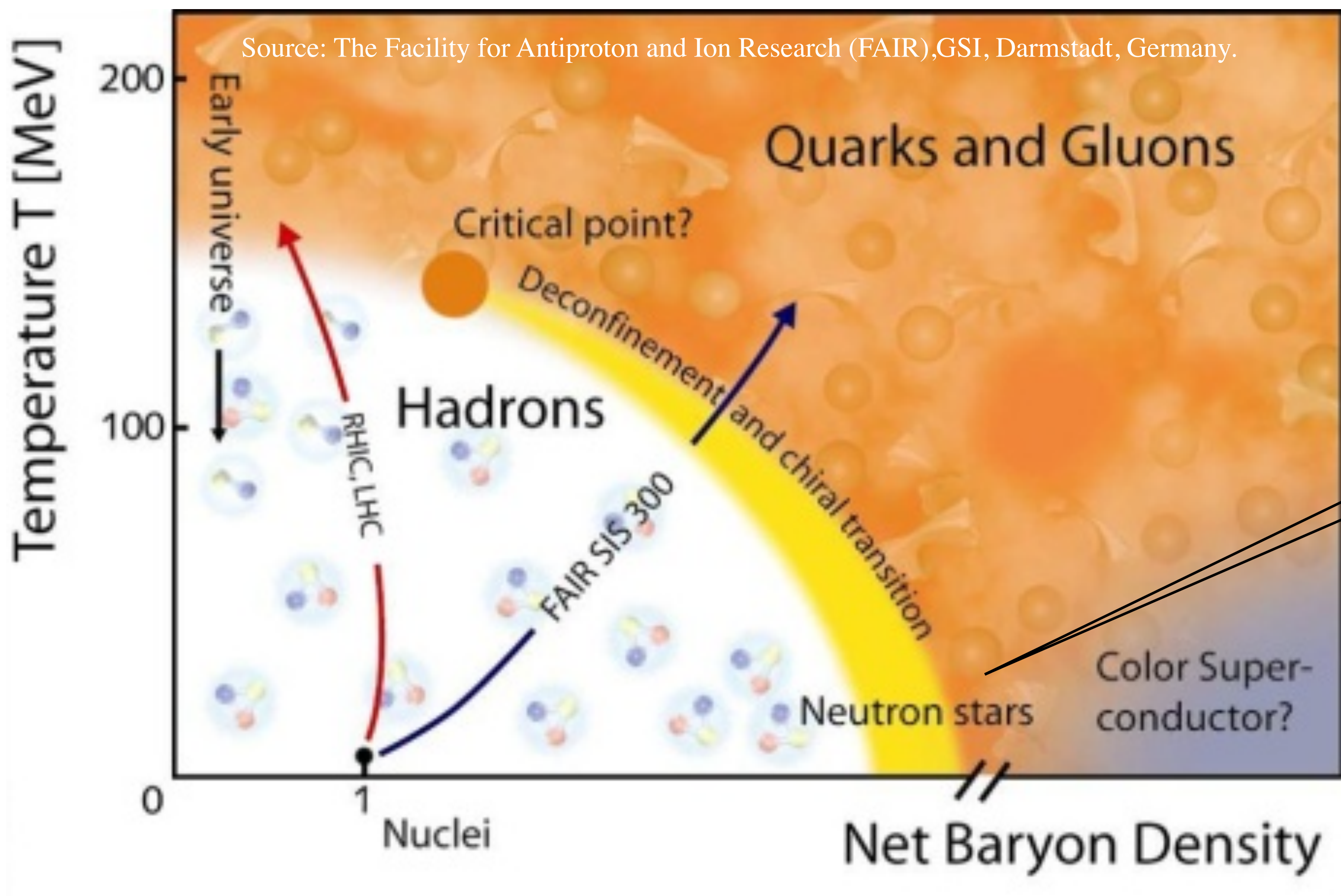
Quantum Computing
and
Lattice Field Theory Program

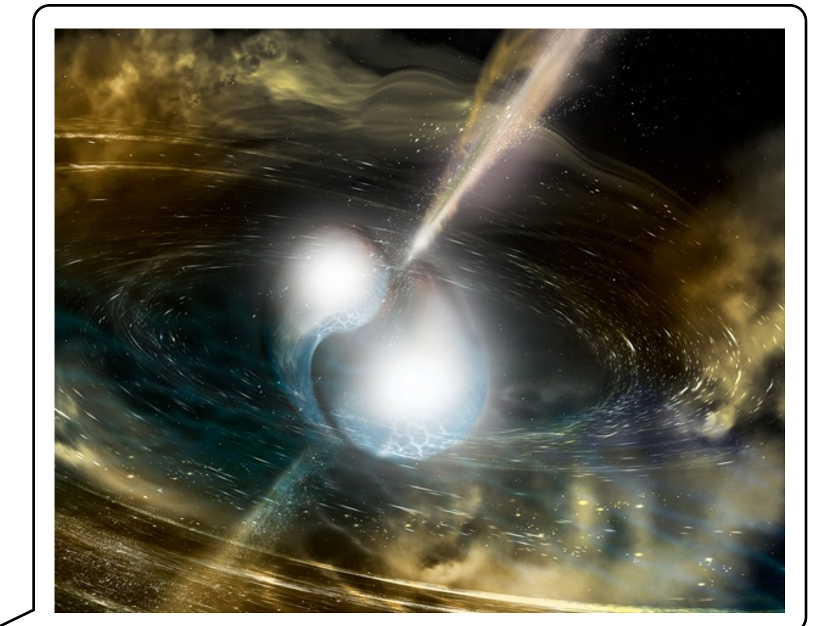
Zohreh Davoudi
University of Maryland, College Park

USQCD All-hands Meeting
Hosted by USQCD/MIT
May 1, 2021

OUR MOTIVATION FOR LEVERAGING QUANTUM TECHNOLOGIES

i) Dense matter EOS, phase diagram of QCD





Path integral formulation…

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

with a complex action:

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

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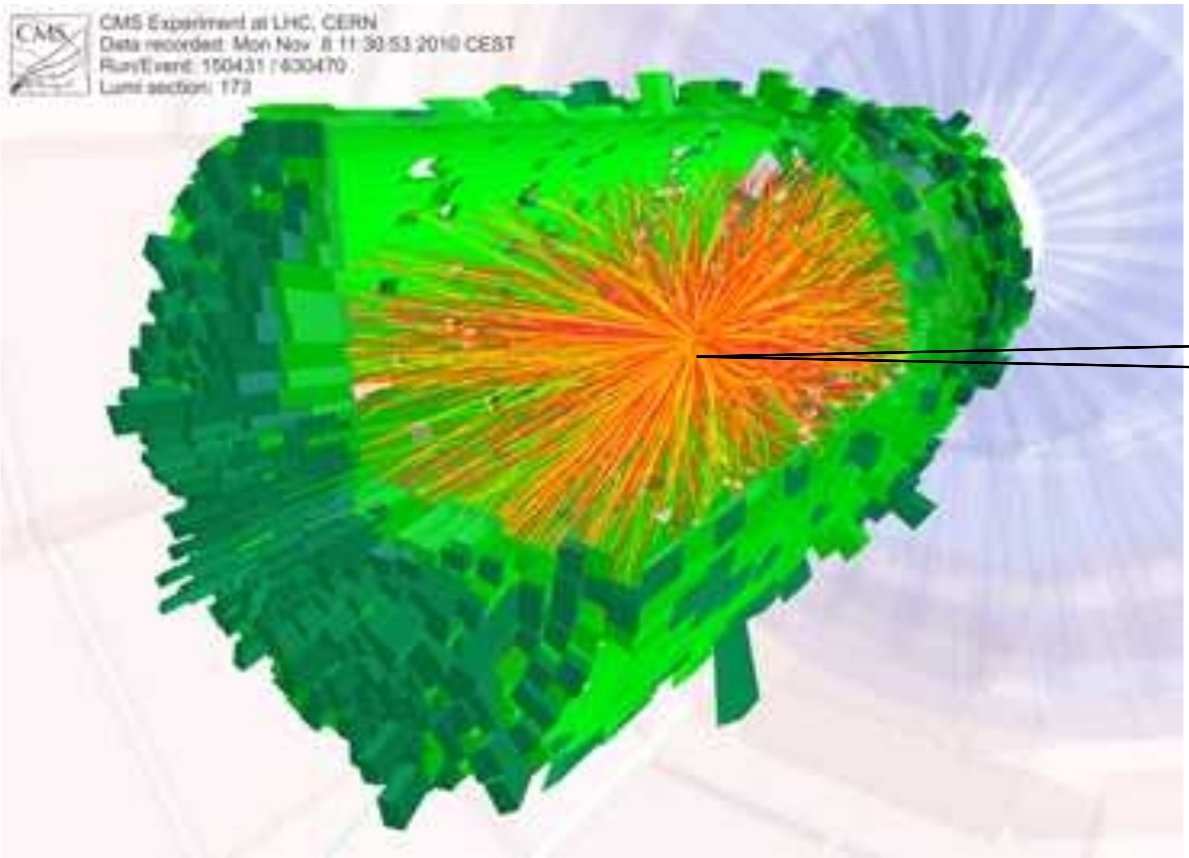
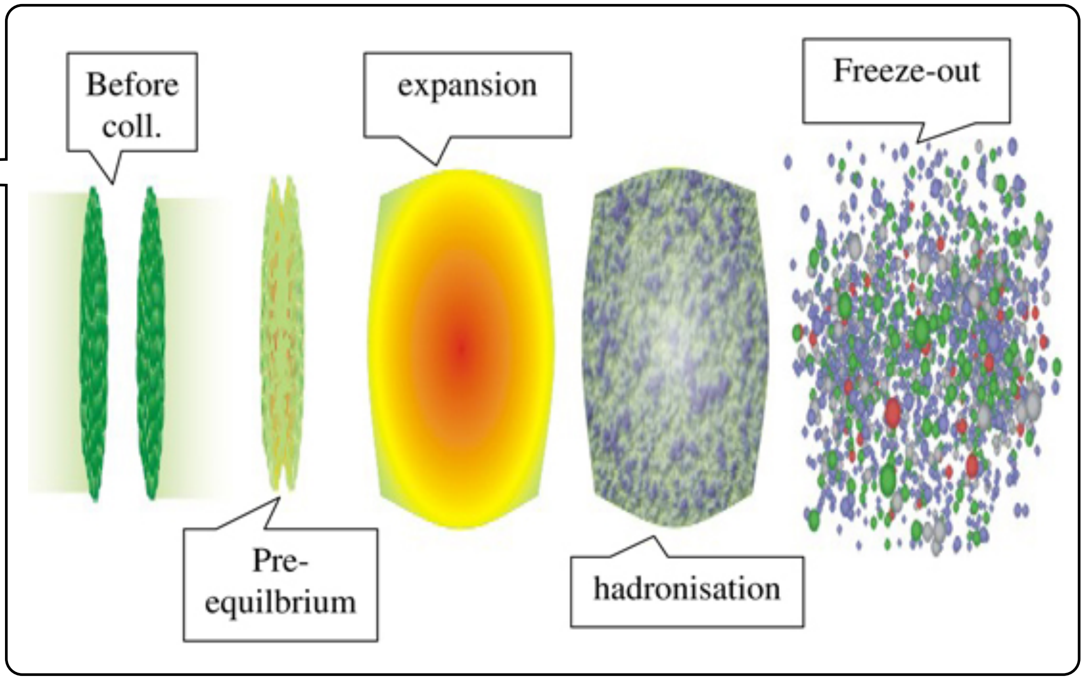
ii) Real-time dynamics of matter (heavy-ion collisions, early universe…)





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

Path integral formulation…

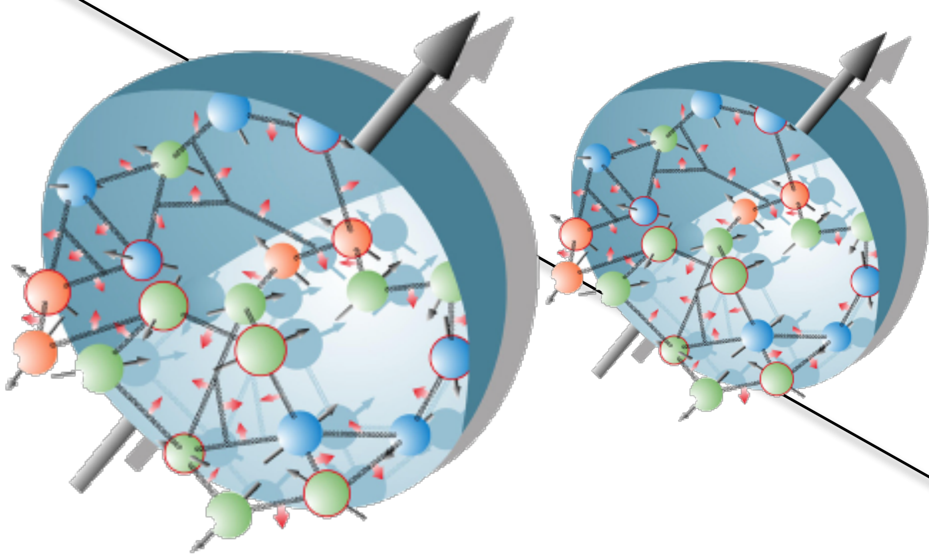
$$\boxed{e^{iS[U,q\bar{q}]}}$$

Hamiltonian evolution:

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

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

QUANTUM CHEMISTRY, CM vs. QUANTUM FIELD THEORY: SOME SIMILARITIES BUT MAJOR DIFFERENCES



Simulations based in Standard Model

Both bosonic and fermionic DOF are dynamical and coupled, exhibit both global and local (gauge) symmetries, relativistic hence non-conservation of particle number, vacuum state nontrivial in strongly interacting theories.

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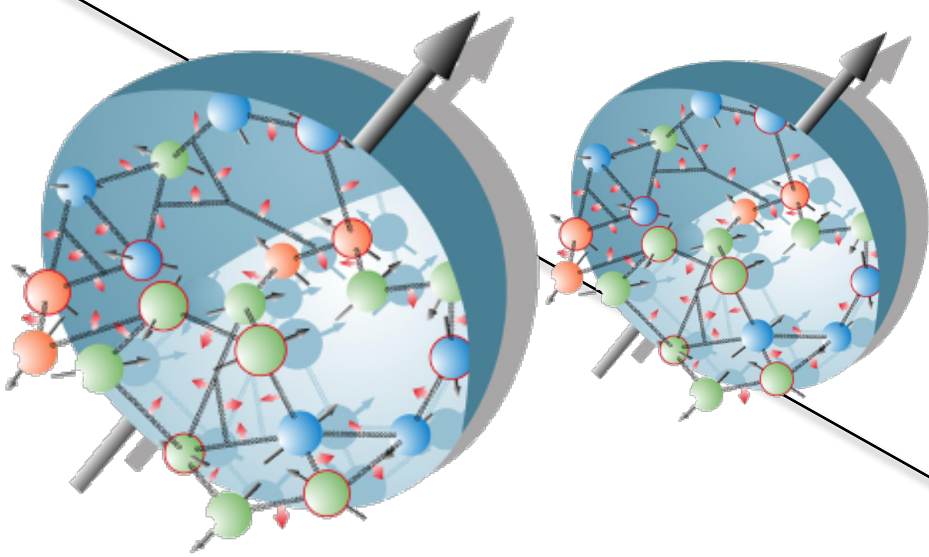

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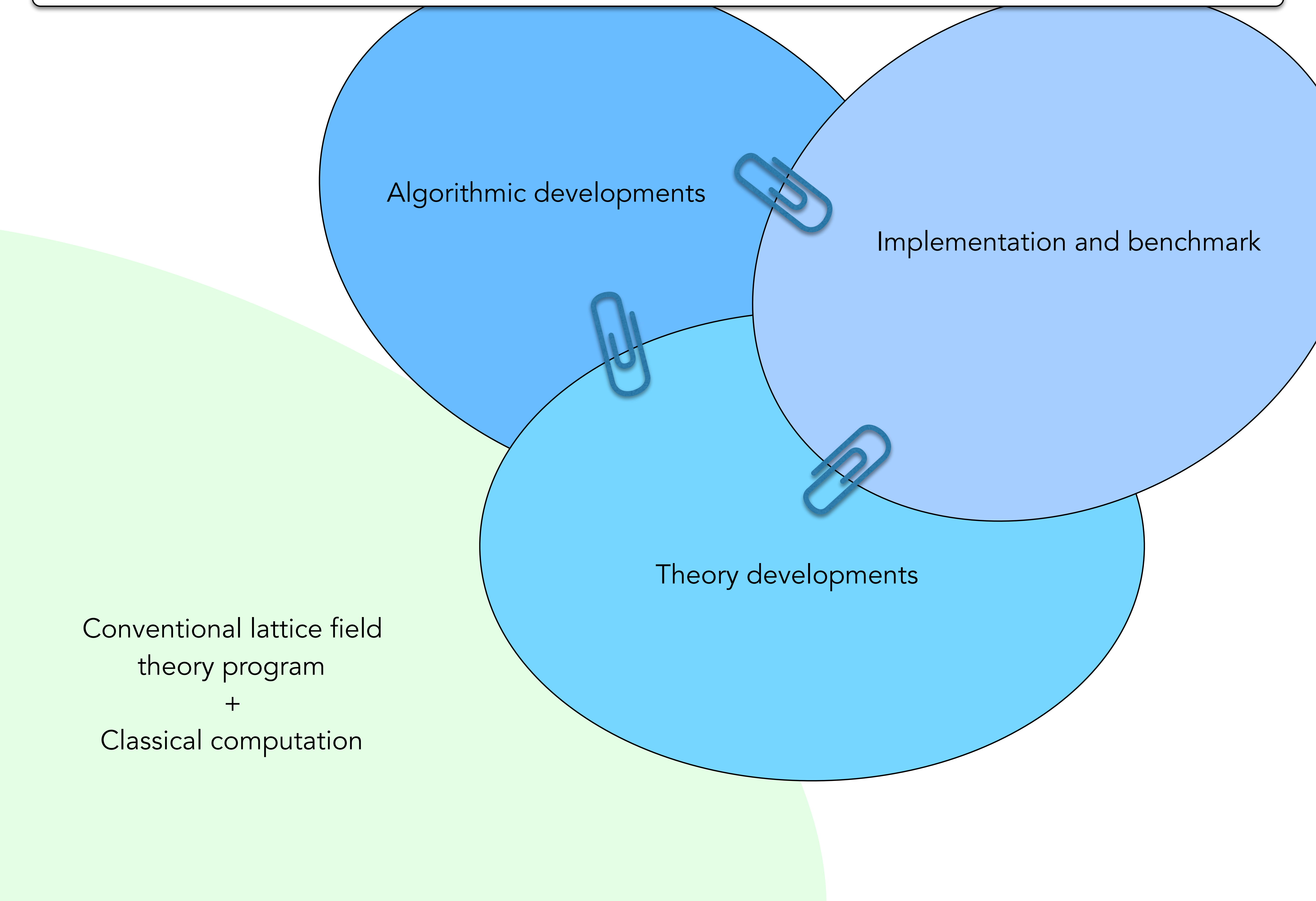
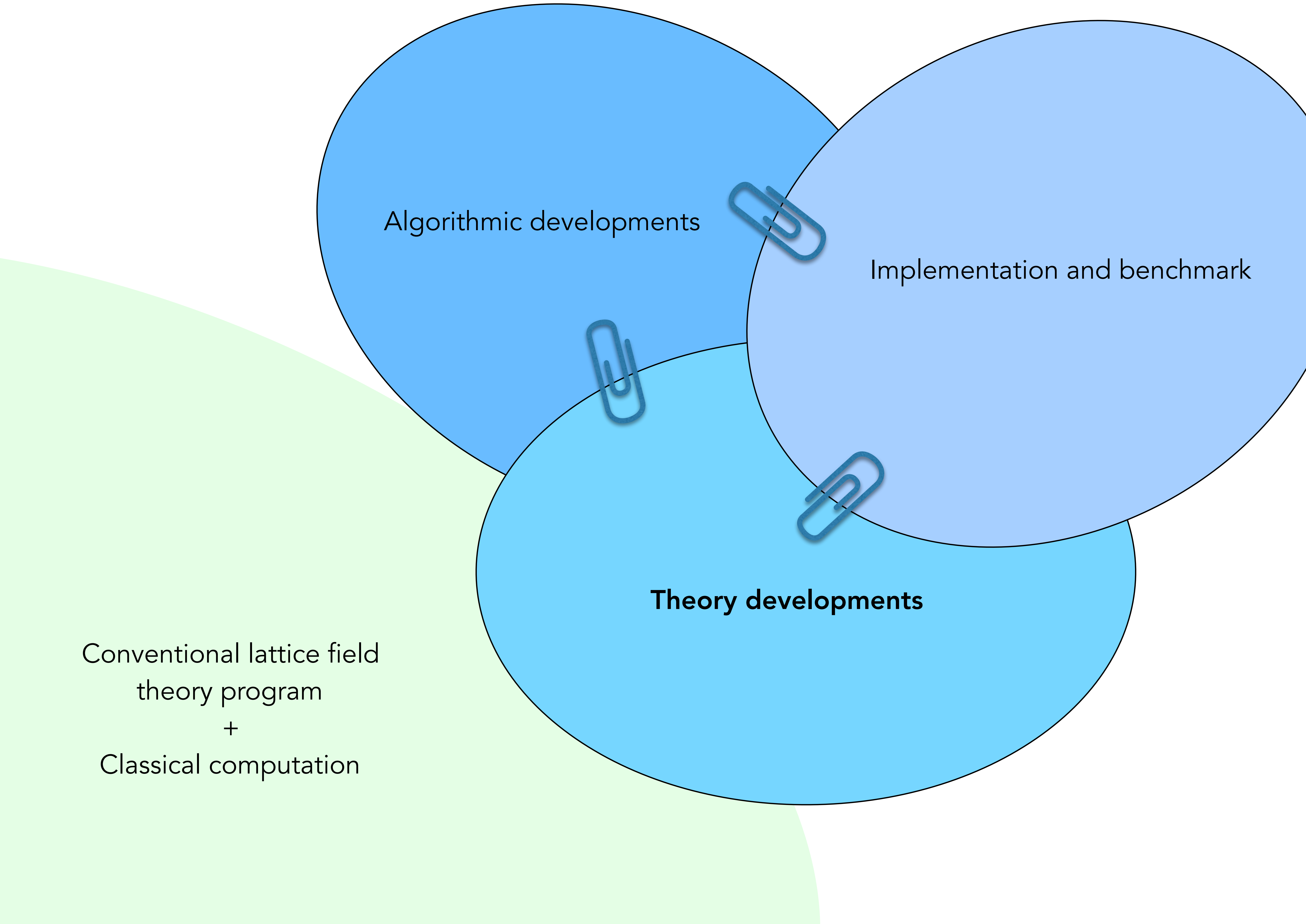
Attempts to cast QFT problems in a language closer to quantum chemistry and NR simulations:
Kreshchuk, Kirby, Goldstein, Beauchemin, Love, arXiv:2002.04016 [quant-ph]
Liu, Xin, arXiv:2004.13234 [hep-th]
Barata , Mueller, Tarasov, Venugopalan (2020)

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




Algorithmic developments
Implementation and benchmark
Theory developments
Conventional lattice field
theory program
+
Classical computation

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:

