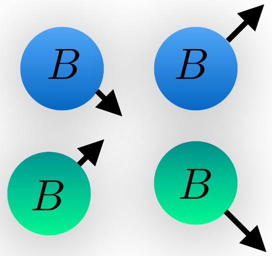




Beane, Kaplan, Klco and Savage, Phys. Rev. Lett. 122, 102001 (2019)

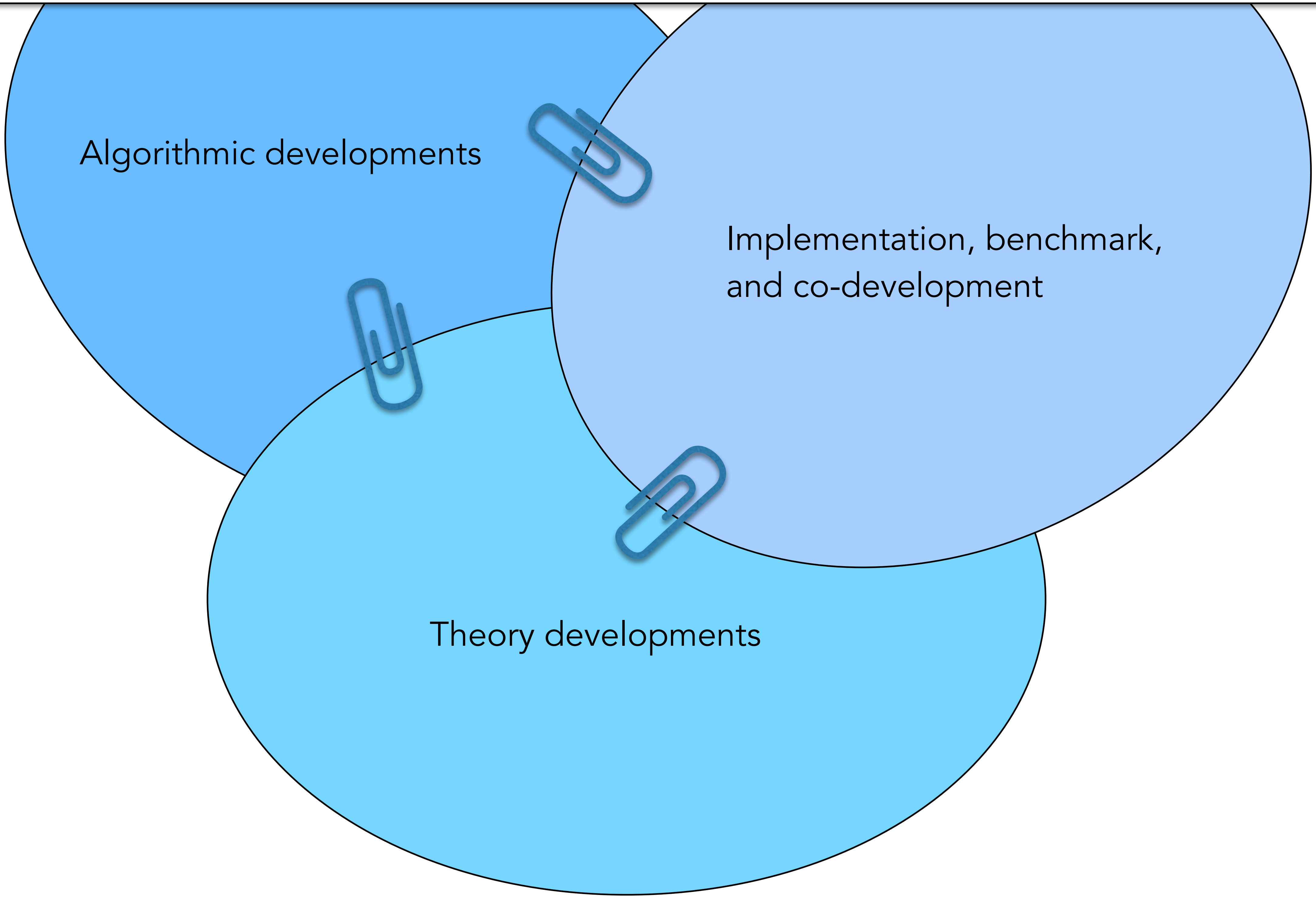
…as are low-energy BB interactions as obtained with lattice QCD.





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

We've got a long way to go to get to **QCD** but we know what to do! If one thing we learned from the successful conventional lattice-QCD program is that **theory/algorithm/experiment** collaborations will be the key. It is even more important in the quantum-computing era since our computers are themselves physical systems!



Algorithmic developments

Implementation, benchmark, and co-development

Theory developments

THANK YOU

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