Hamiltonian methods from Quantum Information Technologies: from Z2 String Dynamics to Continuous U(1) Electrodynamics

Enrique Rico Ortega

Friday 02 October 2026

September 28, 2026 to October 2, 2026
Sun Hall Hotel
Asia/Nicosia timezone

AQTIVATE Conference



CERN-TH-2025-105

Roughening and dynamics of an electric flux string in a (2+1)D lattice gauge theory

Francesco Di Marcantonio,[1,*] Sunny Pradhan,[1,†] Sofia Vallecorsa,[2,‡]
Mari Carmen Bañuls,[3,4,§] and Enrique Rico Ortega[1,2,5,6,¶]

arXiv:2505.23853

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CERN-TH-2025-111

Real-Time Dynamics in a (2+1)-D Gauge Theory: The Stringy Nature on a Superconducting Quantum Simulator

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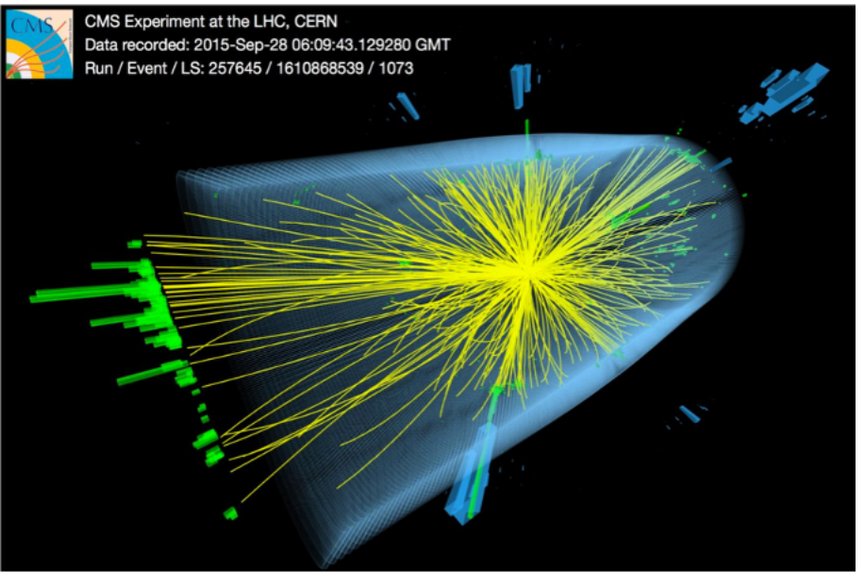
arXiv:2507.08088

CERN-TH-2026-003

Compact U(1) Lattice Gauge Theory in Superconducting Circuits with Infinite-Dimensional Local Hilbert Spaces