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

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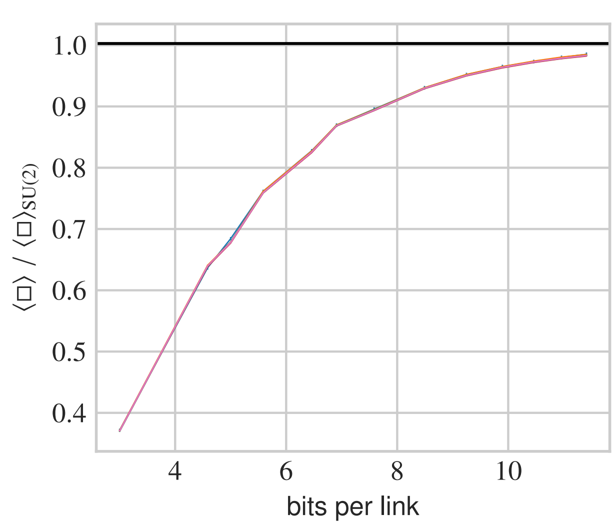
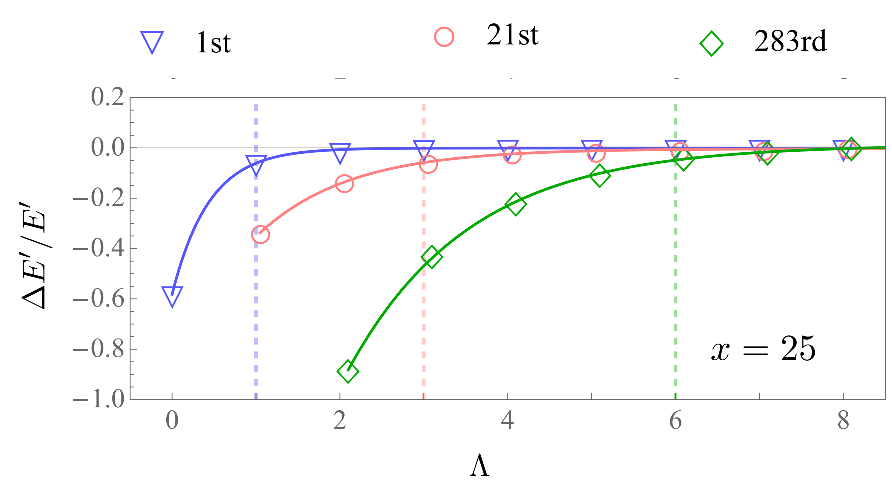
Gauge-field truncation

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



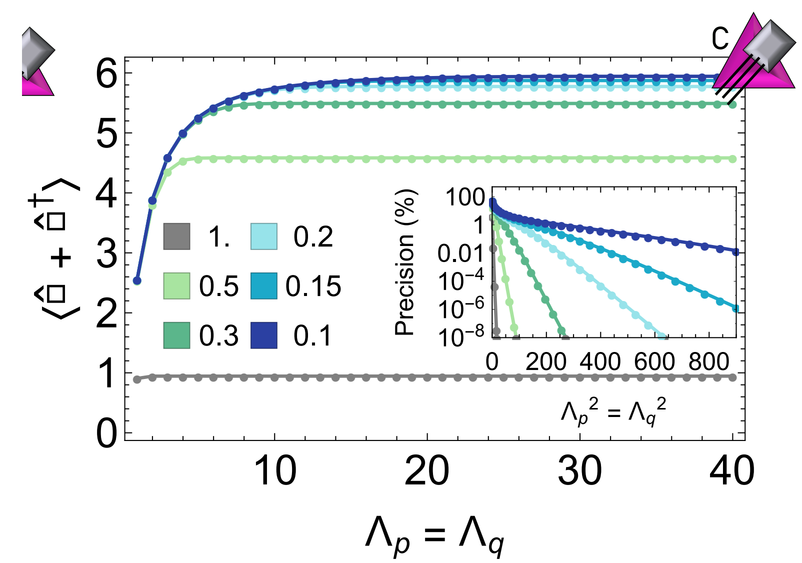
Hackett et al, Phys. Rev. A 99, 062341 (2019)

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

Generator of infinitesimal gauge transformation

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

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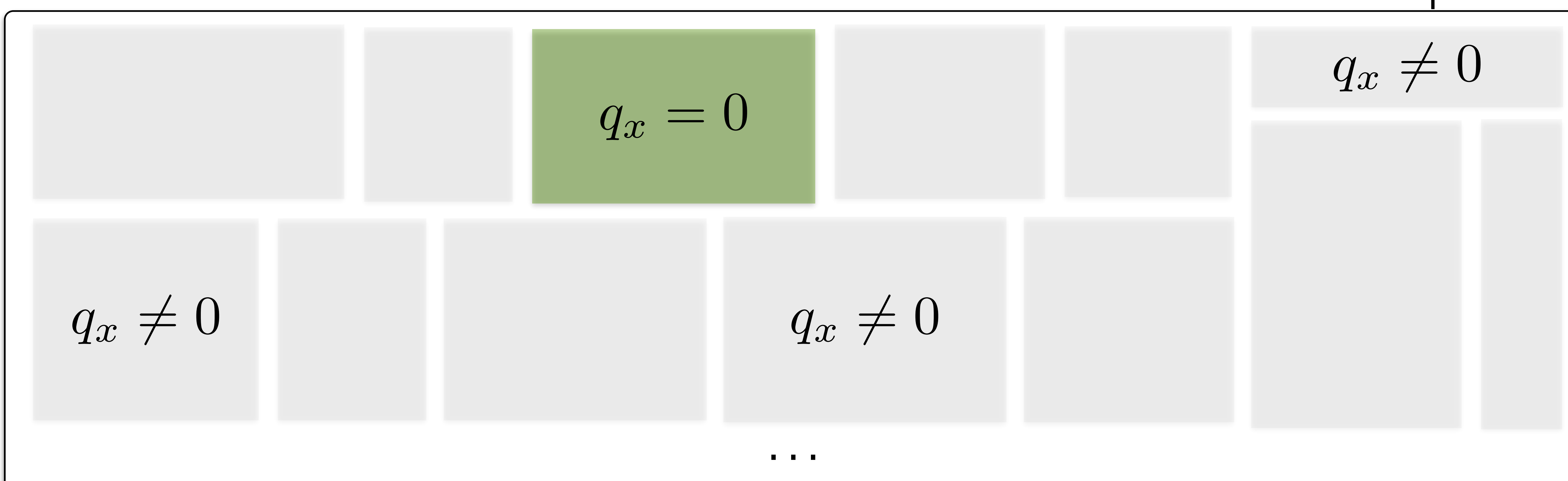
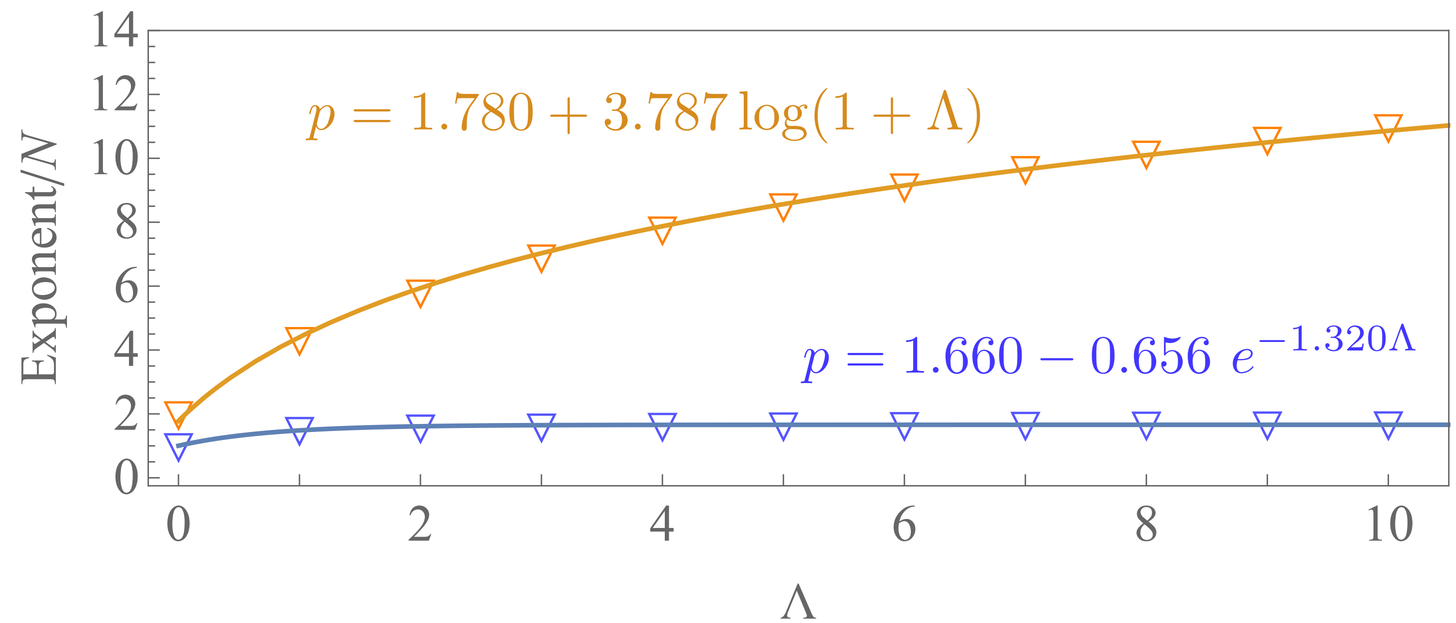


QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

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

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



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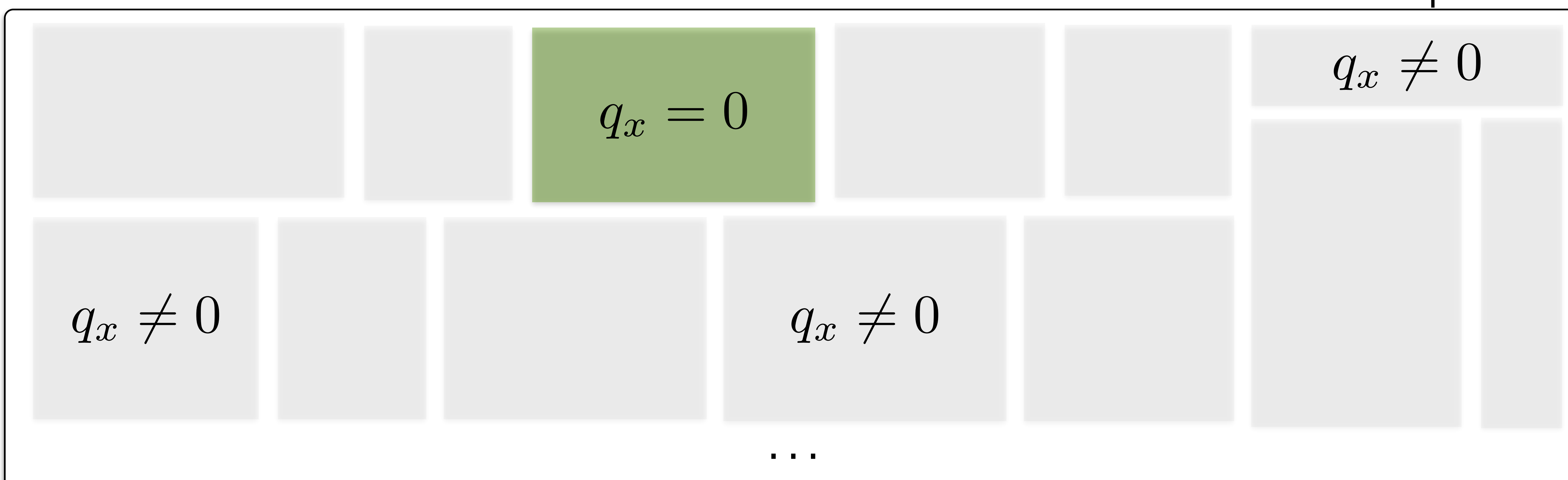
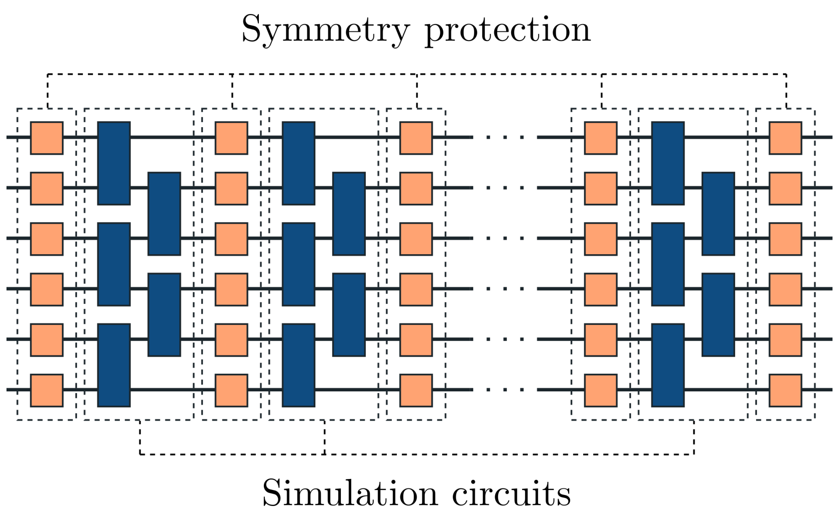


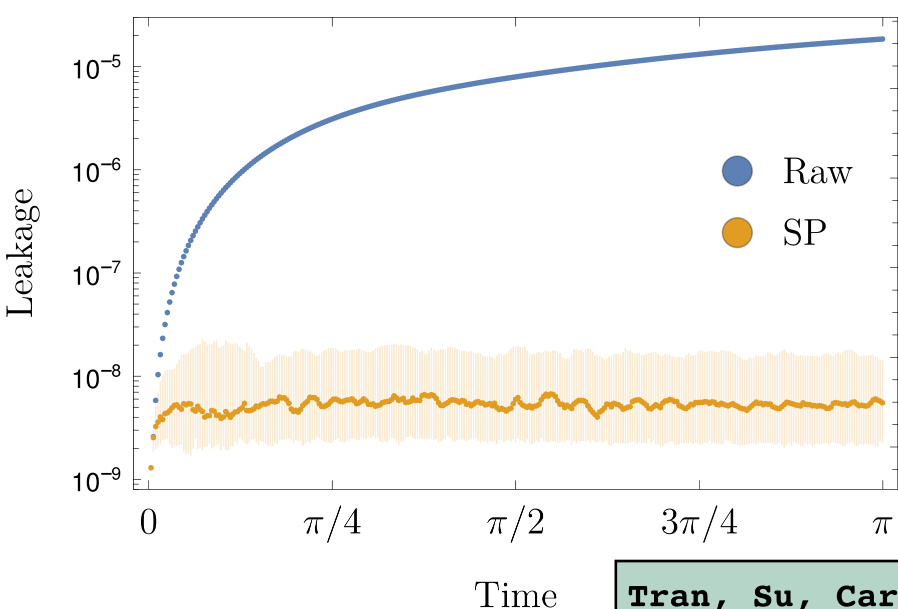
IDEAS TO SUPPRESS LEAKAGE TO UNPHYSICAL SECTOR IN THE SIMULATION

Can restore symmetries lost by Trotter expansion of the evolution…



$$U_t \approx \prod_{k=1}^{r} C_k^\dagger S_{\delta t} C_k. \quad \text{with} \quad [C, H] = 0 \quad \forall\, C \in \mathcal{S}.$$

Example: a 4-site Schwinger model



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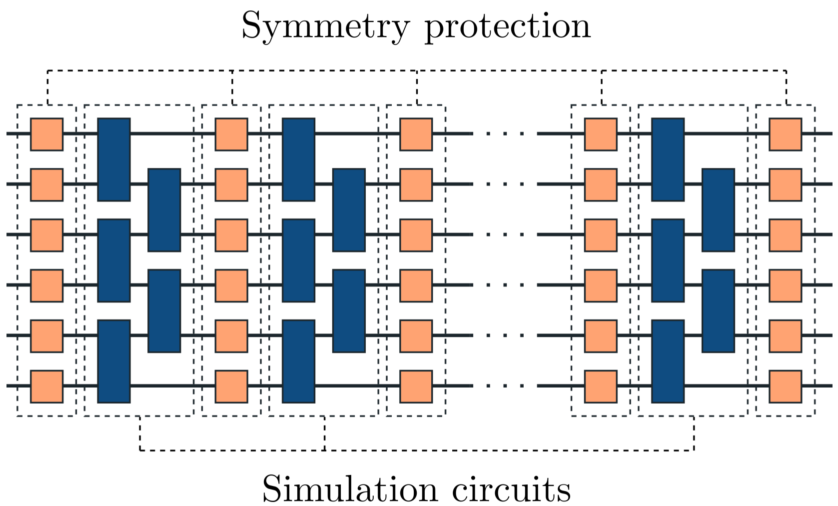

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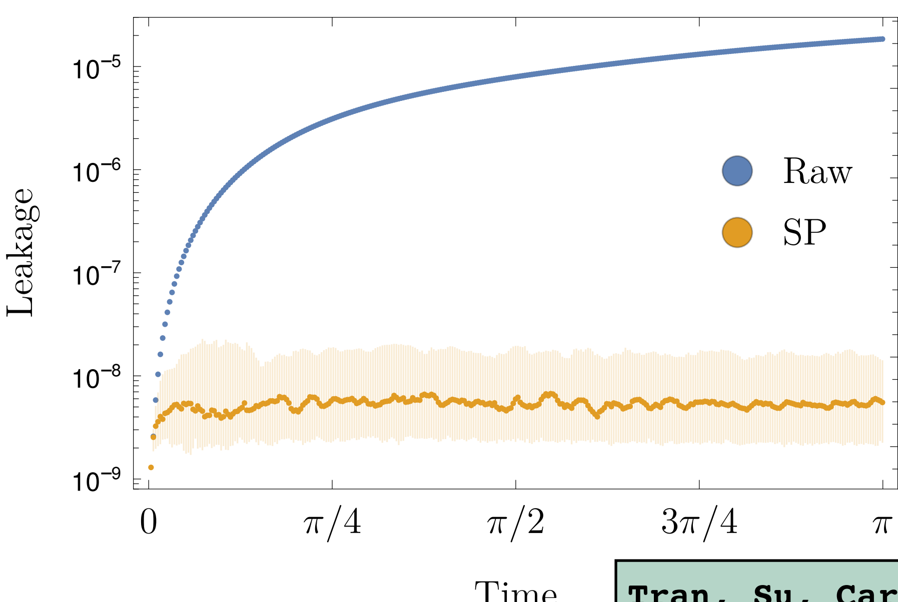

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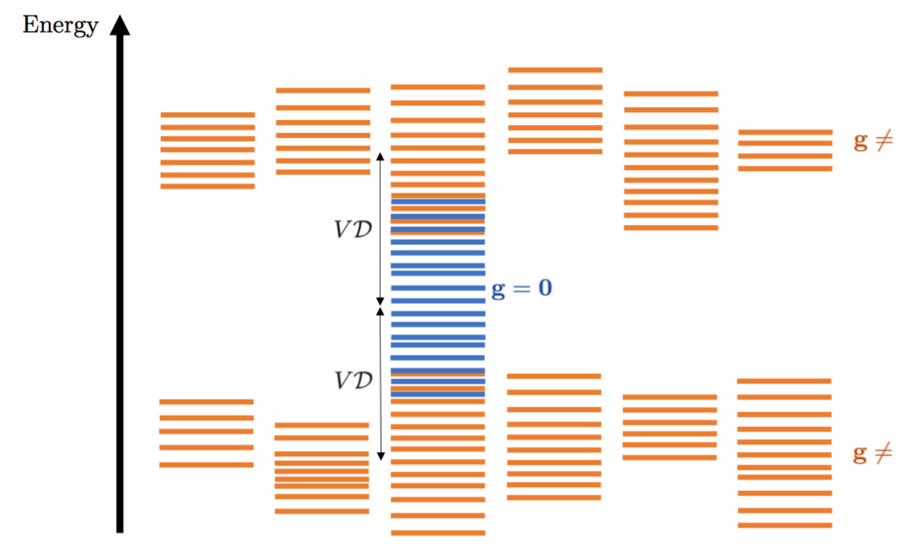
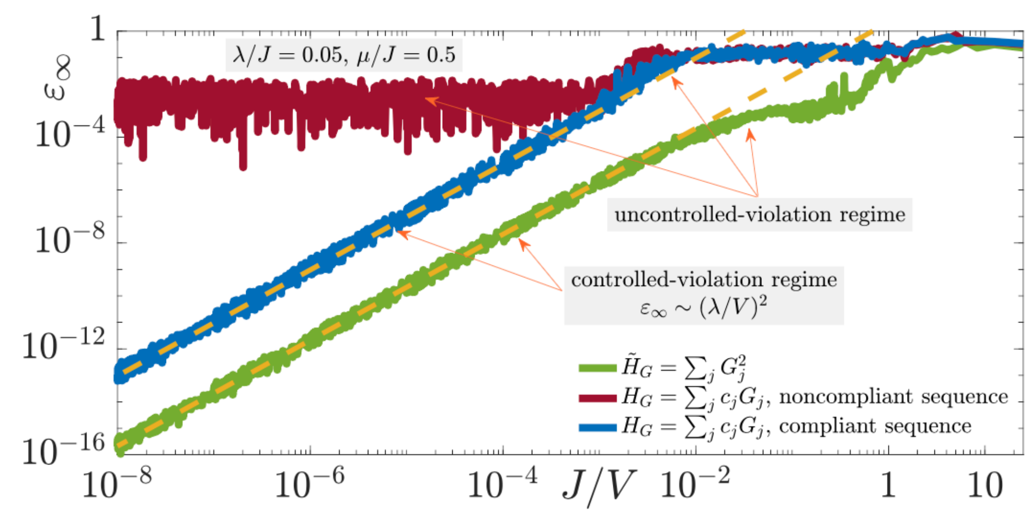
…which mimics a large-angle single-qubit rotations procedure:

Gauss's law operator

Add to the Hamiltonian: $V H_G = V \sum c_j G_j.$





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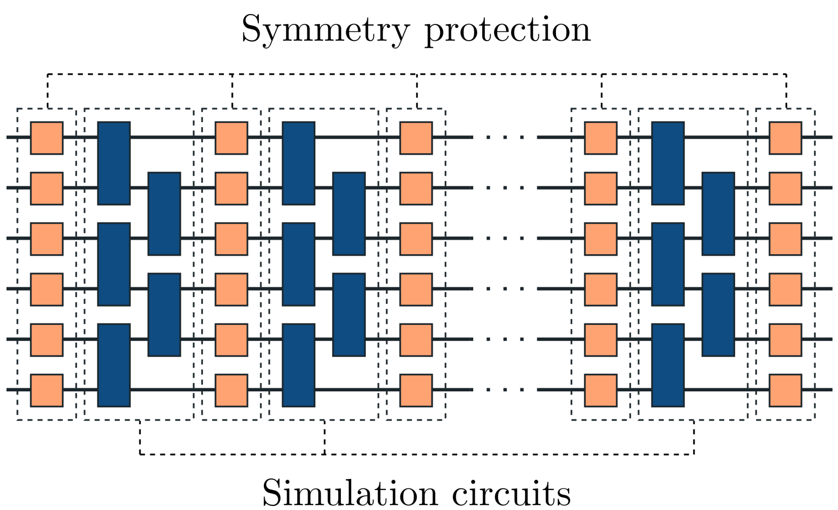

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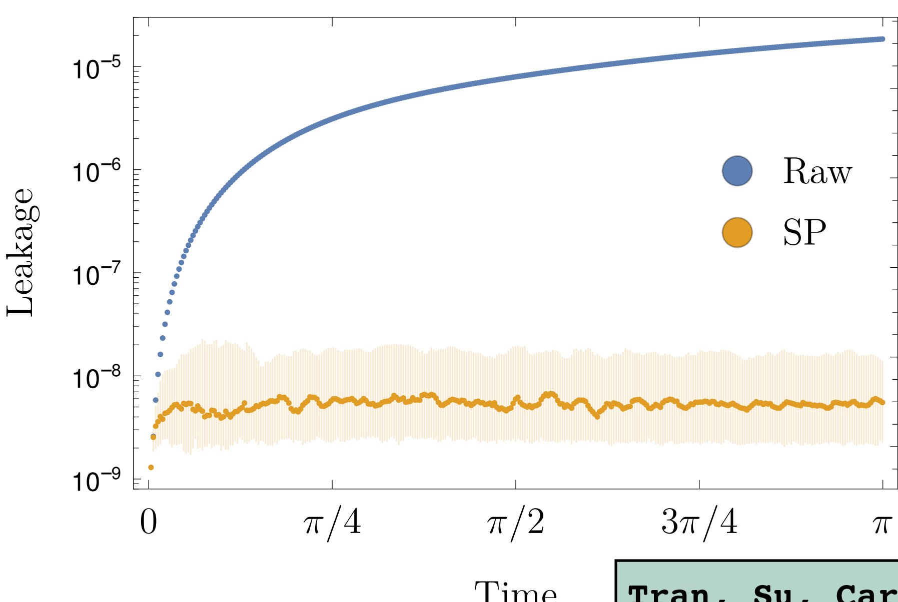

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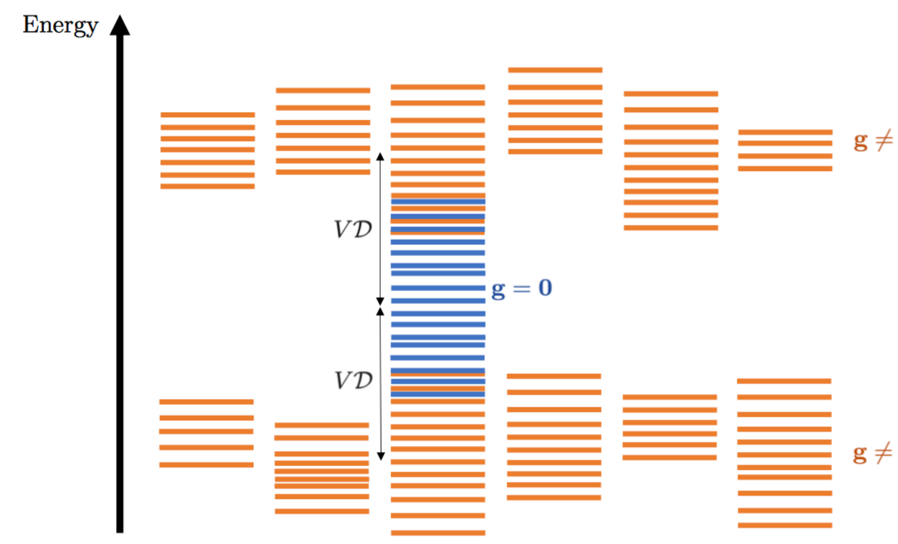

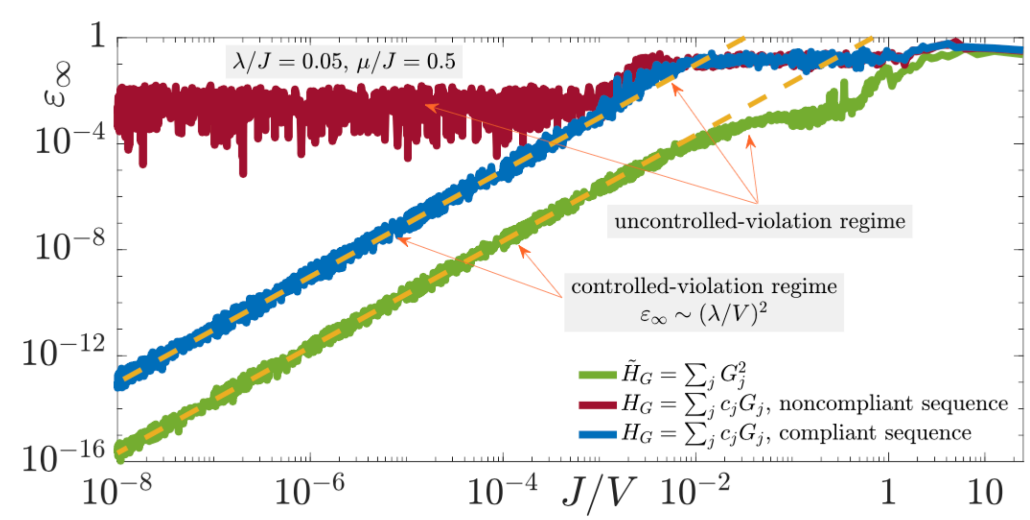

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See also Stannigel, et al, Phys. Rev. Lett. 112, 120406, Lamm, Lawrence, Yamauchi, arXiv:2005.12688 [quant-ph], and Kasper et al, arXiv:2012.08620 [quant-ph] for similar symmetry-protection ideas.

HOW ABOUT CONSTRUCTING THE HAMILTONIAN AND HILBERT SPACE MORE EFFICIENTLY?

The time complexity of classical Hamiltonian-simulation algorithms for various formulations

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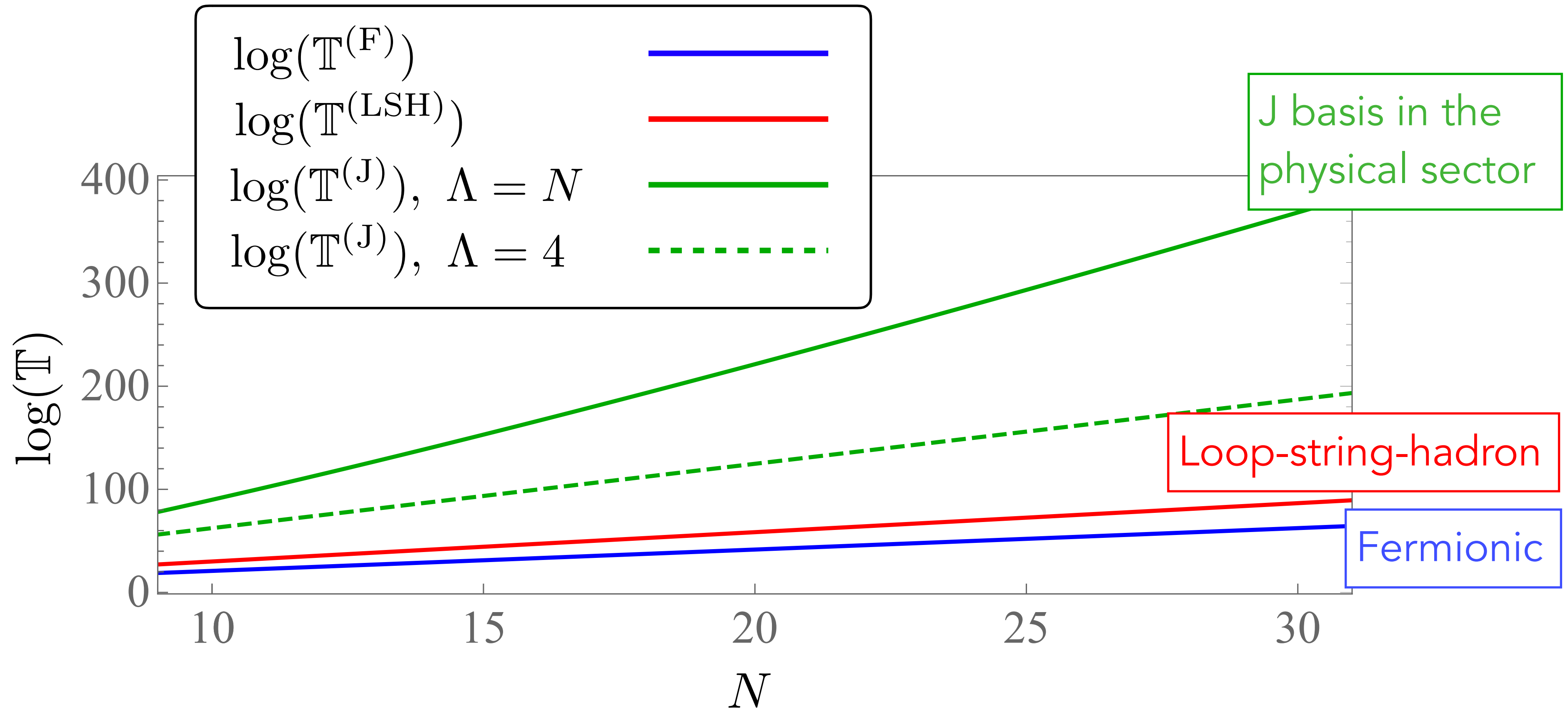

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IN FACT MANY MANY MORE FORMULATIONS EXIST, EACH WITH ITS OWN PROS AND CONS:

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

Bosonic basis
Cirac and Zohar

Spin-dual representation and hydrogen atom basis
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Fermionic basis
Hamer et al; Martinez et al; Banuls et al

Maximal tree and coupled-cluster basis
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Link models and qubit regularization
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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

(Effective) models and light-front quantization
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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.

OBSERVABLES TOO REQUIRE DEDICATED STUDIES TO BE CAST IN HAMILTONIAN LANGUAGE.

Structure functions and PDFs
Mueller, Tarasov, Venugopalan;
Lamm, Lawrence, Yamauchi

Scattering and decay amplitudes
Jordan, Lee, Preskill; Ciavarella;
Surace, Lerose; Gustafson, Meurice, et al

Viscosity and transport coefficients
Cohen, Lamm, Lawrence, Yamauchi

Thermalization and many-body localization
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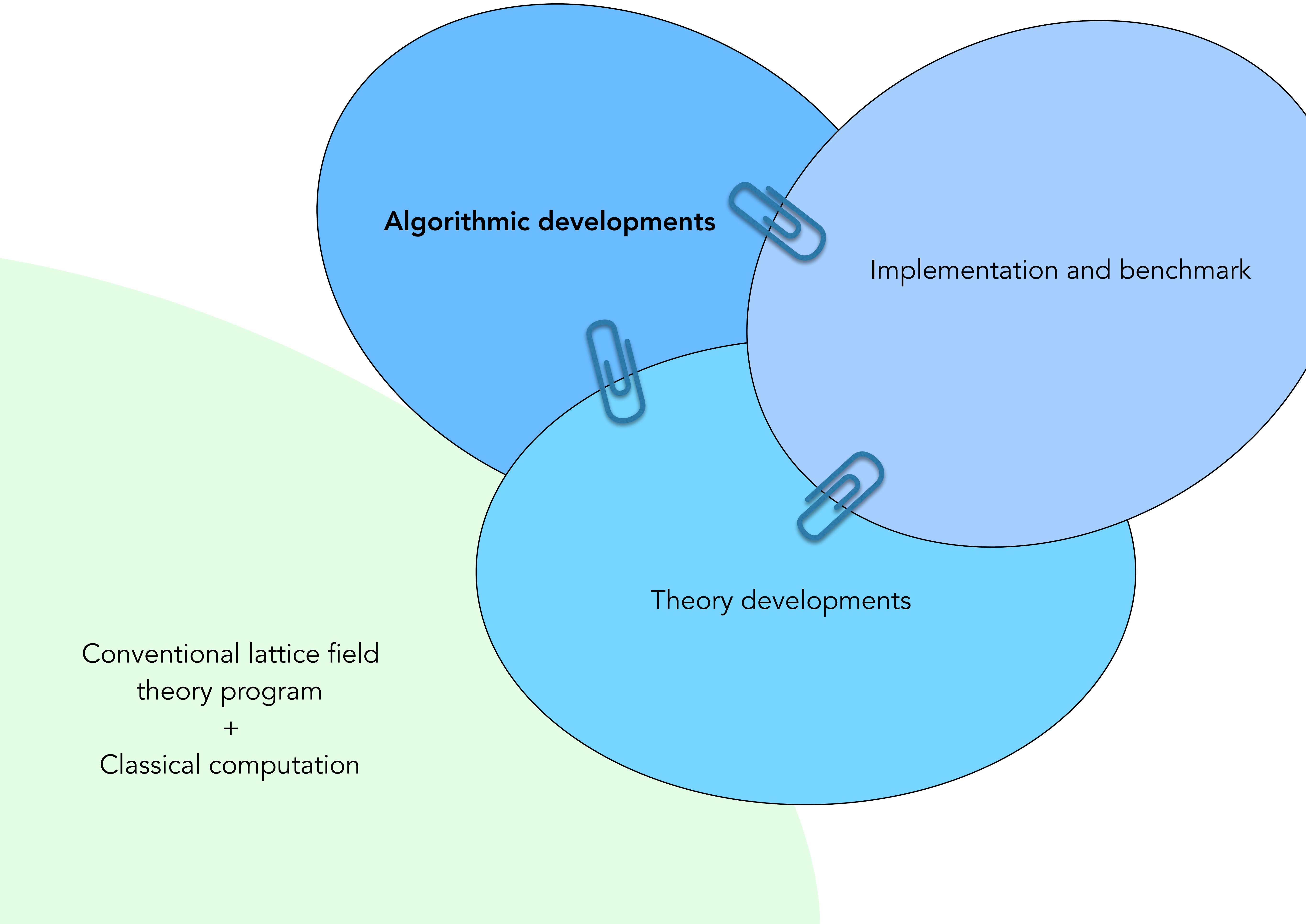
NORMALIZATION AND CONTINUUM LIMIT, TRUNCATION ERRORS, FINITE-VOLUME EFFECTS, etc. ALL MUST BE UNDERSTOOD.

Renormalization and continuum limit
Klco, Savage; Mueller et al

Finite-volume effects in Minkowski amplitudes
Briceno, Hansen, et al; ZD, Kadam

Truncation effects in scalar and gauge theories
Hackett, et al; Klco, Savage; ZD, Raychowdhury, Shaw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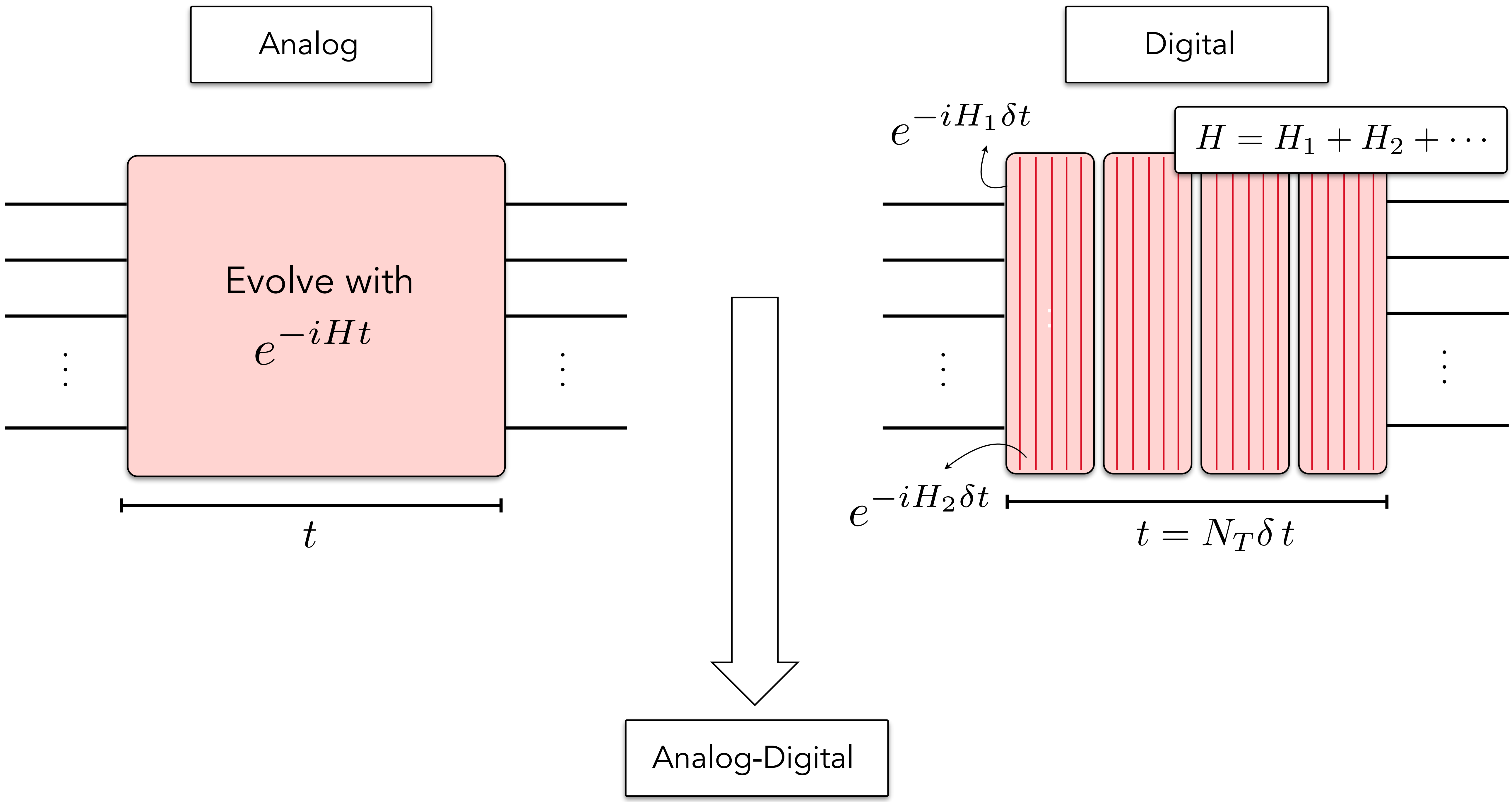
DIFFERENT APPROACHES TO QUANTUM SIMULATION



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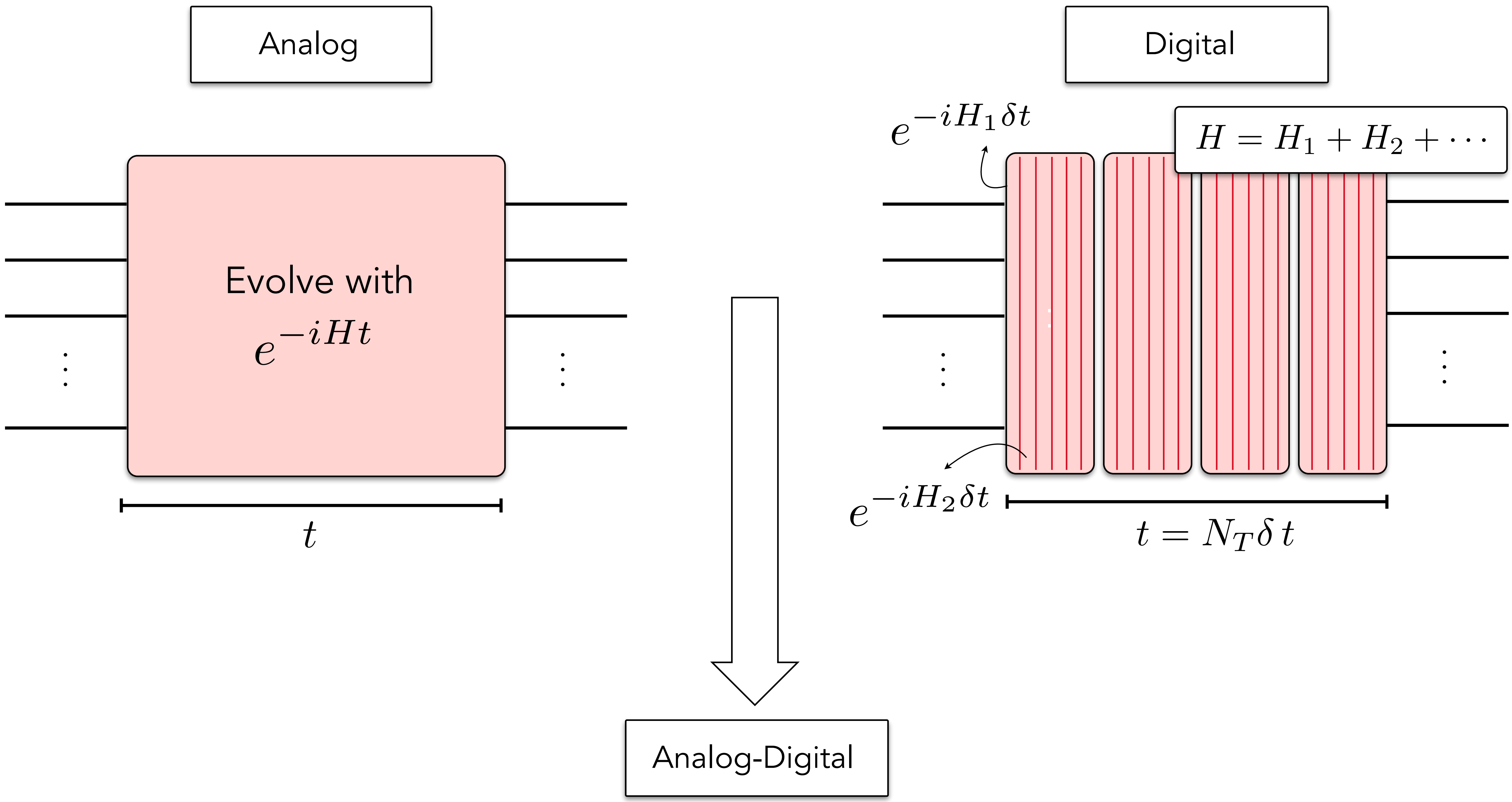
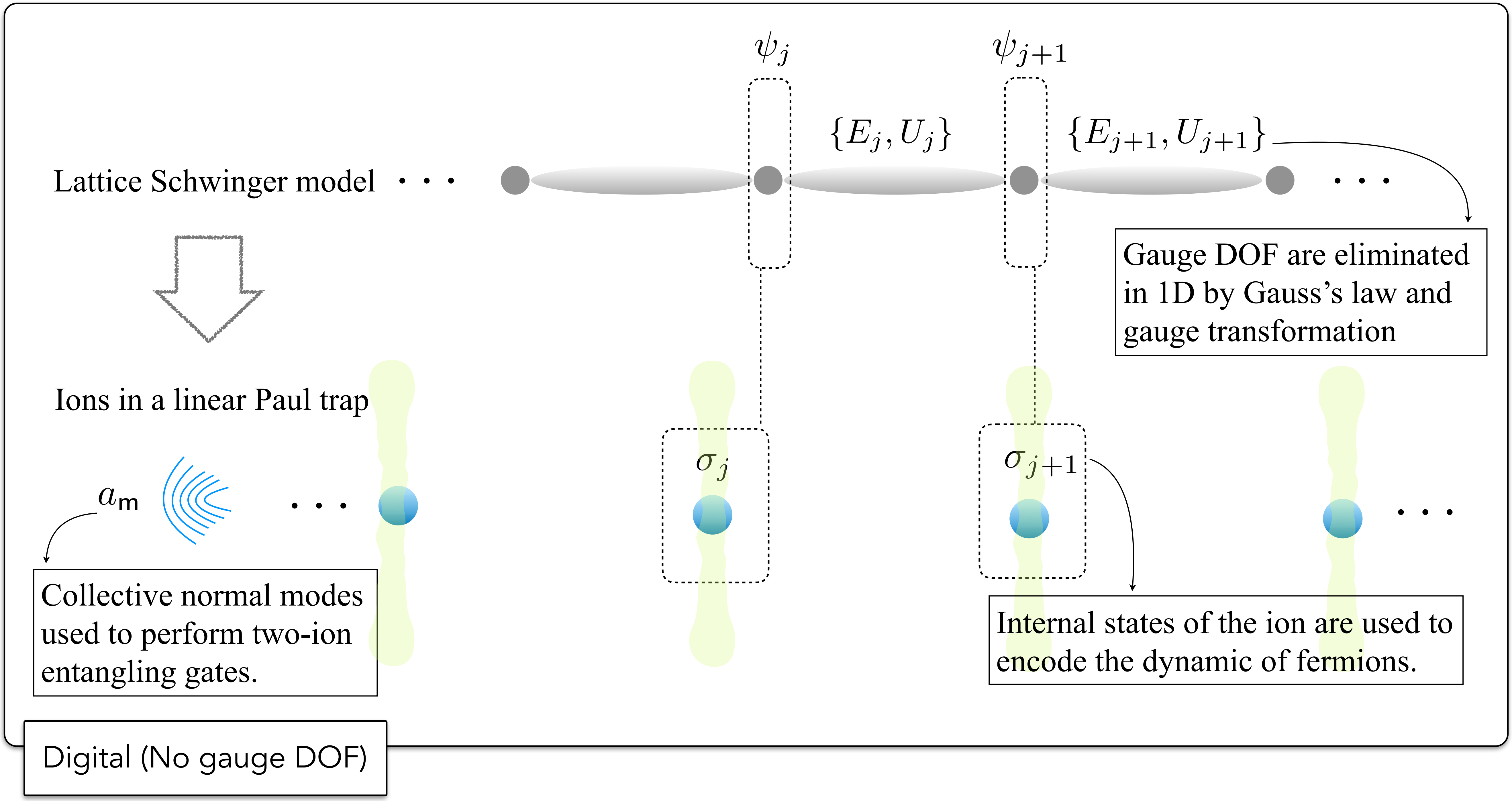
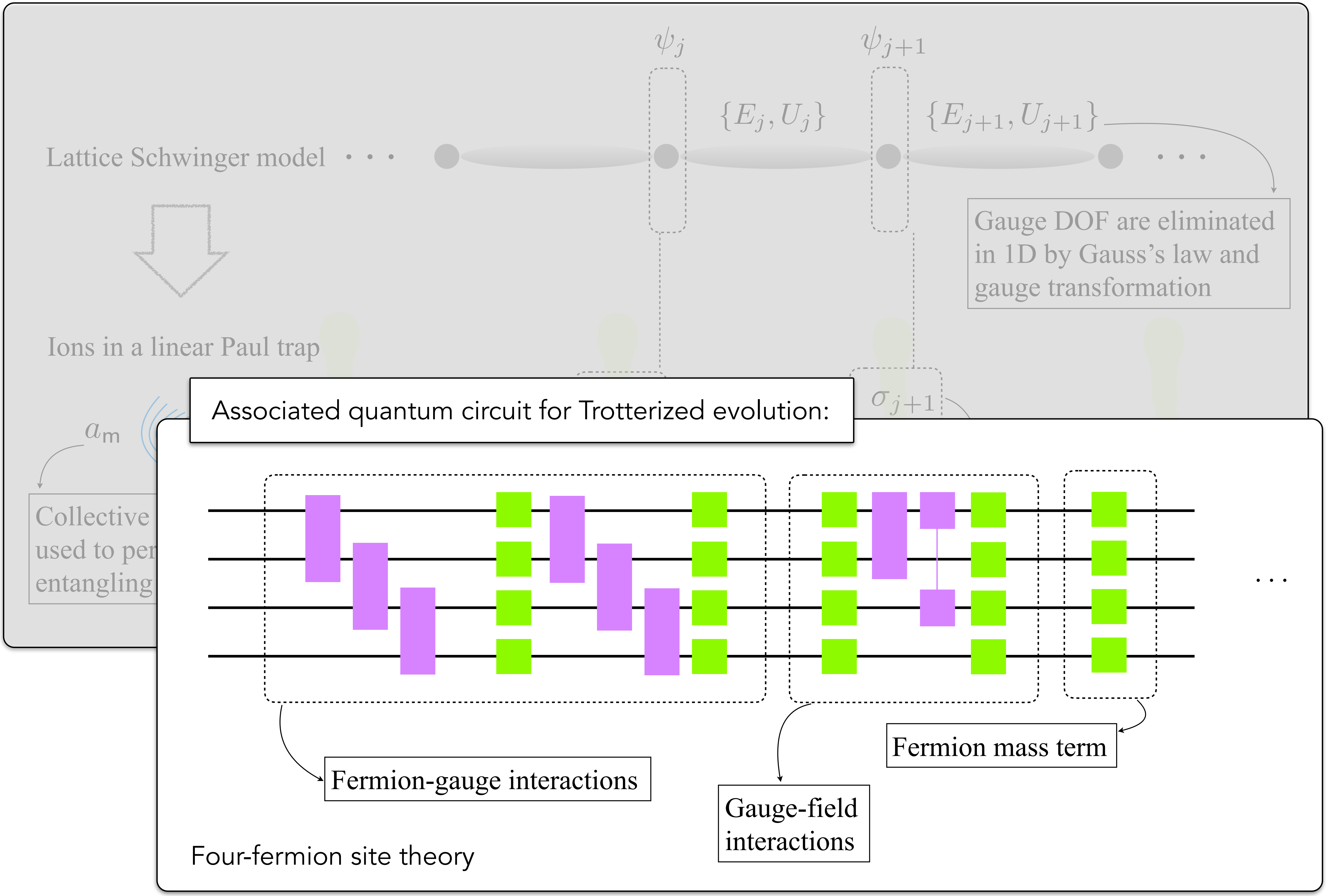