J. M. Alcaine-Cuervo,[1,2,*] S. Pradhan,[1,3,†] E. Rico,[1,3,4,5,‡] Z. Shi,[6,§] and C.M. Wilson[6,¶]

arXiv:2601.23150

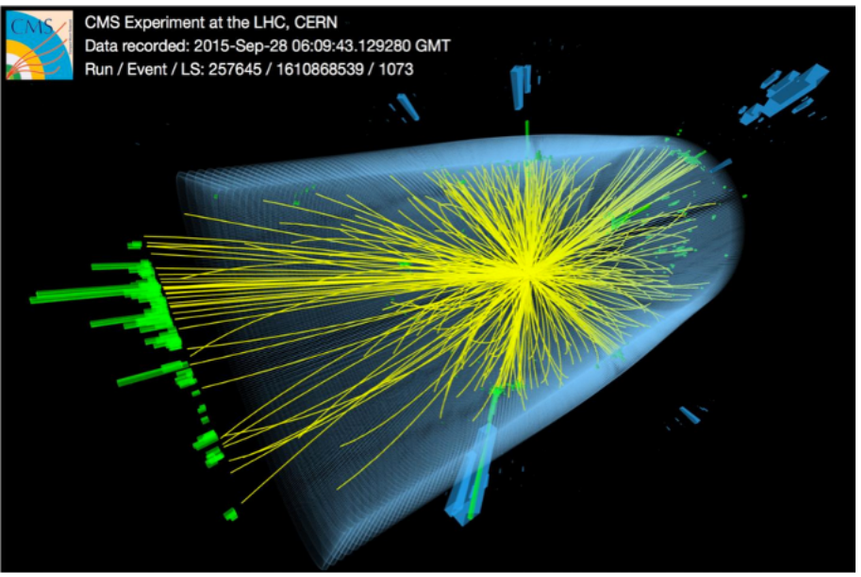


The Grand Challenge:
Simulating the strong force (QCD)

Build purpose-driven hardware to solve fundamental physics

Co-designed hardware as a physics laboratory

“History doesn't repeat itself, but it often rhymes.”



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K. G. Wilson,
Phys. Rev. D (1974)

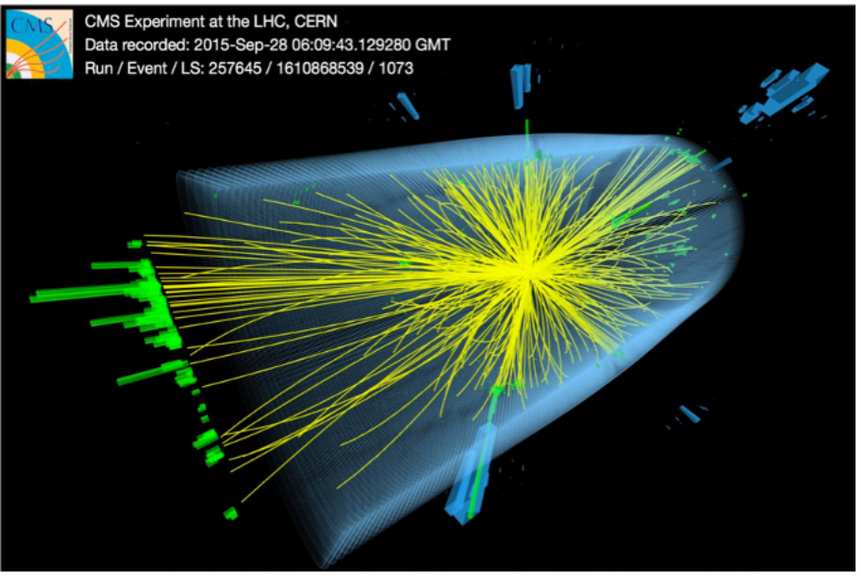


BlueGene & QCDOC

Classical Co-Design for QCD

Solved static properties
(e.g., hadron masses)

Non-efficient for real-time dynamics.



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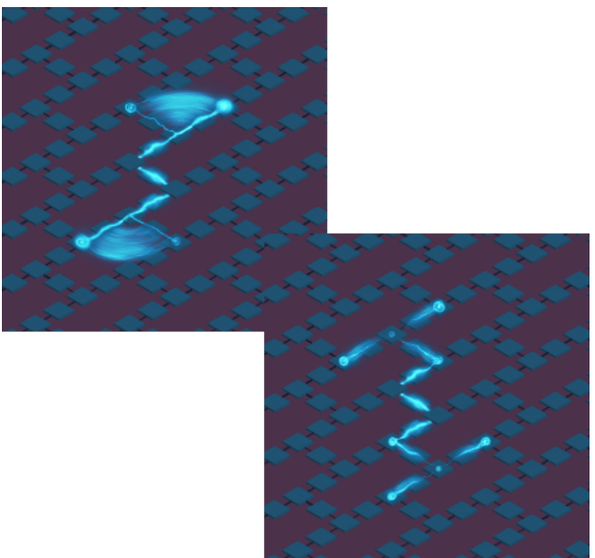