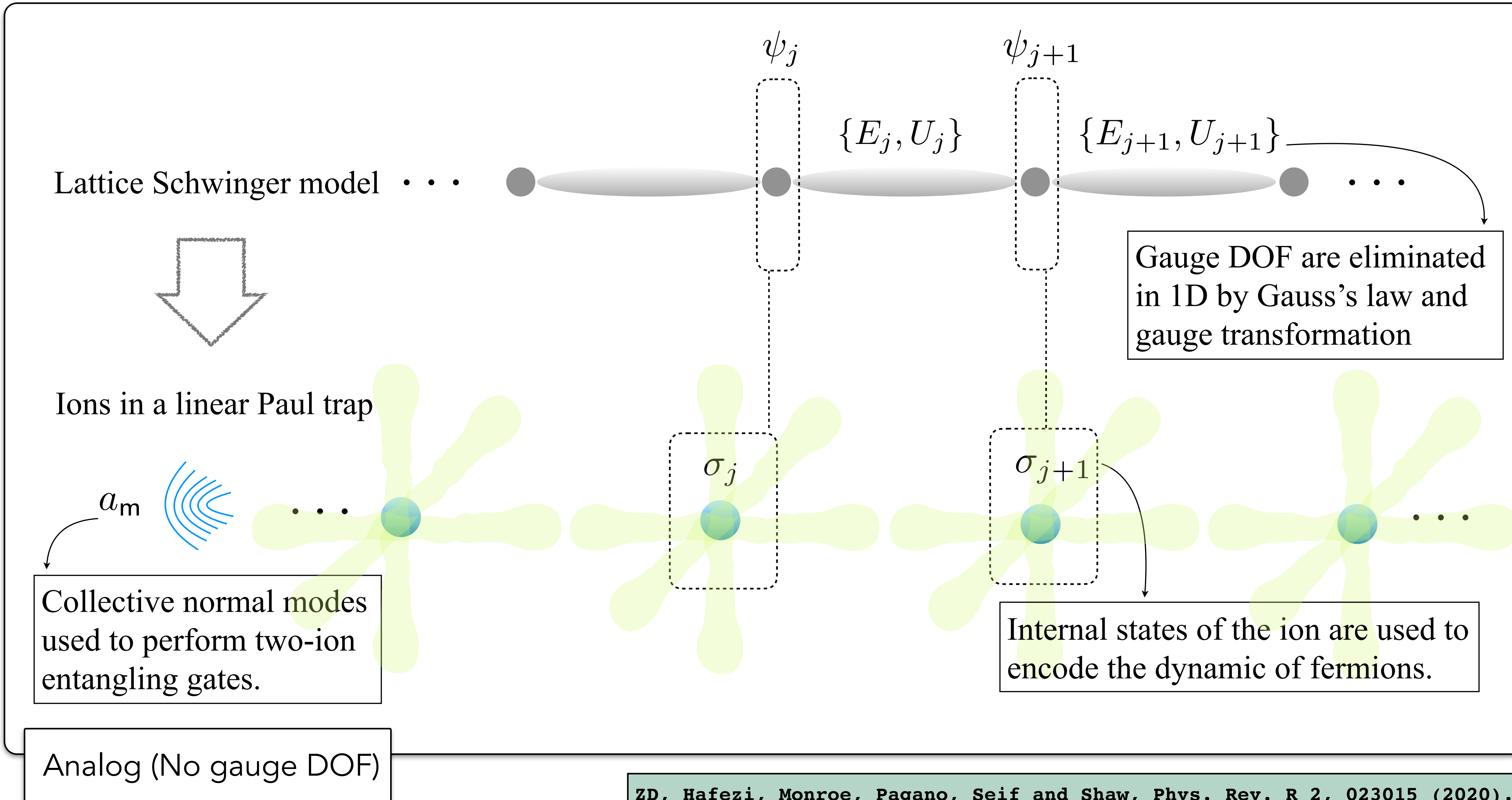
LET US PICK A PLATFORM (TRAPPED IONS) AND A MODEL (SCHWINGER MODEL) TO DEMONSTRATE FEATURES OF THESE APPROACHES:



ψ_j
ψ_{j+1}
$\{E_j, U_j\}$
$\{E_{j+1}, U_{j+1}\}$
Lattice Schwinger model
Gauge DOF are eliminated in 1D by Gauss's law and gauge transformation
Ions in a linear Paul trap
σ_j
σ_{j+1}
a_{m}
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)

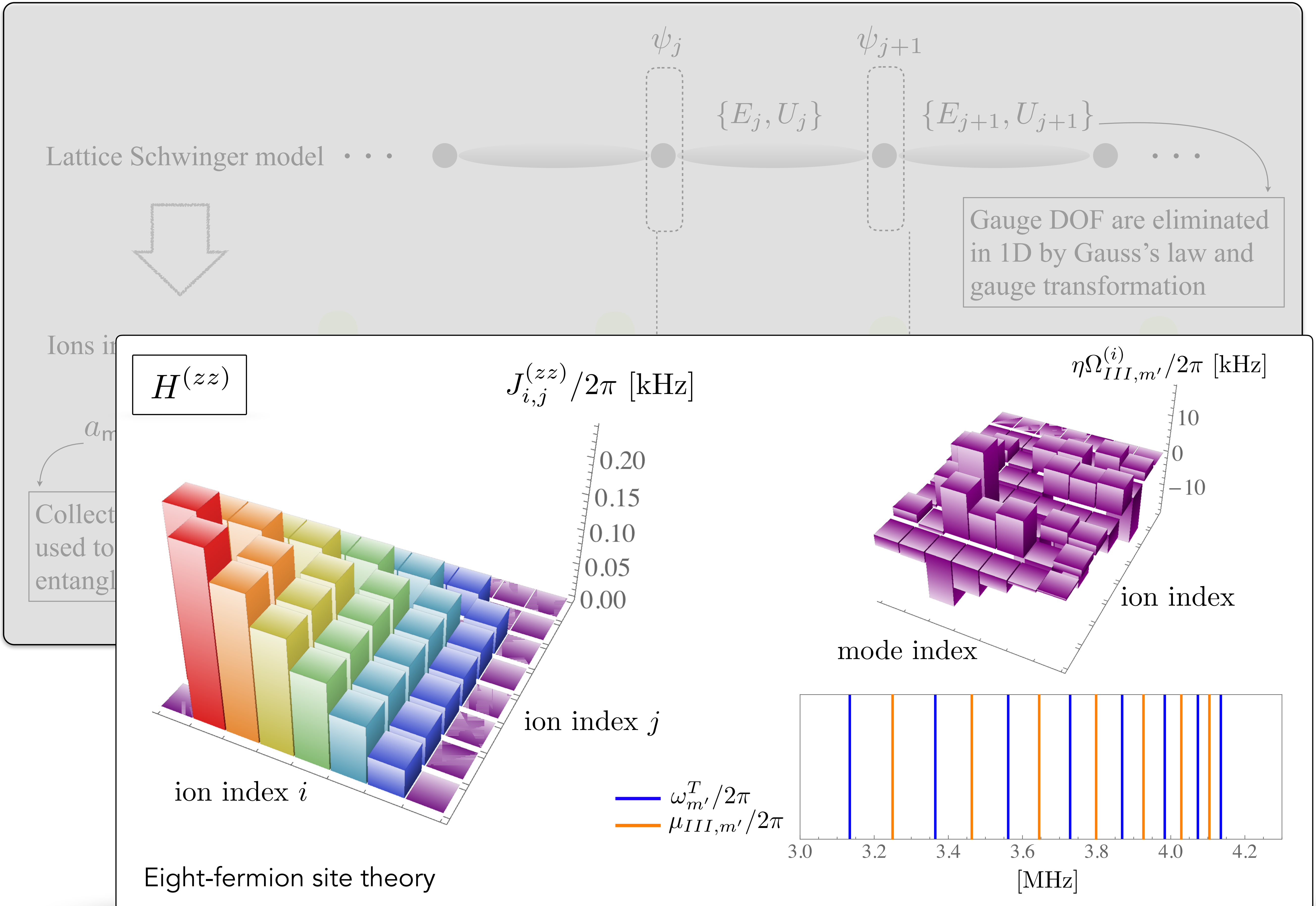


Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)



ZD, Hafezi, Monroe, Pagano, Seif and Shaw, Phys. Rev. R 2, 023015 (2020).

See also Yang et al, Physical Review A 94, 052321 (2016) for a phonon-ion based analog proposal of lattice Schwinger Model.



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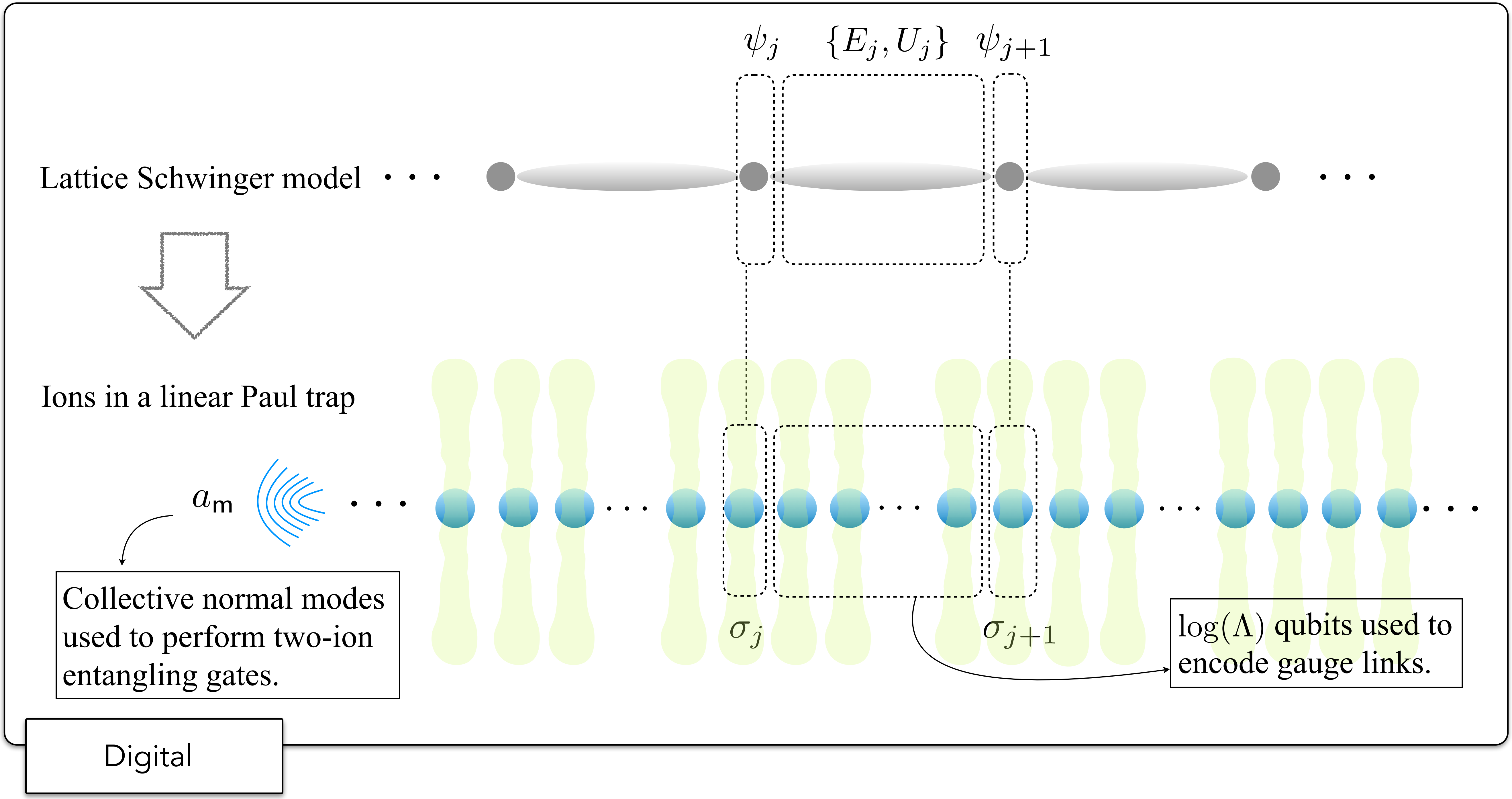

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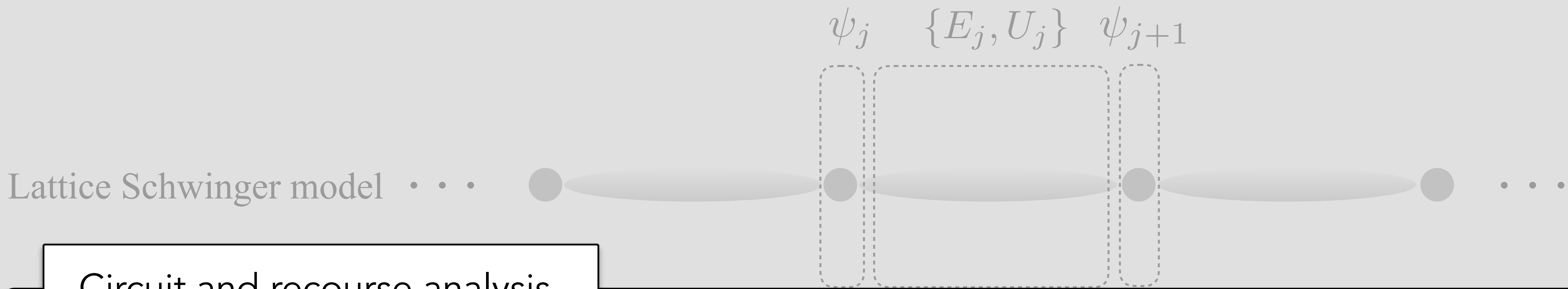
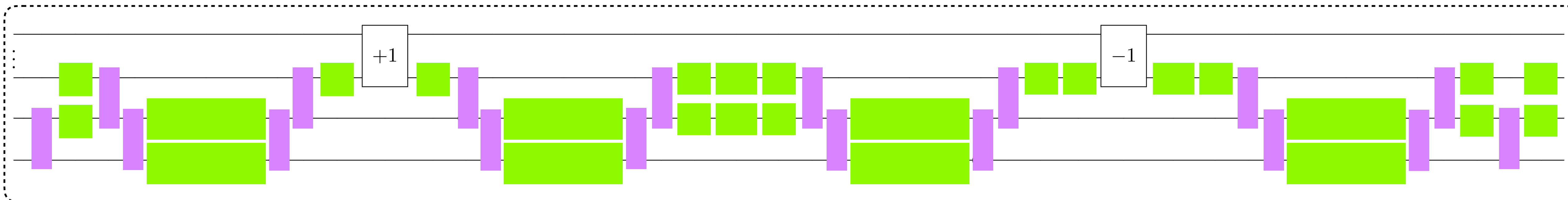
Lattice Schwinger model
Ions in a linear Paul trap
a_m
Collective normal modes used to perform two-ion entangling gates.
σ_j
σ_{j+1}
$\log(\Lambda)$ qubits used to encode gauge links.
Digital



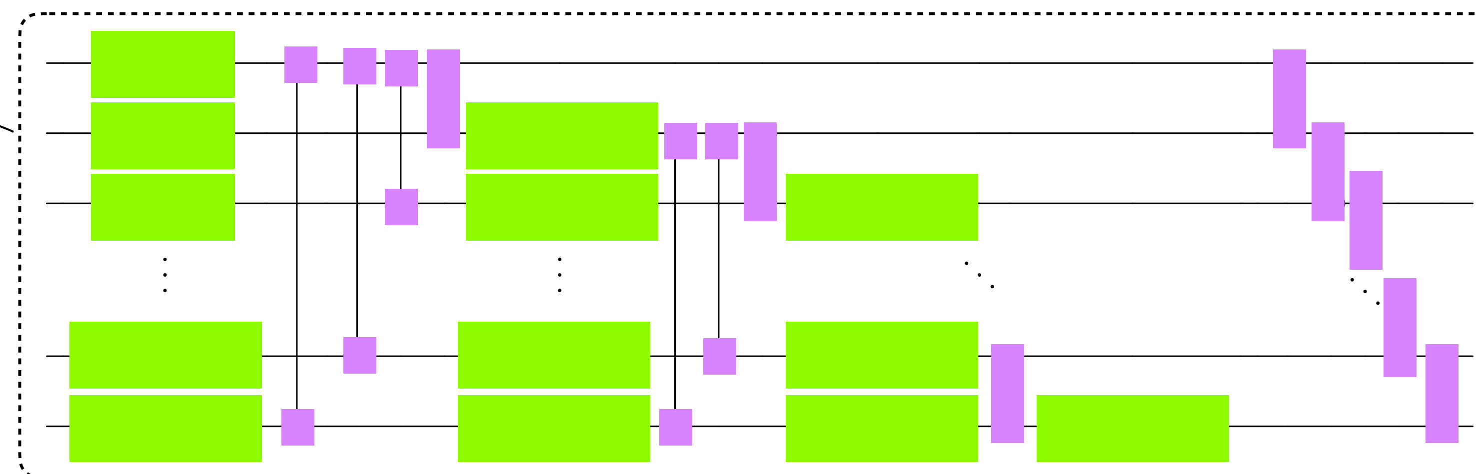
Circuit and recourse analysis

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



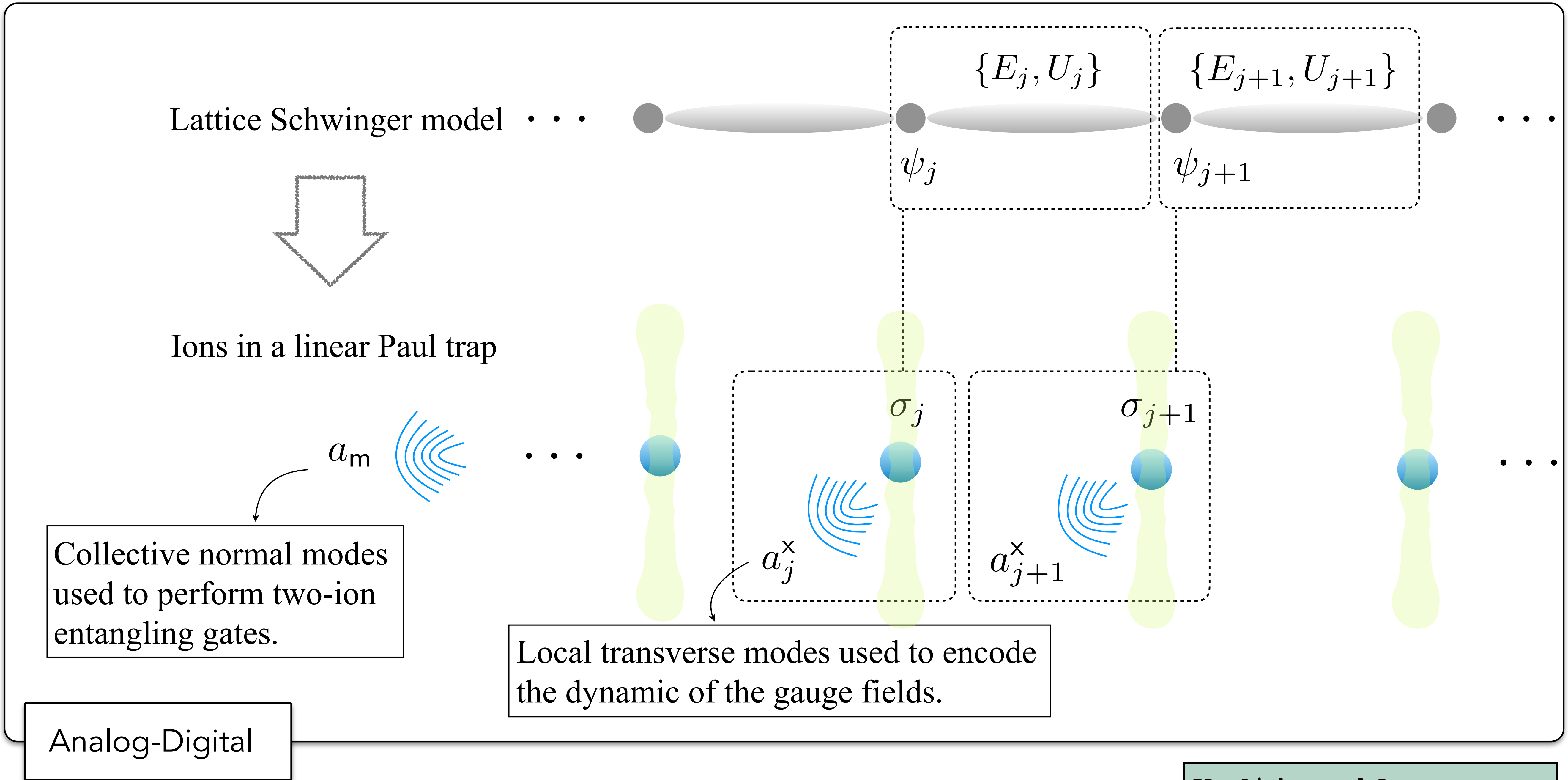
Sample gauge-fermion interaction block

Part of electric field interactions acting on gauge DOF registers



Near term cost

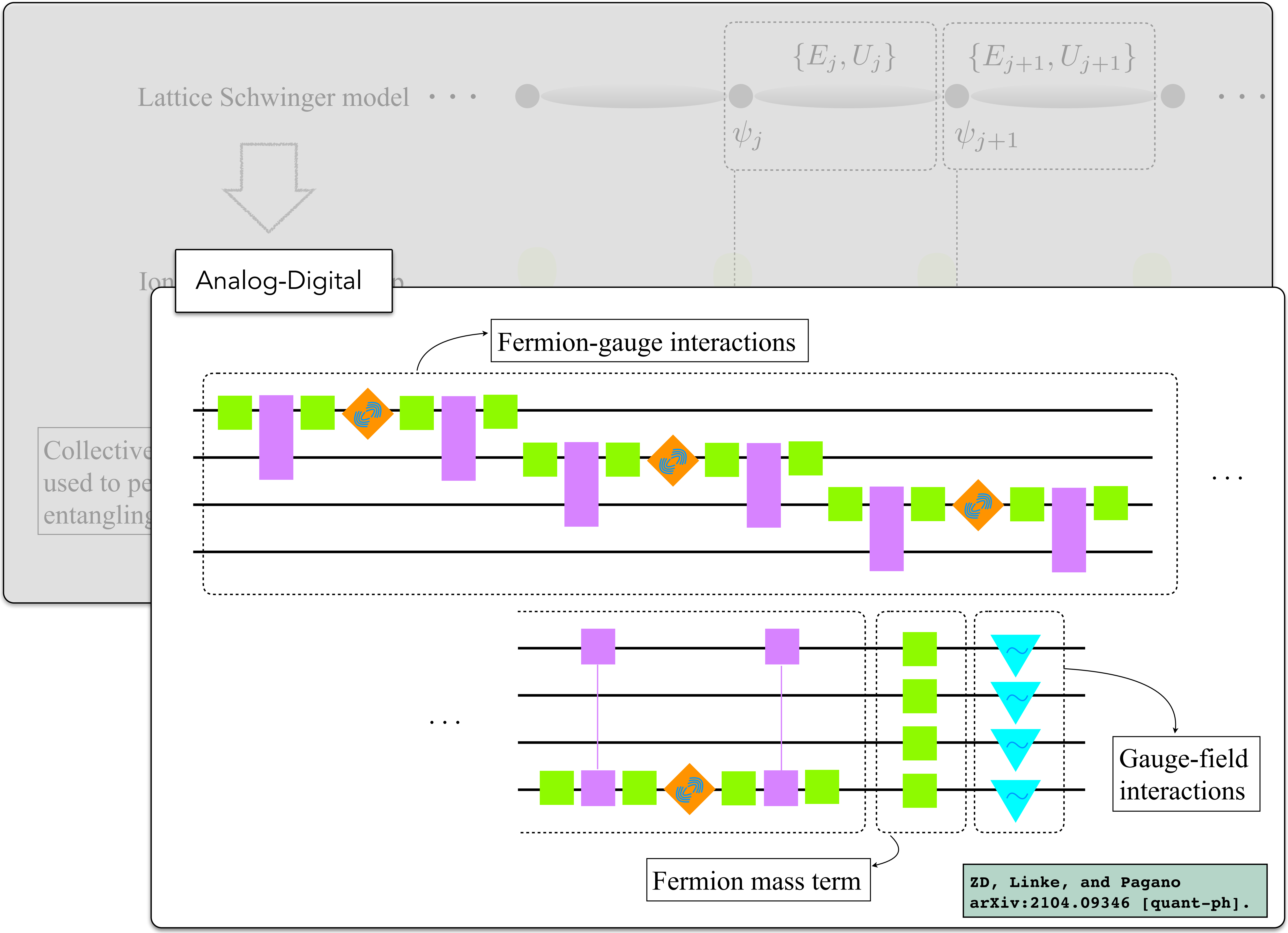
	$\delta_g = 10^{-3}$		$\delta_g = 10^{-4}$		$\delta_g = 10^{-5}$		$\delta_g = 10^{-6}$		$\delta_g = 10^{-7}$	
	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT
$x = 10^{-2}$	—	7.3e4	—	1.6e5	—	3.4e5	—	7.3e5	5.6e-2	1.6e6
$x = 10^{-1}$	—	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



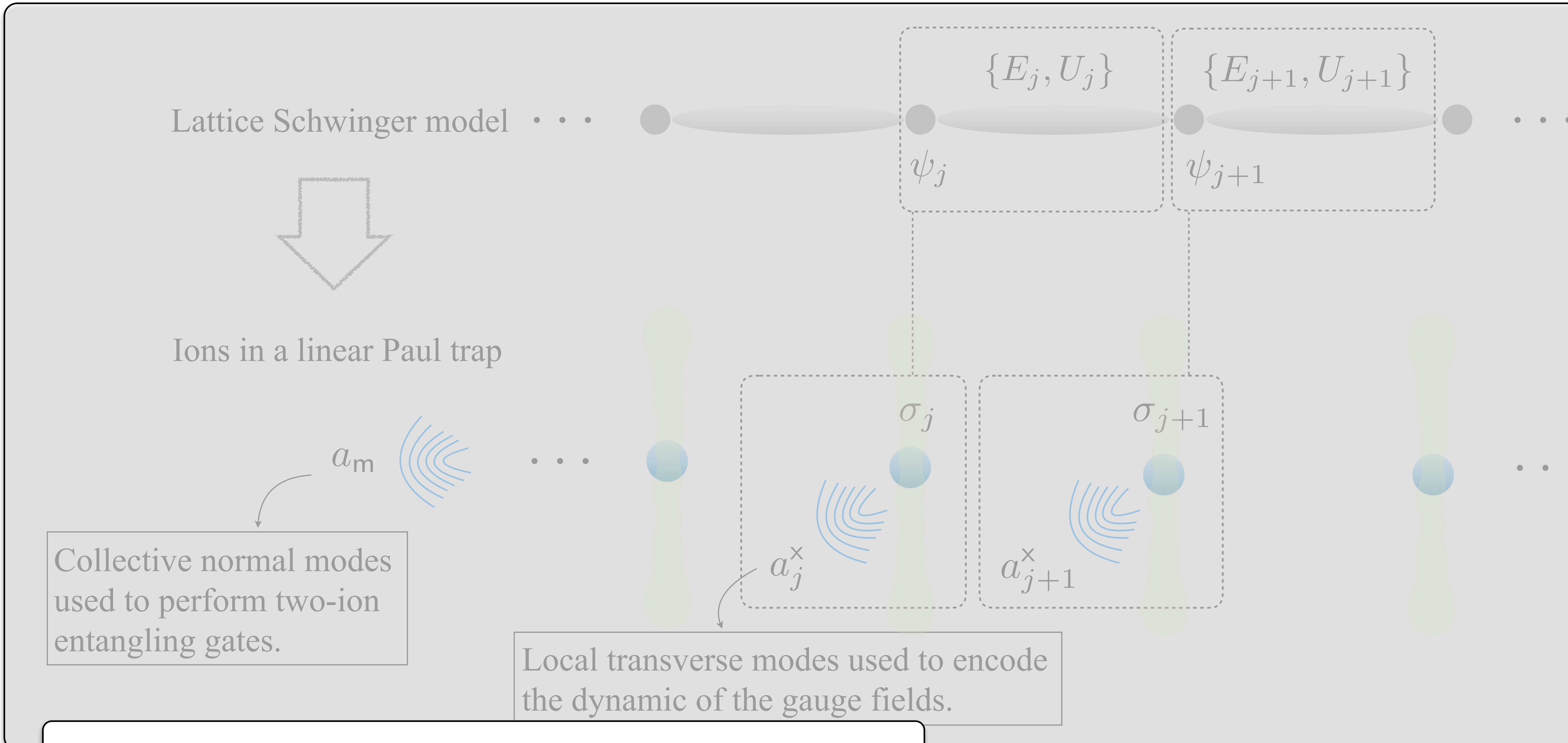
ZD, Linke, and Pagano arXiv:2104.09346 [quant-ph].

See Yang et al, Physical Review A 94, 052321 (2016) for the highly-occupied bosonic model of the Schwinger model.

See also Casanova et al, Phys. Rev. Lett. 108, 190502 (2012), Lamata et al, EPJ Quant. Technol. 1, 9 (2014), and Mezzacapo et al, Physical review let- ters 109, 200501 (2012) for analog-digital approaches to other interacting fermion-boson theories.



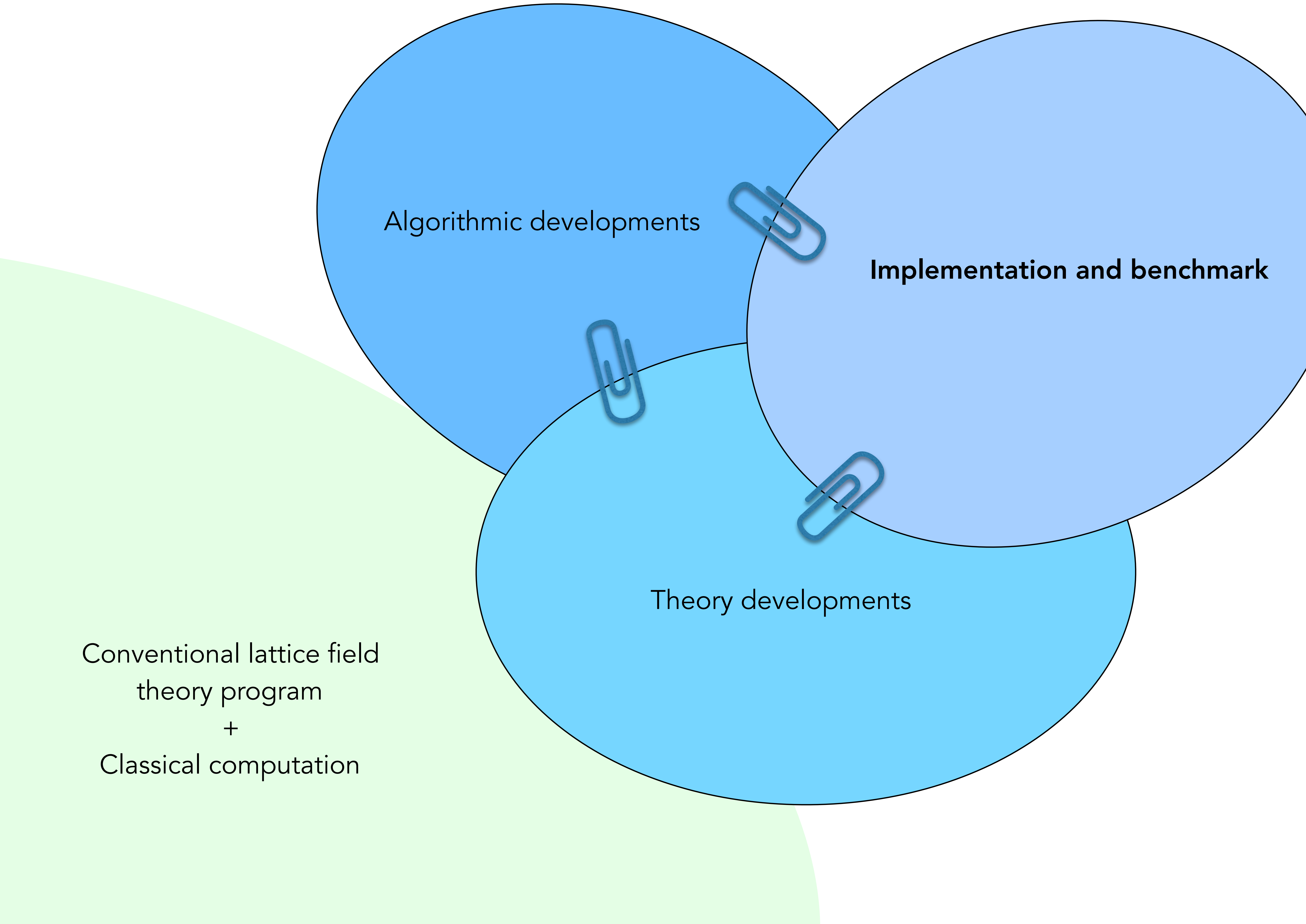
Lattice Schwinger model
$\{E_j, U_j\}$
$\{E_{j+1}, U_{j+1}\}$
ψ_j
ψ_{j+1}
Analog-Digital
Fermion-gauge interactions
Gauge-field interactions
Fermion mass term
ZD, Linke, and Pagano
arXiv:2104.09346 [quant-ph].



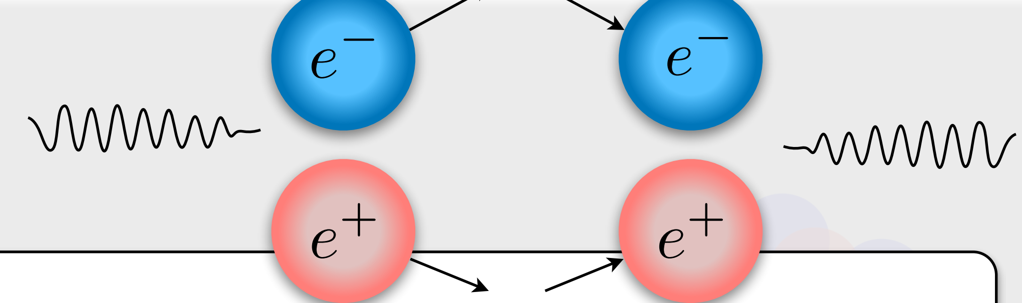
Let us compare the circuit structure of digital and analog-digital cases when gauge DOF are present:

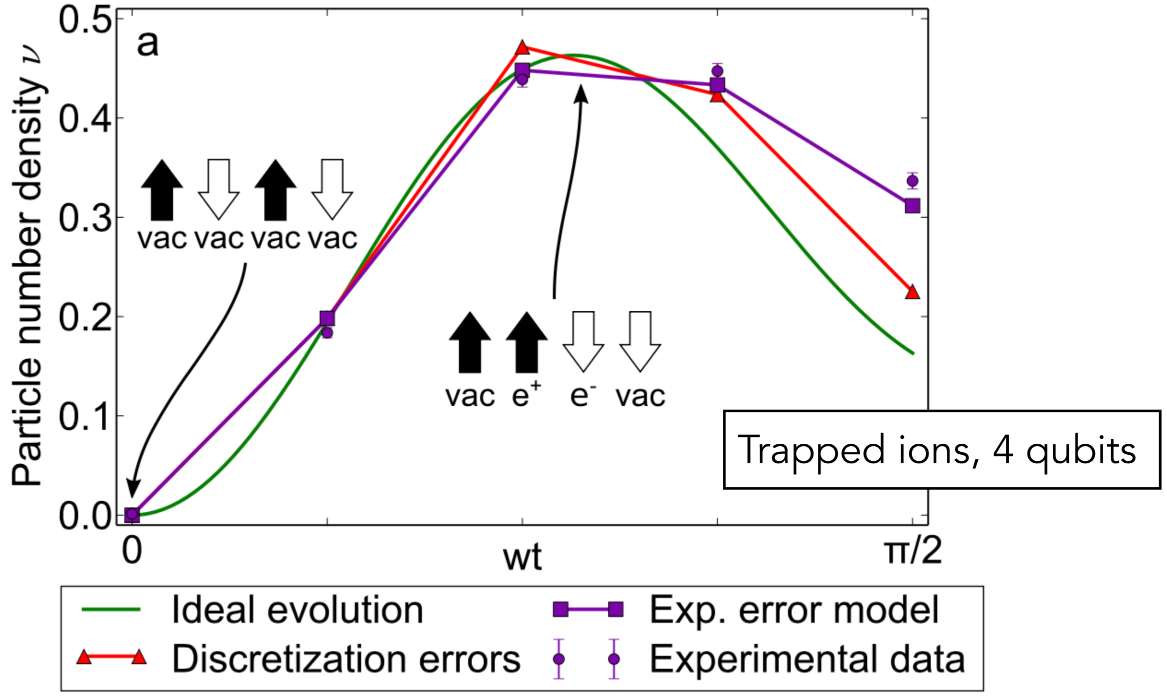
ZD, Linke, and Pagano arXiv:2104.09346 [quant-ph].

Schwinger model			
	Fermion-gauge interaction	Fermion mass	Electric-field term
Analog-digital	$\mathcal{O}(N)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
Digital	$\mathcal{O}\left(N(\log\Lambda)^2\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(N(\log\Lambda)^2\right)$

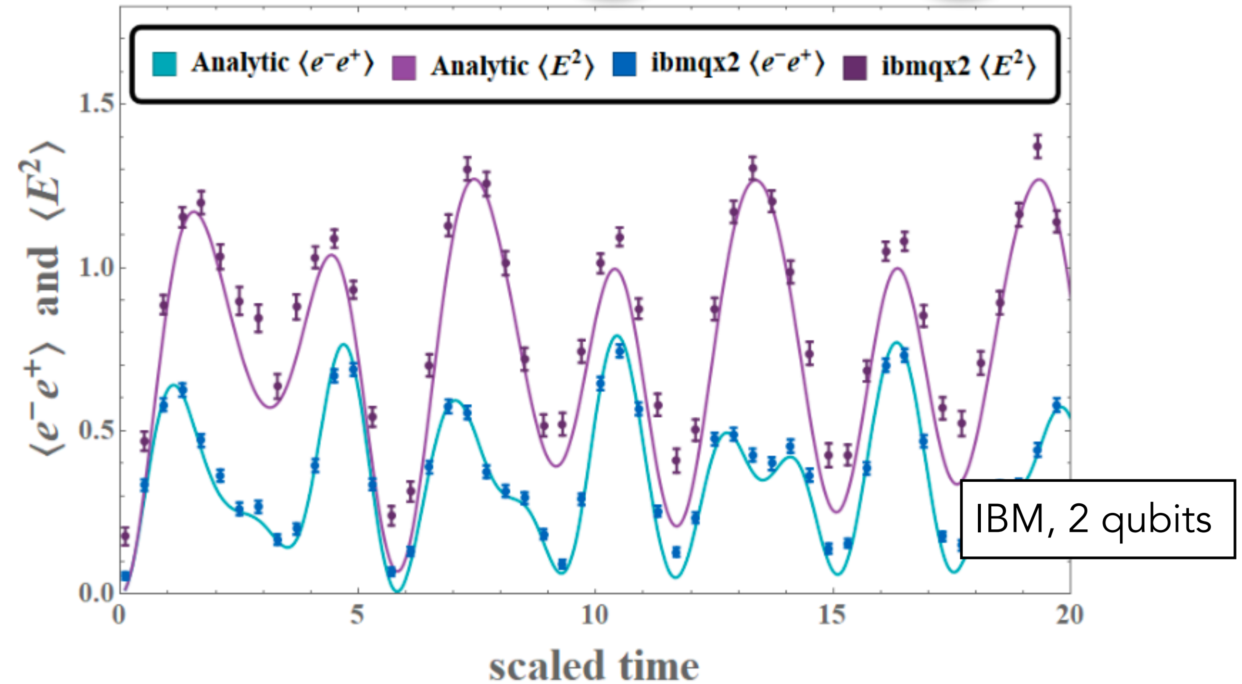

Algorithmic developments
Implementation and benchmark
Theory developments
Conventional lattice field theory program + Classical computation

DIGITAL EXAMPLES FOR SCHWINGER MODEL

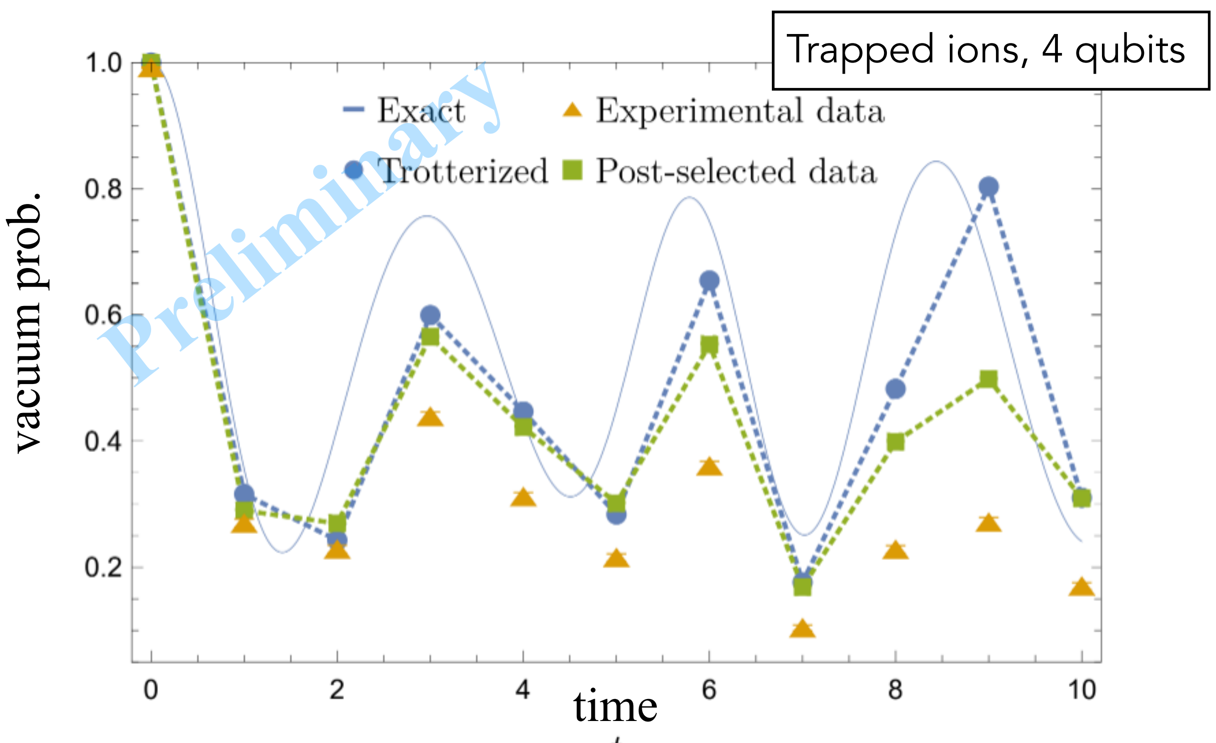


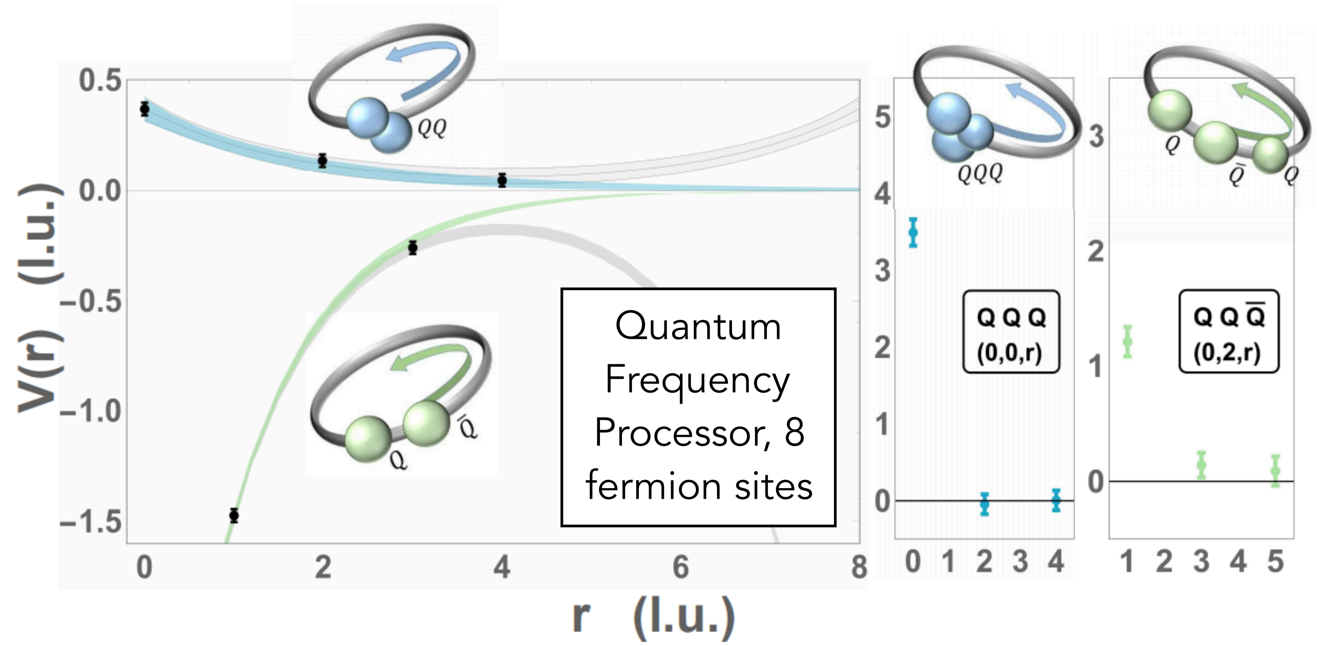


Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)