TODAY

Quantum Co-Design for QCD

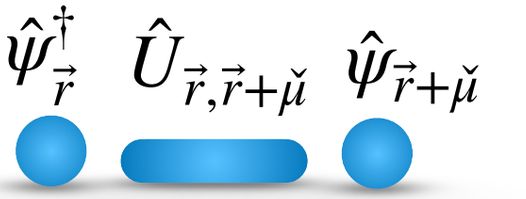
Solved dynamical properties

(e.g., string dynamics)

R. P. Feynman,
Int. J. Theor. Phys. (1982)



What?: Lattice Gauge Theories



Temporal gauge - Local (gauge) symmetry

J. Kogut, L. Susskind, Phys. Rev. D (1975)

M. Creutz, Phys. Rev. D (1977)

$$\hat{H} = \frac{g^2}{2}\sum_{\vec{r},\check{\mu}}[\hat{E}_{\vec{r},\vec{r}+\check{\mu}}]^2 + \frac{1}{2}\sum_{\vec{r},\check{\mu}}\hat{\psi}^{\dagger}_{\vec{r}}\hat{U}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + m\sum_{\vec{r}}(-1)^{\vec{r}}\hat{\psi}^{\dagger}_{\vec{r}}\hat{\psi}_{\vec{r}} + \mathrm{h.c.}$$

$$-\frac{1}{g^2}\sum_{\vec{r},\check{\mu},\check{\nu}}\hat{U}_{\vec{r},\vec{r}+\check{\mu}}\hat{U}_{\vec{r}+\check{\mu},\vec{r}+\check{\mu}+\check{\nu}}\hat{U}^{\dagger}_{\vec{r}+\check{\nu},\vec{r}+\check{\mu}+\check{\nu}}\hat{U}^{\dagger}_{\vec{r},\vec{r}+\check{\nu}} + \mathrm{h.c.} \qquad [\hat{E},\hat{U}] = \hat{U}$$

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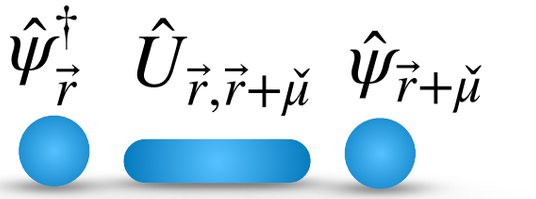

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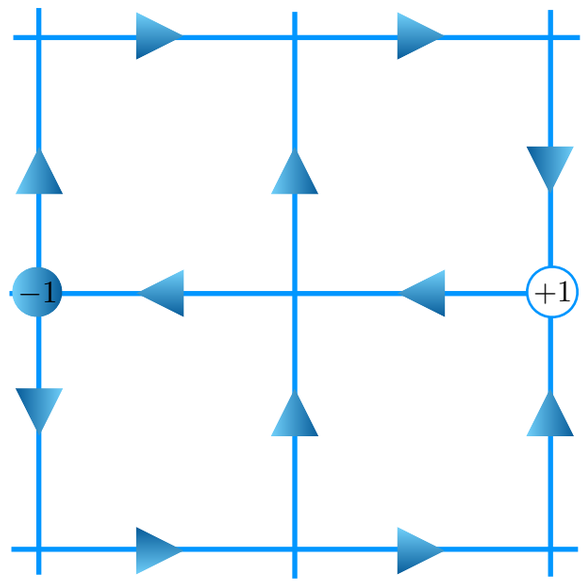
gauge generator

$$\hat{G}_{\vec{r}} = \hat{\psi}^\dagger_{\vec{r}} \hat{\psi}_{\vec{r}} - \sum_{\check{\mu}} \left(\hat{E}_{\vec{r},\vec{r}+\check{\mu}} - \hat{E}_{\vec{r}-\check{\mu},\vec{r}} \right) \qquad [\hat{H}, \hat{G}_{\vec{r}}] = 0 \ \forall \vec{r}$$