Klco, Dumitrescu, McCaskey, Morris, Pooser, Sanz, Solano, Lougovski, Savage, Phys. Rev. A 98, 032331 (2018)

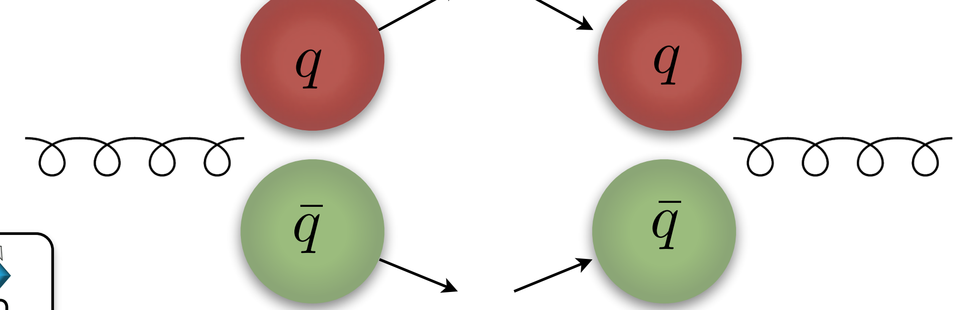


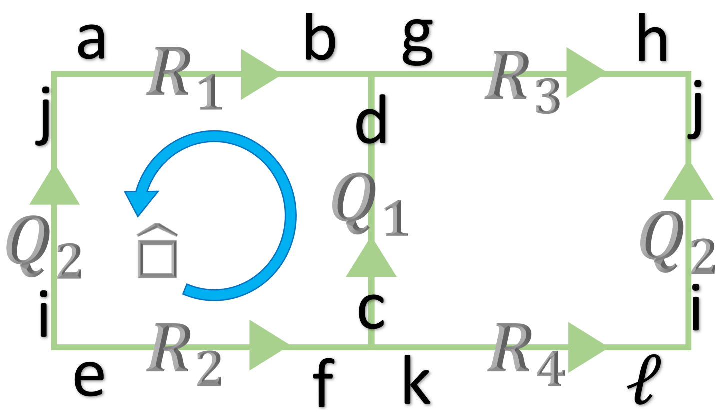


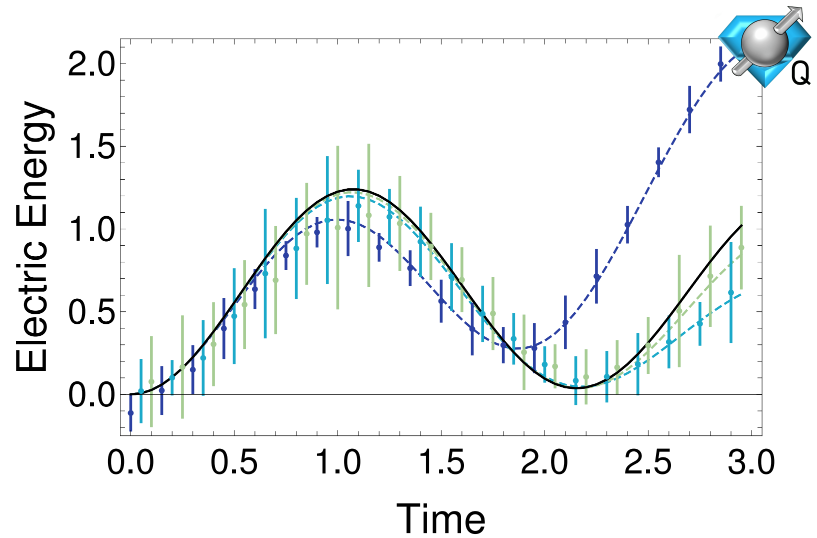
Nguyen, Shaw, Zhu, Huerta Alderete, ZD, Linke (2020)

Lu, Klco, Lukens, Morris, Bansal, Ekström, Hagen, Papenbrock, Weiner, Savage, Lougovski, Phys. Rev. A 100, 012320 (2019)

DIGITAL EXAMPLES FOR NON-ABELIAN LGTs



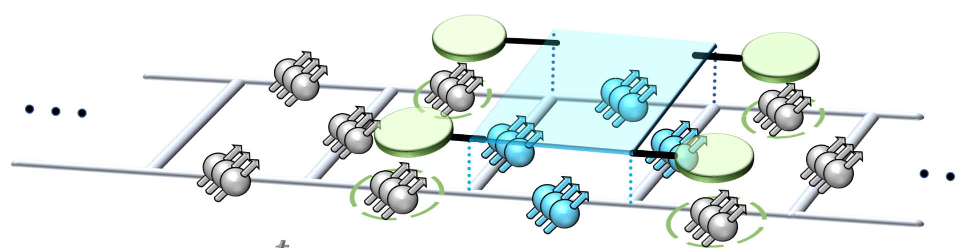


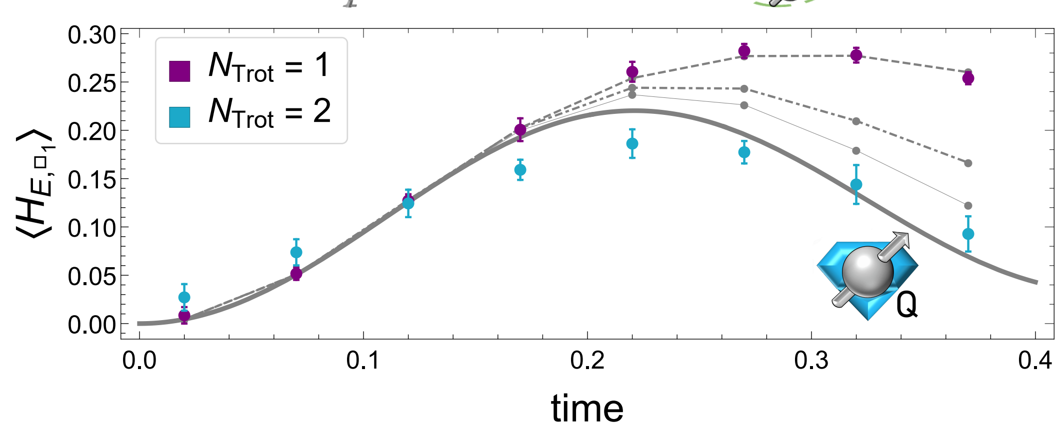


Real-time dynamic of pure SU(3) with global irrupts on IBM

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

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

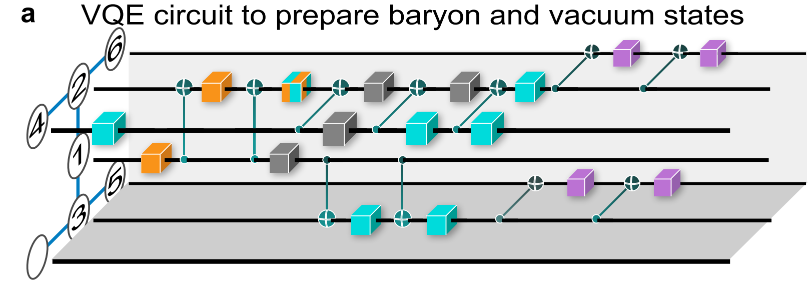




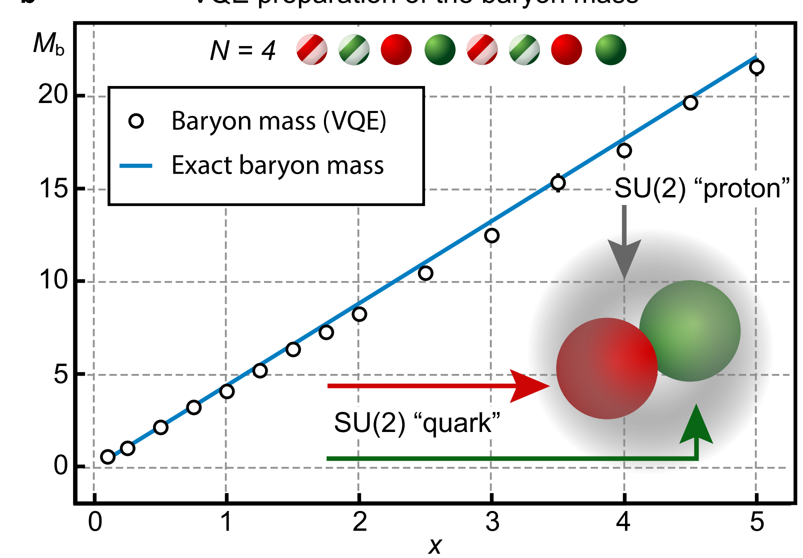
Klco, Savage, and Stryker, Phys. Rev. D 101, 074512 (2020).

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

a VQE circuit to prepare baryon and vacuum states



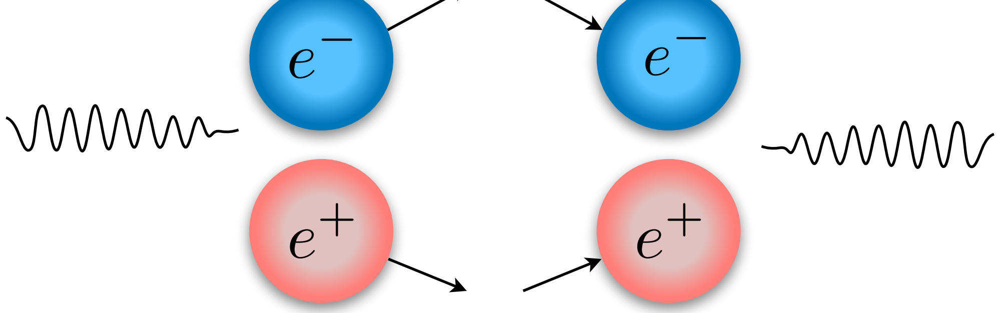
b VQE preparation of the baryon mass



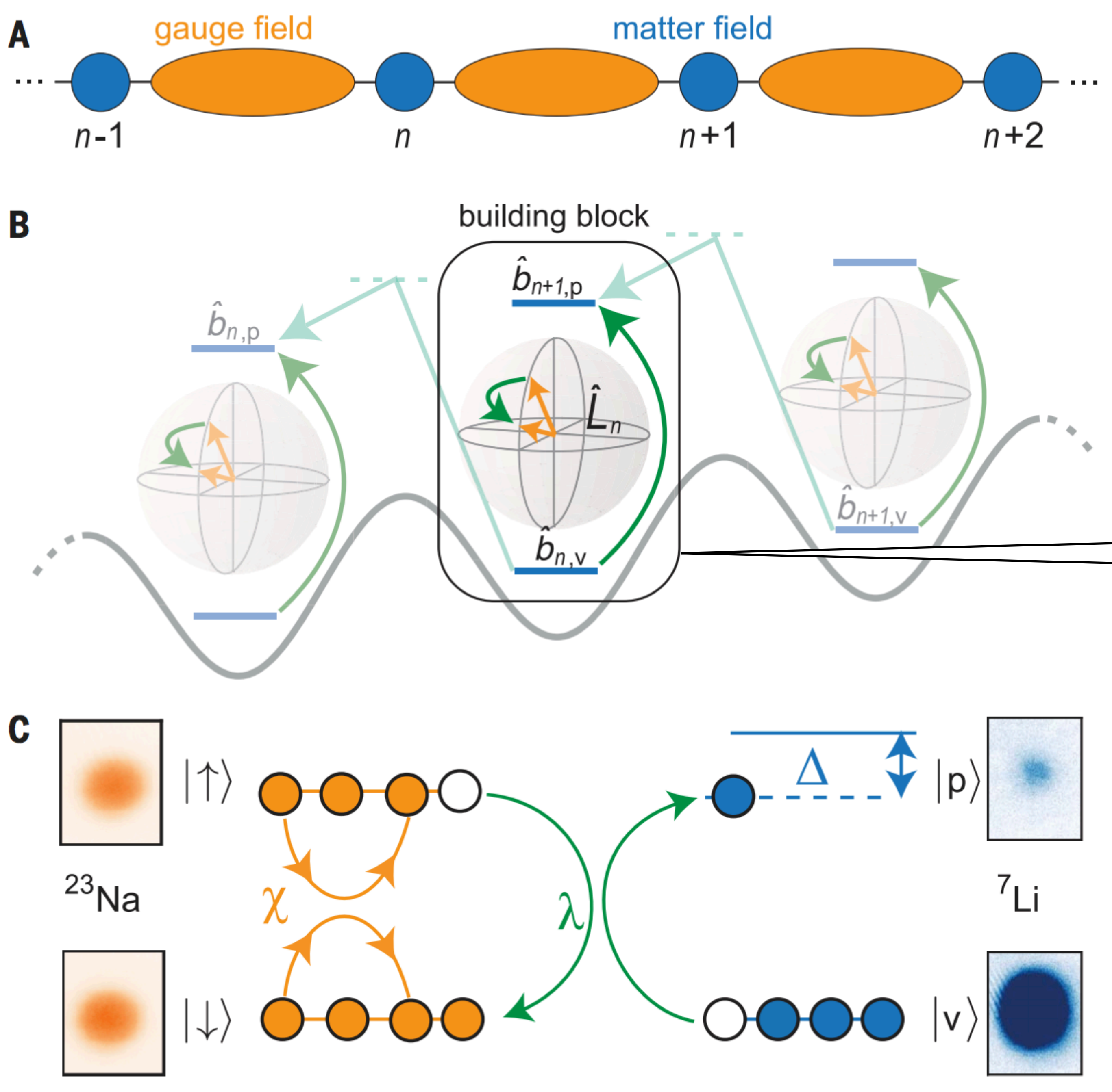
Atas et al, arXiv:2102.08920 [quant-ph]

See also another SU(2) study on D-wave by Rahman et al, arXiv:2103.08661 [hep-lat]

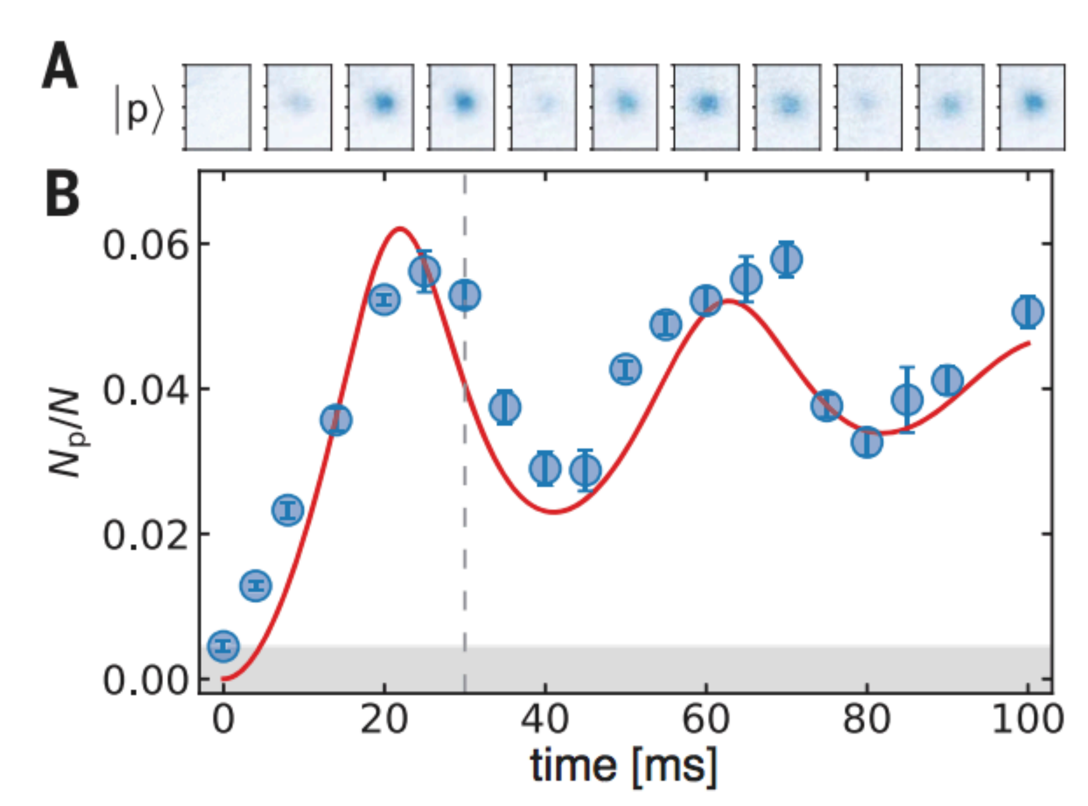
ANALOG EXAMPLES FOR SCHWINGER MODEL



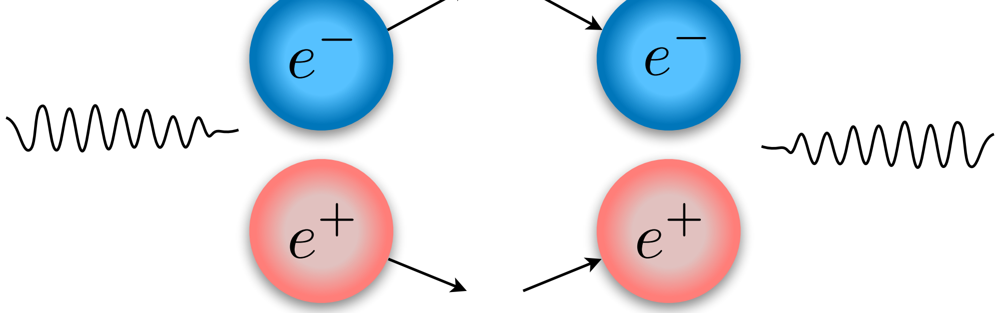
A realization of lattice Schwinger model within QLM with cold atoms in a trapping potential



Mil, Zache, Hegde, Xia, Bhatt, Oberthaler, Hauke, Berges, Jendrzejewski, Science 367, 1128-1130 (2020)



ANALOG EXAMPLES FOR SCHWINGER MODEL



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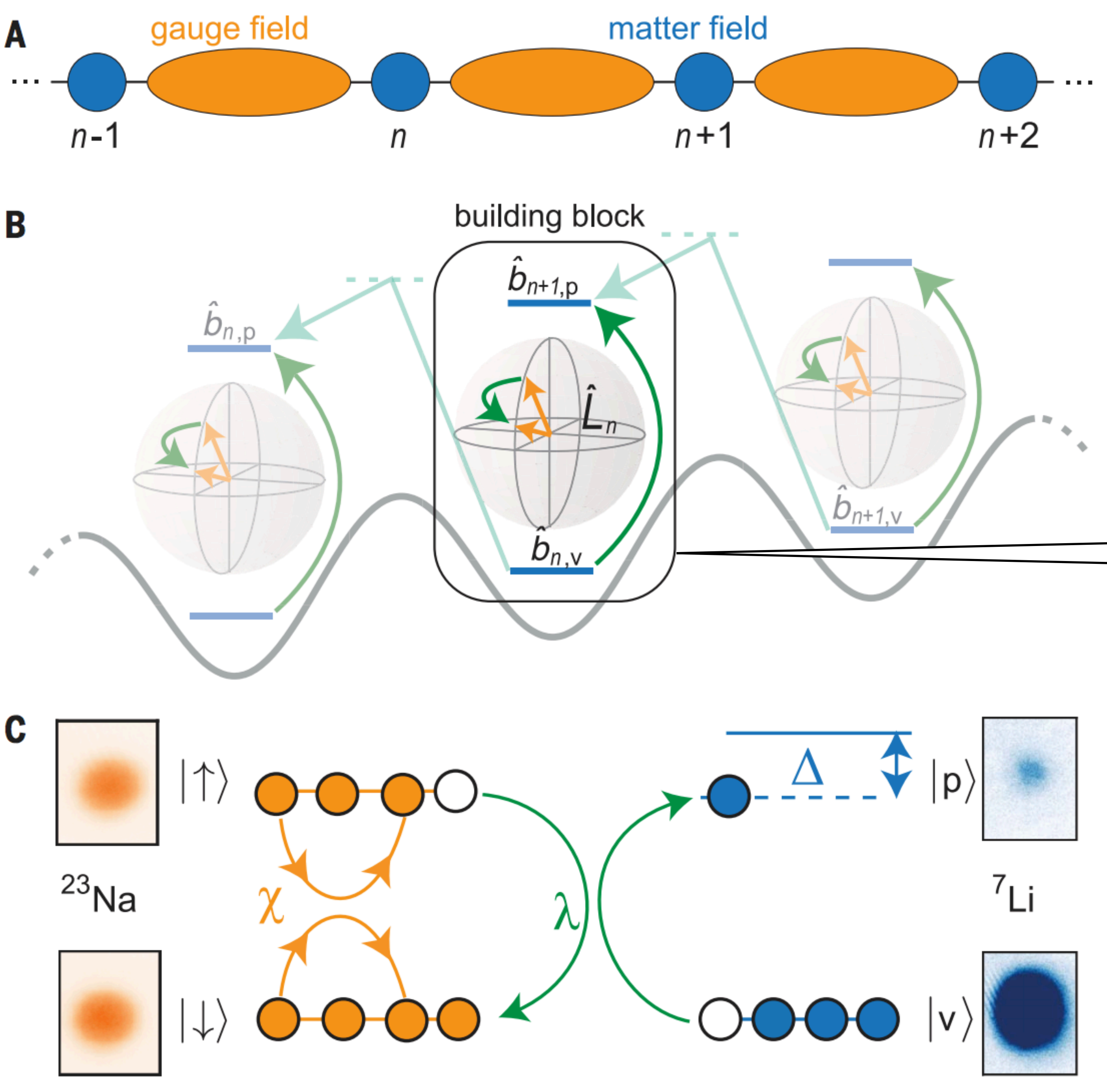
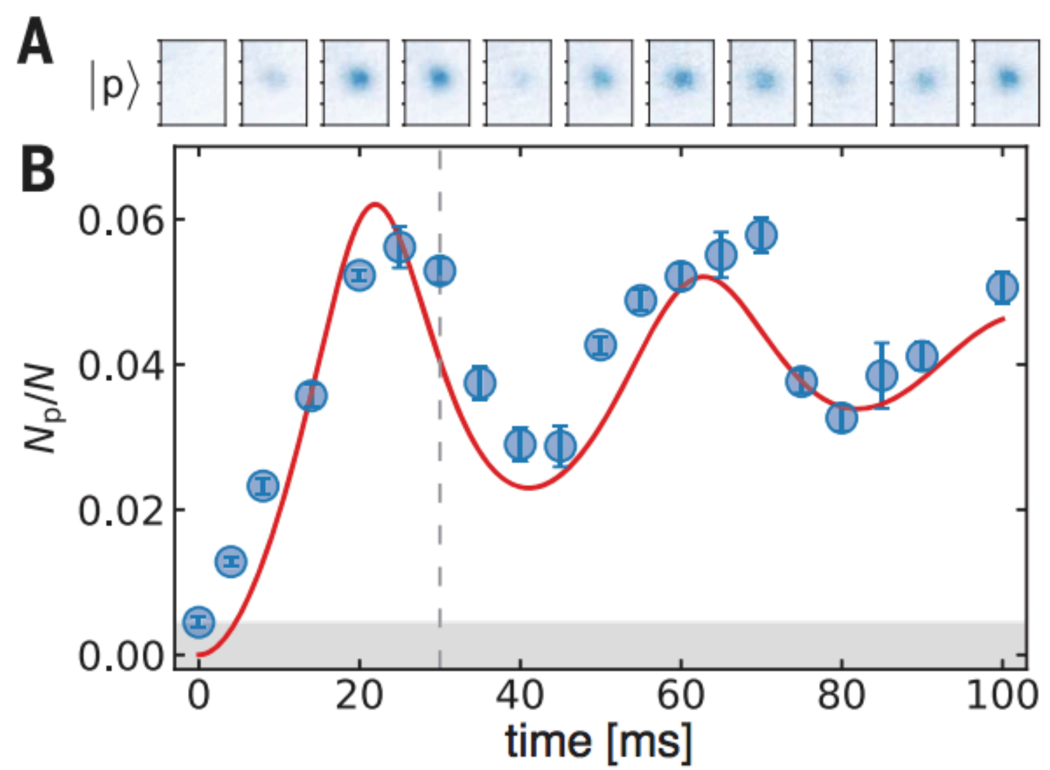
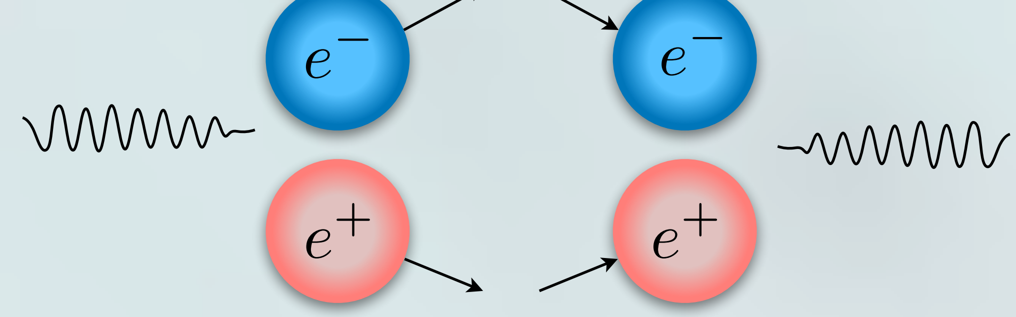


More Abelian gauge theory analog proposals: Bazavov, Meurice, Tsai, Unmuth-Yockey, Zhang, Phys. Rev. D 92, 076003 (2015). Luo, El-Khadra, et al, Phys. Rev. A 102, 032617 (2020).

Mil, Zache, Hegde, Xia, Bhatt, Oberthaler, Hauke, Berges, Jendrzejewski, Science 367, 1128-1130 (2020)

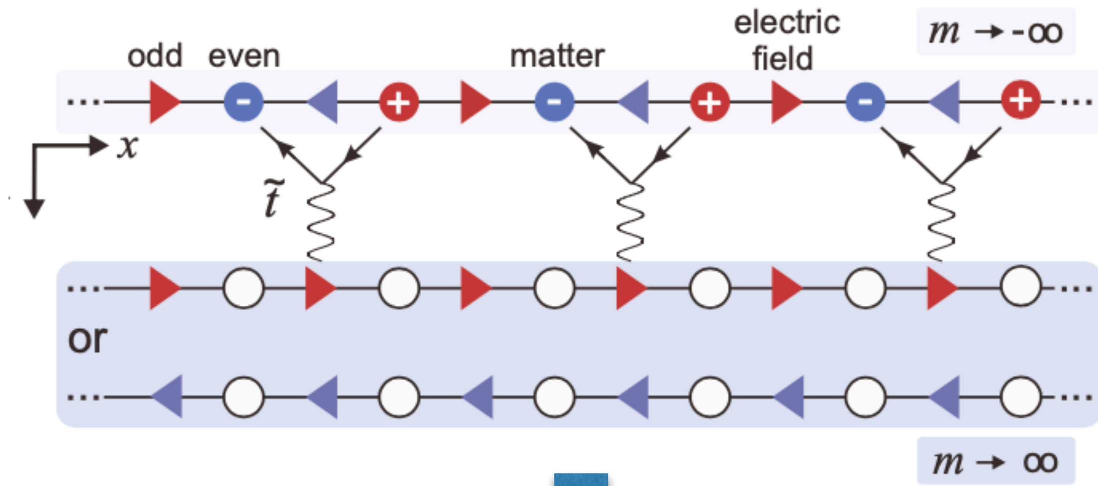


ANALOG EXAMPLES FOR SCHWINGER MODEL

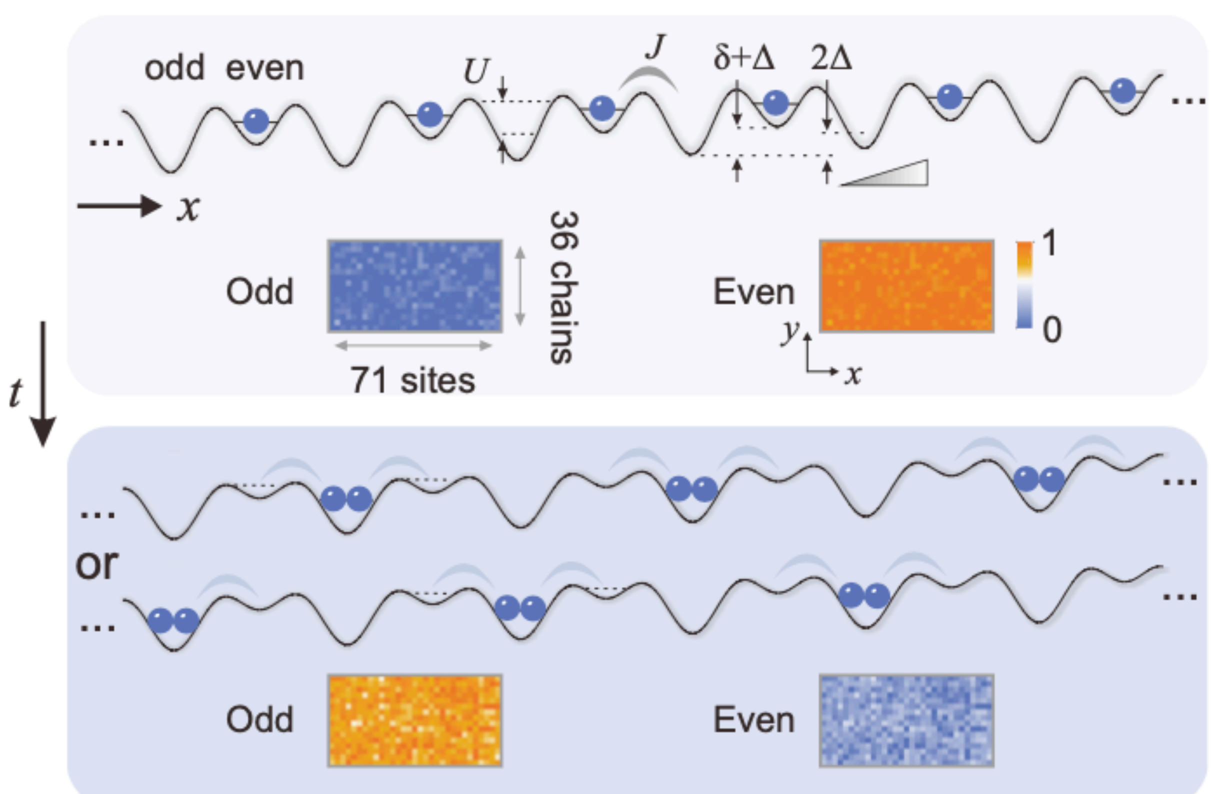


Yang et al, *Nature* 587 (2020) 7834, 392-396.

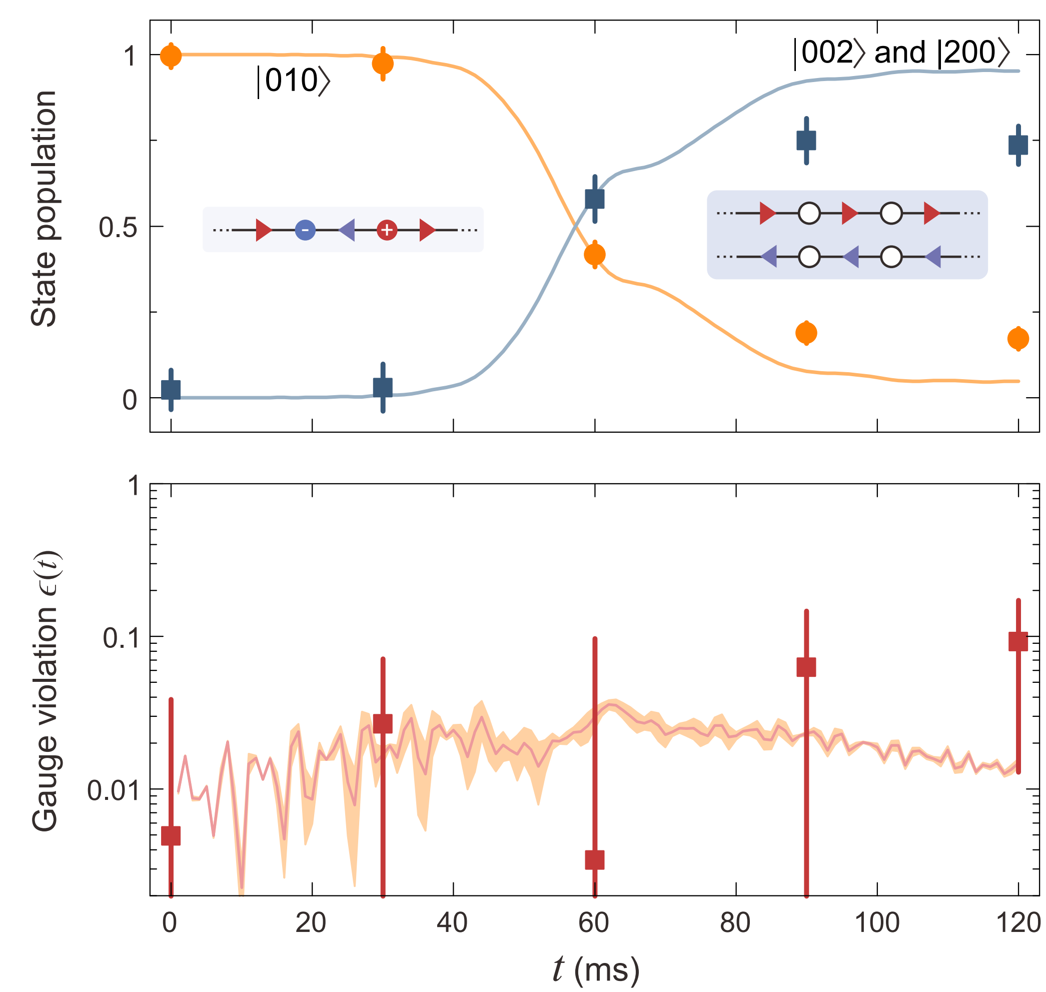
Schwinger model within quantum link model formulation…



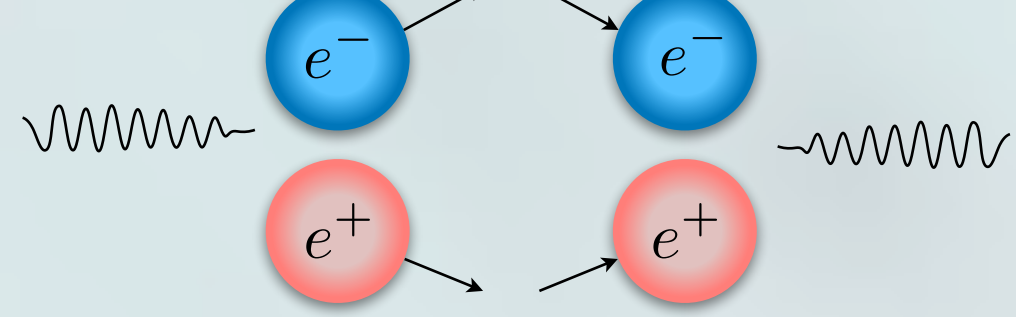
…mapped to a 71-site Bose-Hubbard quantum simulator:



Gauss's law violating effects are suppressed:



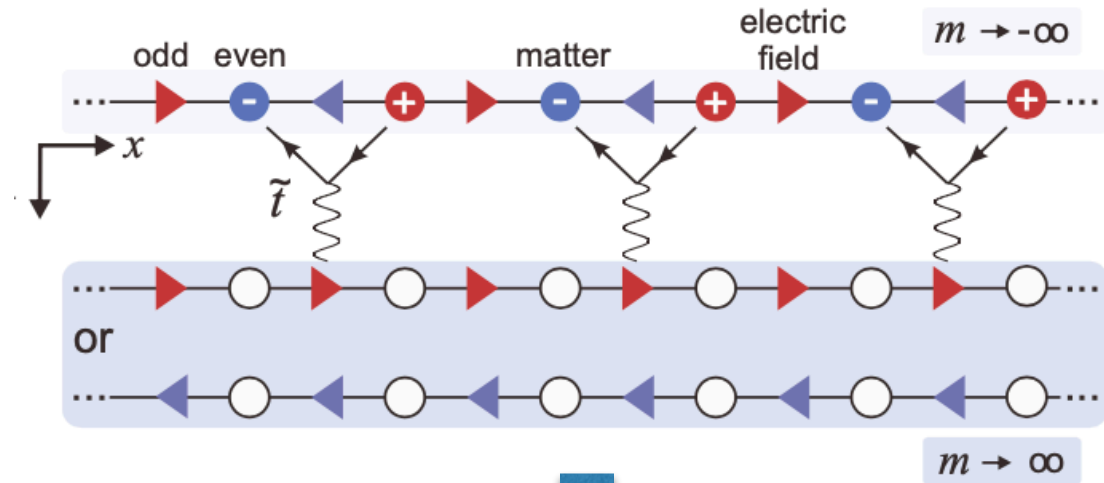
ANALOG EXAMPLES FOR SCHWINGER MODEL



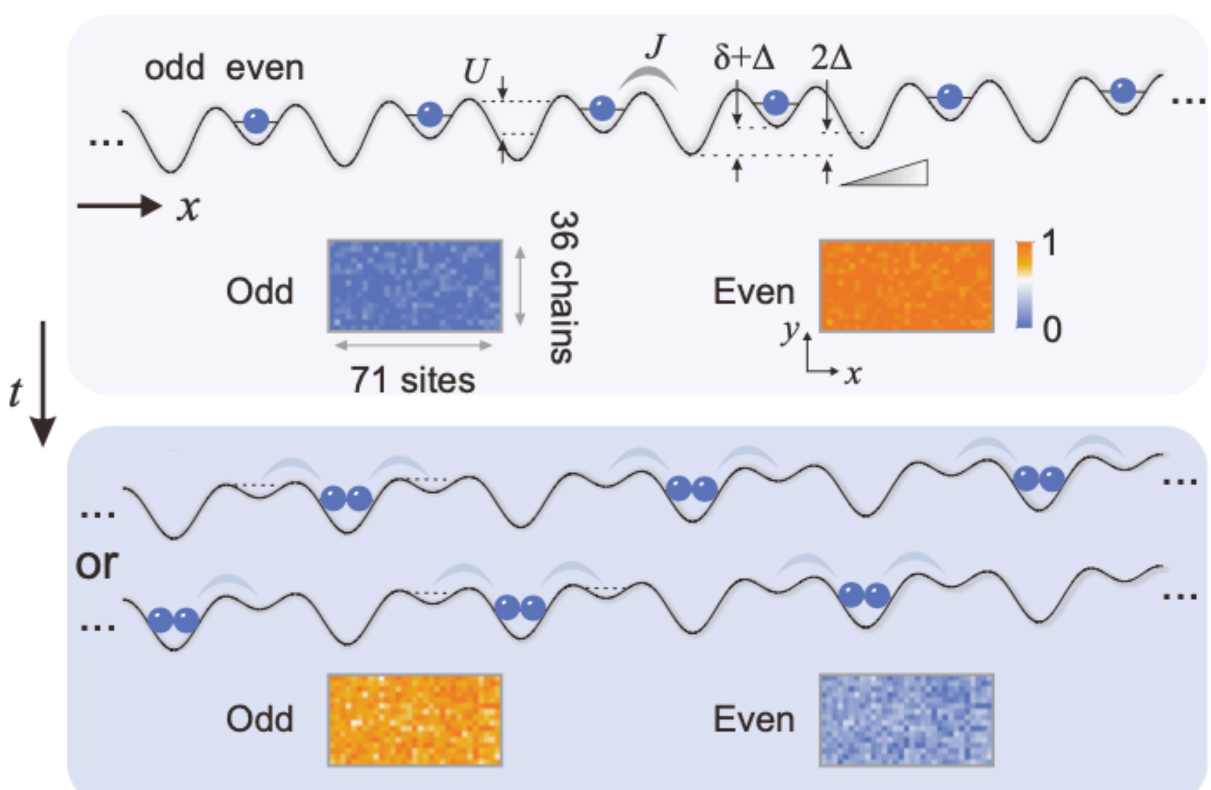
Some non-Abelian gauge theory analog proposals: Zohar, Cirac, Reznik, Phys. Rev. A 88 023617 (2013). Zohar, Cirac, Reznik, Phys. Rev. Lett. 110, 125304 (2013), Phys. Rev. A 88 023617 (2013), Rep. Prog. Phys. 79, 014401 (2016). González Cuadra, Zohar, Cirac, New J. Phys. 19 063038 (2017).Dasgupta and Raychowdhury, arXiv:2009.13969 [hep-lat].

Yang et al, *Nature* 587 (2020) 7834, 392-396.

Schwinger model within quantum link model formulation…



…mapped to a 71-site Bose-Hubbard quantum simulator:



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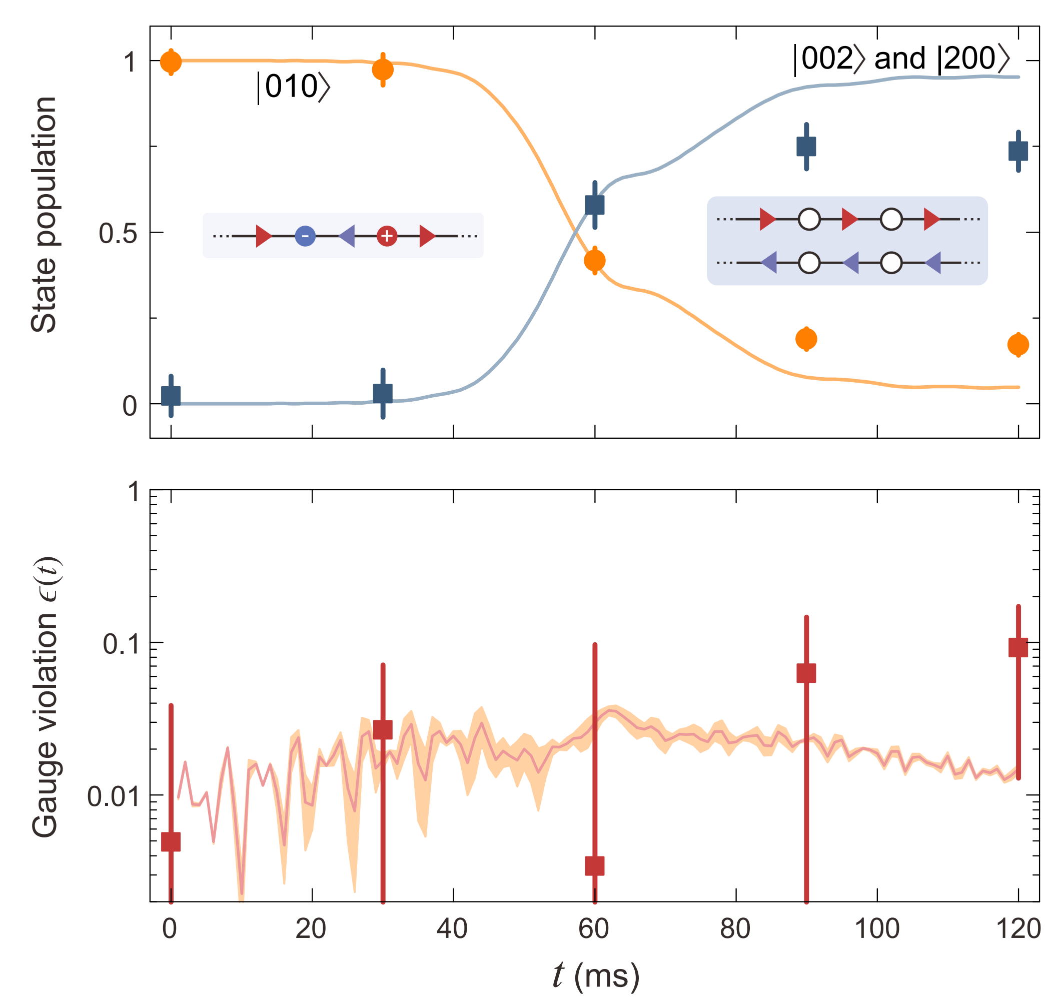
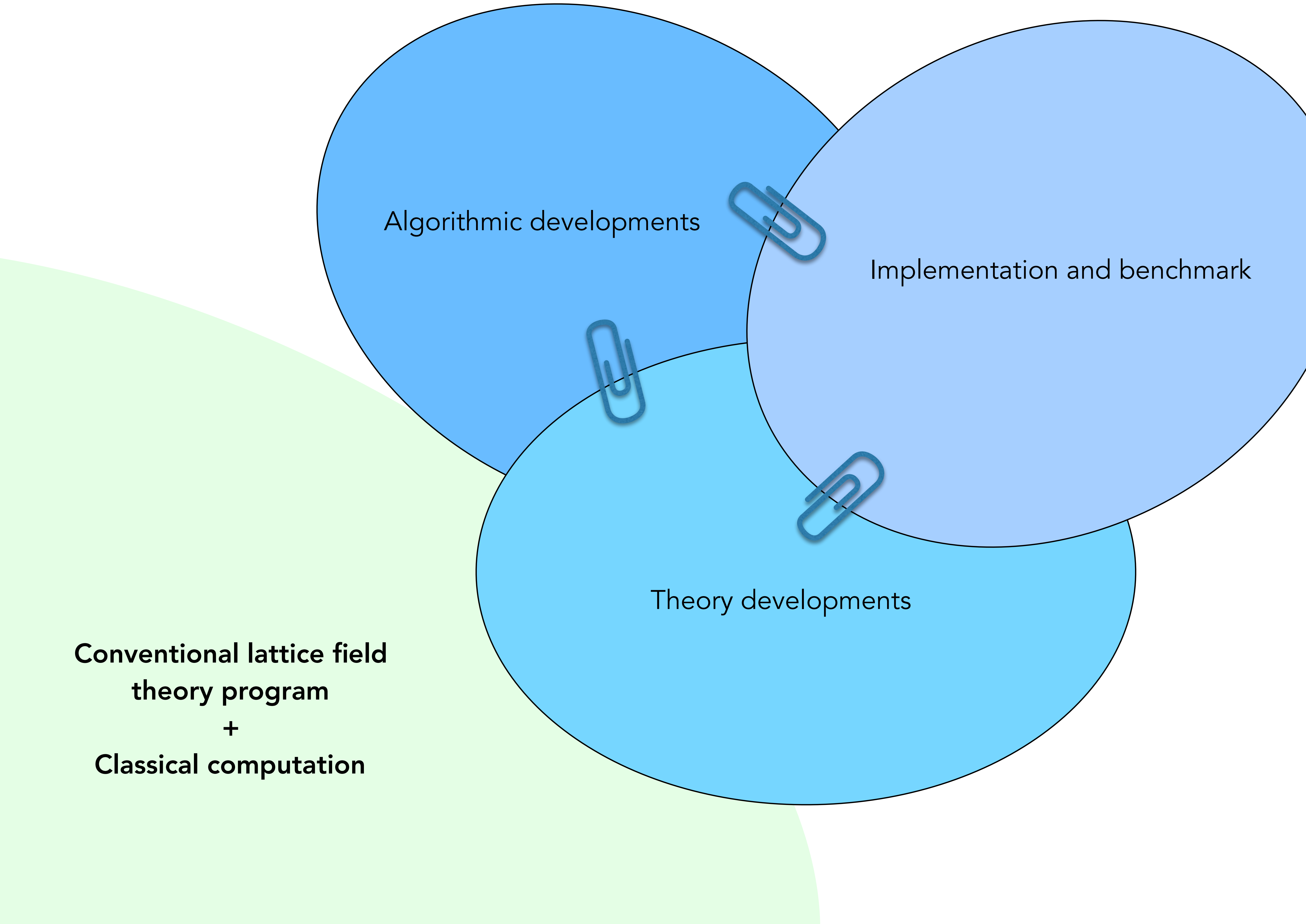
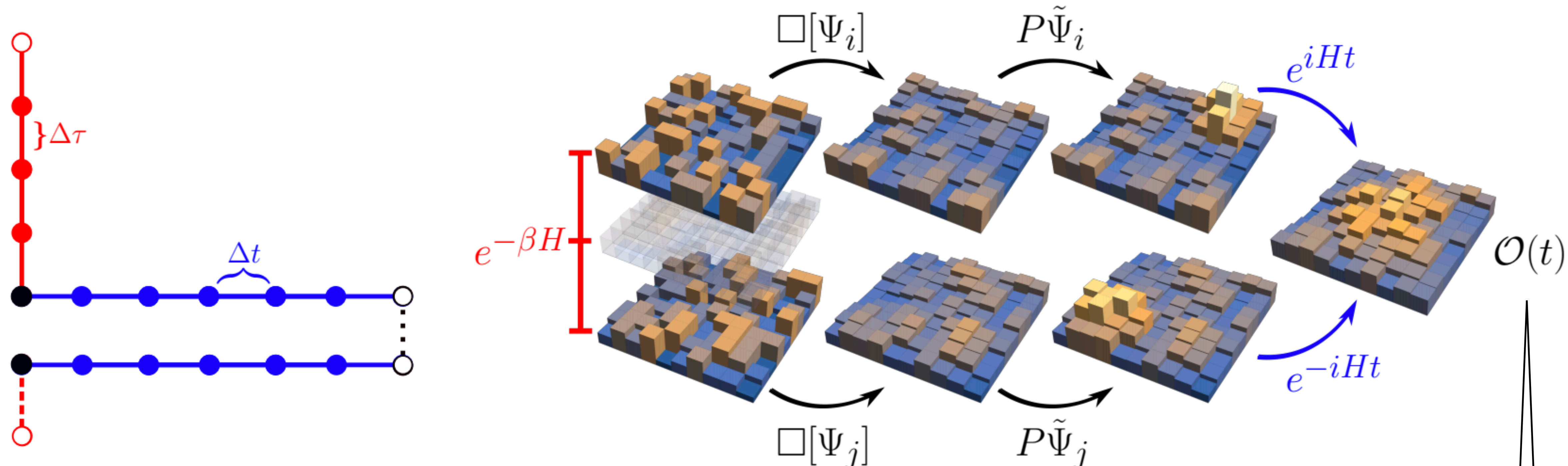
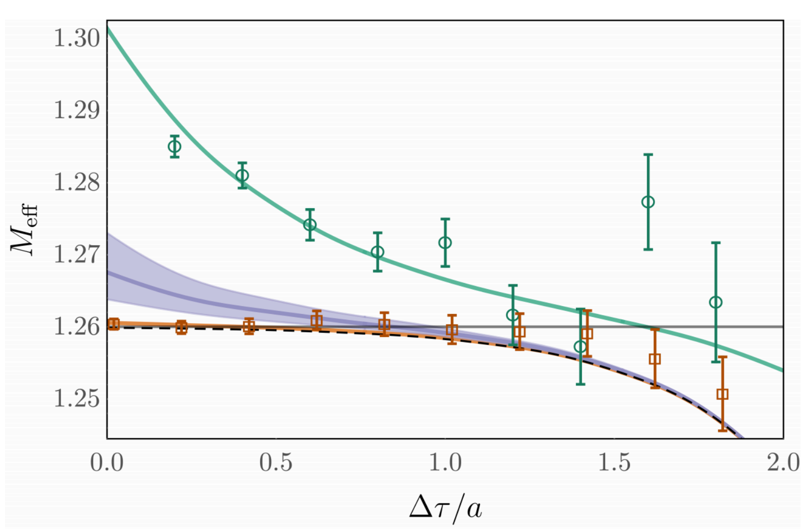



Algorithmic developments
Implementation and benchmark
Theory developments
Conventional lattice field theory program
+
Classical computation

EXAMPLE I: STATE PREPARATION ROUTINE FOR LATTICE GAUGE THEORIES

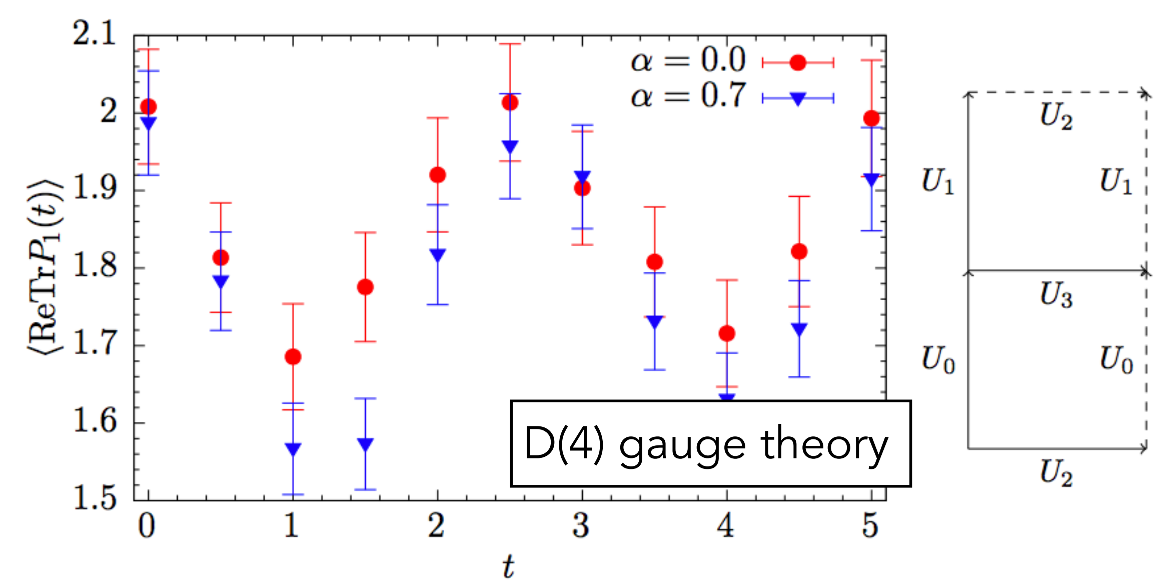
State preparation can be done using Monte Carlo methods if no sign or signal-to-noise problems occur, and time evolution can be ported to quantum hardware.





The use of VQE to generate optimized operators to in Monte Carlo simulation of lattice Schwinger model.

Avkhadiev, Shanahan, Young, Phys. Rev. Lett. 124, 080501 (2020)



Harmalkar, Lamm, Lawrence1, arXiv:2001.11490 [hep-lat]
Gustafson and Lamm and Phys. Rev. D 103, 054507 (2021)

EXAMPLE II: VARIATIONAL QUANTUM SIMULATION OF LATTICE SCHWINGER MODEL

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Kokail et al, Nature 569, 355 (2019).
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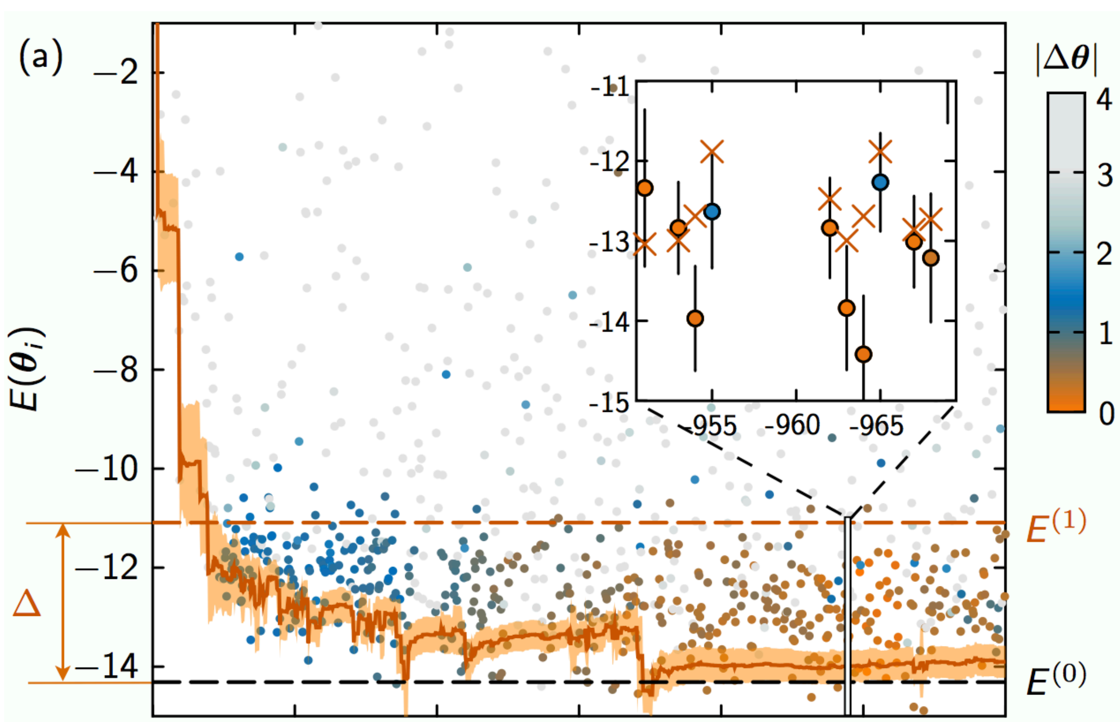
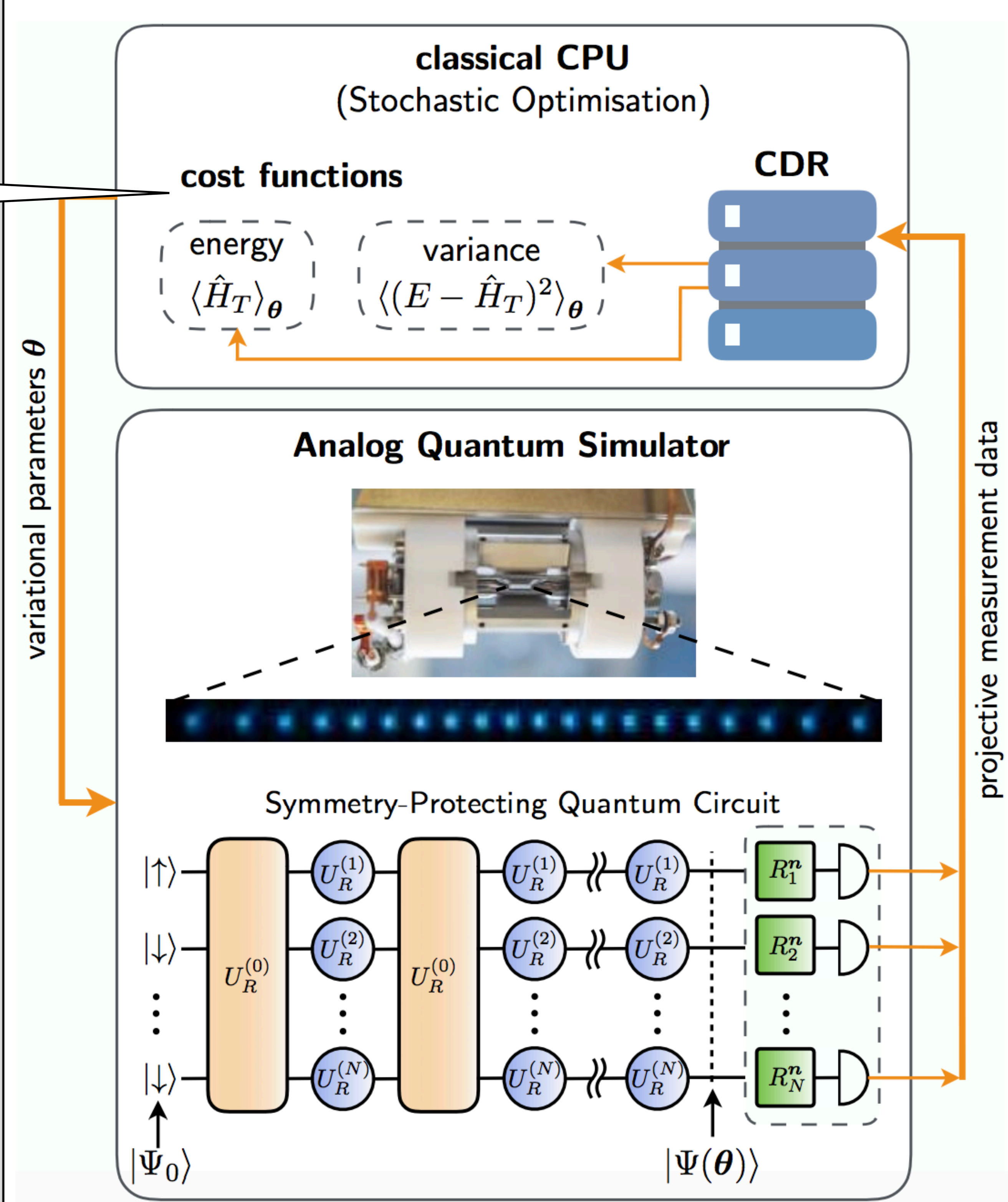
Hamiltonian under which the system evolves respects some symmetries of the original theory and is implemented in an analog fashion.



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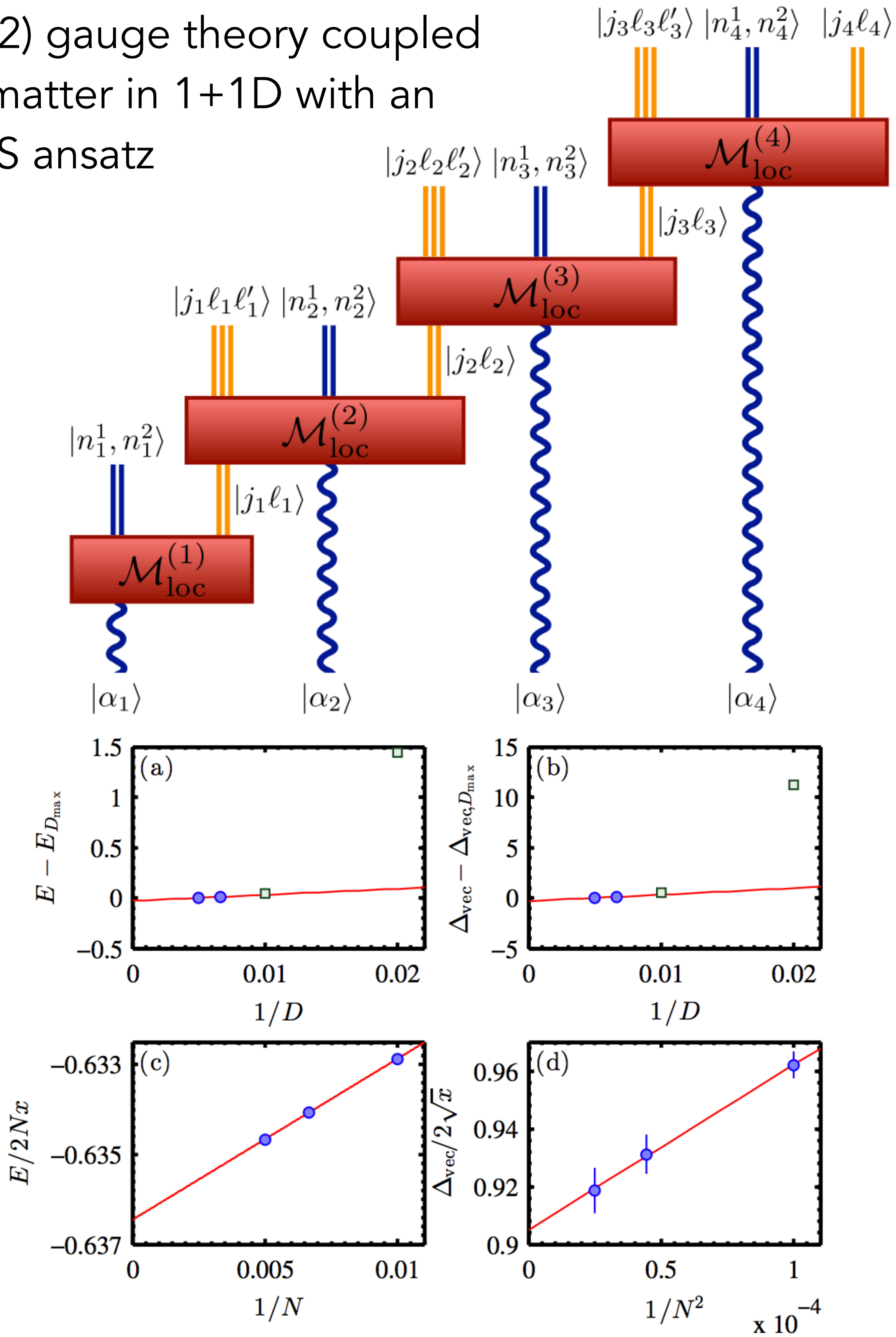
See also Atas et al,
arXiv:2102.08920 [quant-ph] for a VQE
study of SU(2) hadrons.
```

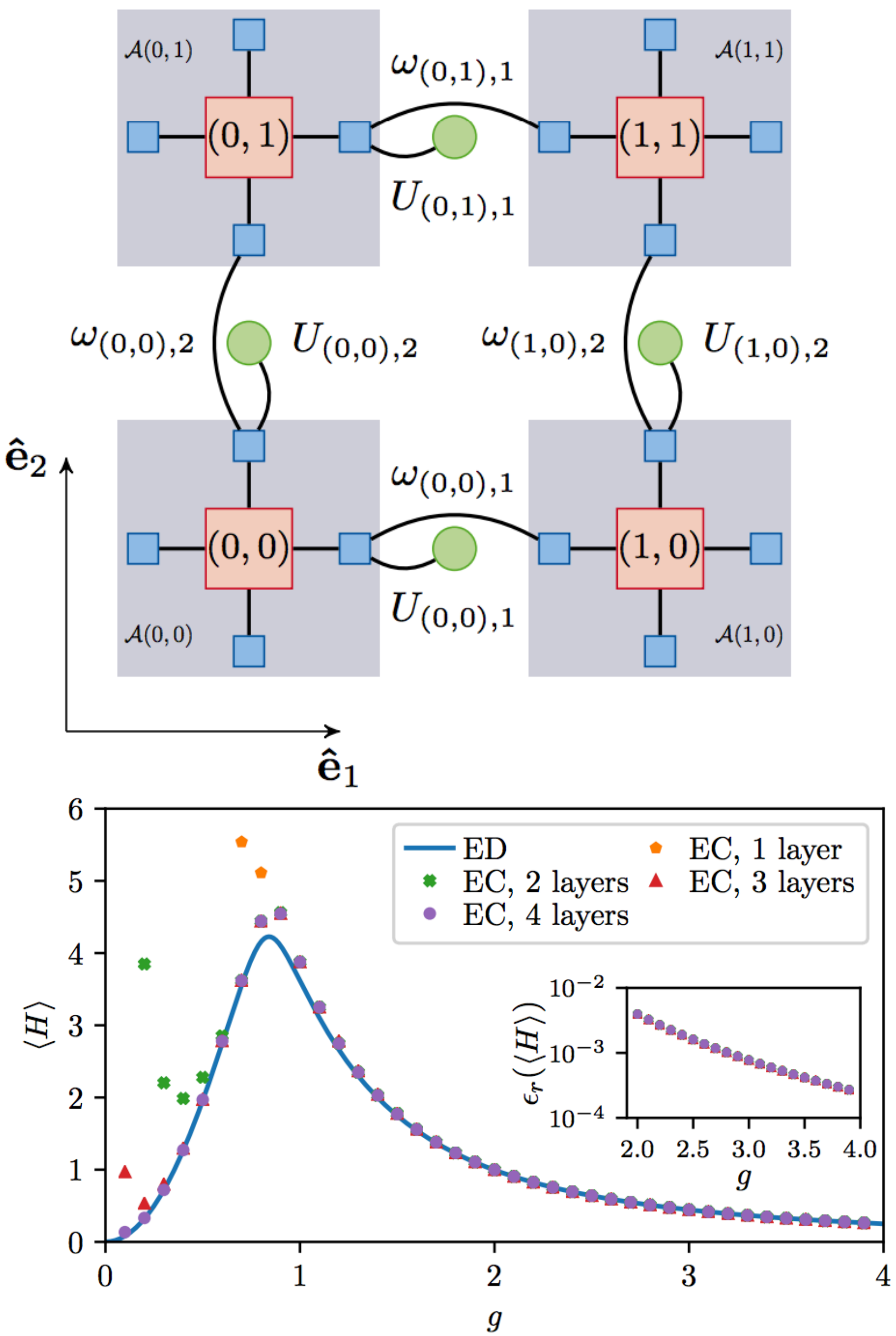
EXAMPLE III: TENSOR NETWORKS FORM CLASSICAL TO QUANTUM COMPUTING

SU(2) gauge theory coupled to matter in 1+1D with an MPS ansatz



Bañuls, Cichy, Cirac, Jansen, Kühn, Phys. Rev. X 7, 041046 (2017)

Z(3) gauge theory in 2+1D with a PEPS ansatz



Emonts, Bañuls, Cirac, Zohar, Phys. Rev. D 102, 074501 (2020)

For a recent nice review see: Meurice, Sakai, Unmuth-Yockey, arXiv:2010.06539 [hep-lat]

SUMMARY

Quantum computing holds the promise of enabling access to quantities which are intractable with our current techniques due to sign and signal-to-noise problem.

Theory, algorithm, and implementation and benchmark on hardware define the pillars of the program now and in upcoming years. Hardware co-design and interactions with other disciplines will be crucial.

Even if scalable noise-resilient quantum computers were available today, we are still not ready to express our LGT simulations in their language.

The rate of progress and magnitude of developments are significant and lattice gauge theorists, including USQCD physicists, are making impactful contributions.

OUTLOOK FOR USQCD

USQCD has formed a **sub-committee on QIS+QC** (chair: Martin Savage, members: Bazavov, ZD, Hasenfratz, Kronfeld, Meurice, Osborn, Petreczky, Simone, and El-Khadra), but concrete activities are yet to be planned.

USQCD members, acting as conveners in the **Snowmass process** and representing QIS+QC in LGT, are: Catterall, ZD, Izubuchi, Neil, and Savage, and of course El-Khadra and Gottlieb as co-leaders of Theory and Comp. Frontiers.

A **Snowmass whitepaper in Quantum Simulation for HEP** is commissioned by the Comp. Frontier and with Theory Frontier representatives (editors: Brauer and ZD). We will try to define better the role of USQCD there.

We begin with a cross country trip in 1967, from Brooklyn NY to Palo Alto CA.

 ➔  → 

The George Washington Bridge | My GTO | The Golden Gate Bridge

So much for history. Now we are in a new era. Hopefully the efforts of the past will inspire great progress in the next era of Quantum Computing!

This is a new field, full of workers with "fire in the belly". That's great! ***You remind of the characters in this story.***

Taken from a nice recent presentation by J. Kogut.

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DATE
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THANK YOU

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