physical Hilbert space $\hat{G}_{\vec{r}} |\mathbf{phys}\rangle = 0 \ \forall \vec{r}$



in the continuum $\hat{\rho} = \vec{\nabla} \cdot \hat{\vec{E}}$

charge is the source of electric field

Eur. Phys. J. D (2020) 74: 165
https://doi.org/10.1140/epjd/e2020-100571-8

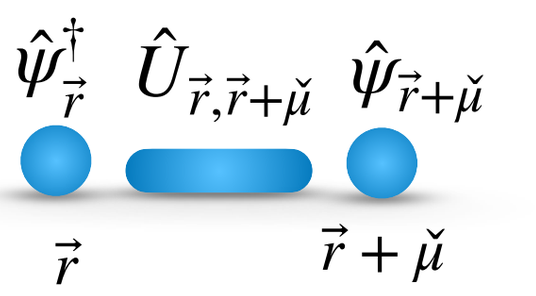
How?: Quantum Technologies

THE EUROPEAN PHYSICAL JOURNAL D

Colloquium

Simulating lattice gauge theories within quantum technologies

Mari Carmen Bañuls[1,2], Rainer Blatt[3,4], Jacopo Catani[5,6,7], Alessio Celi[3,8], Juan Ignacio Cirac[1,2], Marcello Dalmonte[9,10], Leonardo Fallani[5,6,7], Karl Jansen[11], Maciej Lewenstein[8,12,13], Simone Montangero[14,15,a], Christine A. Muschik[3], Benni Reznik[16], Enrique Rico[17,18], Luca Tagliacozzo[19], Karel Van Acoleyen[20], Frank Verstraete[20,21], Uwe-Jens Wiese[22], Matthew Wingate[23], Jakub Zakrzewski[24,25], and Peter Zoller[3]



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How?: Quantum Technologies

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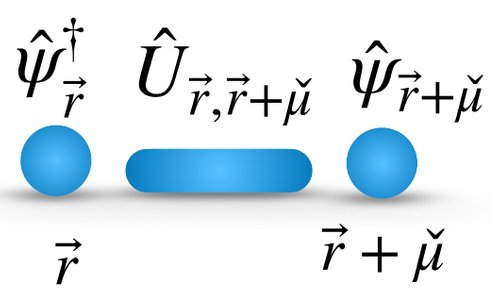
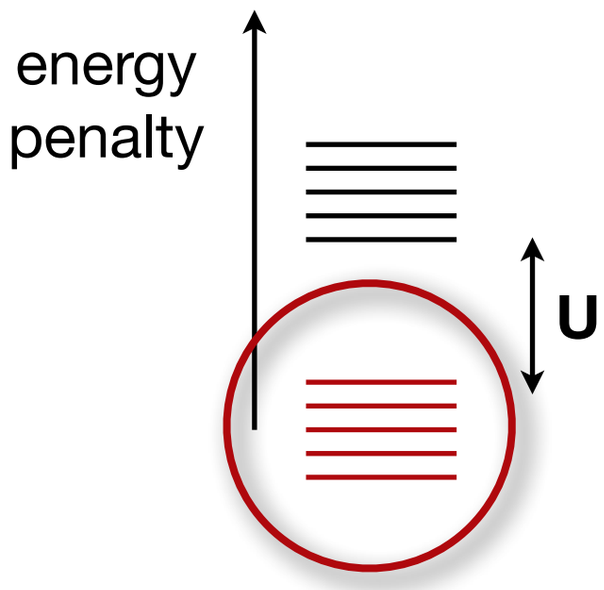
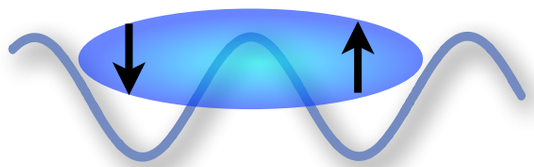


- Implementing the gauge invariant dynamics





color singlet
hopping

Internal symmetry



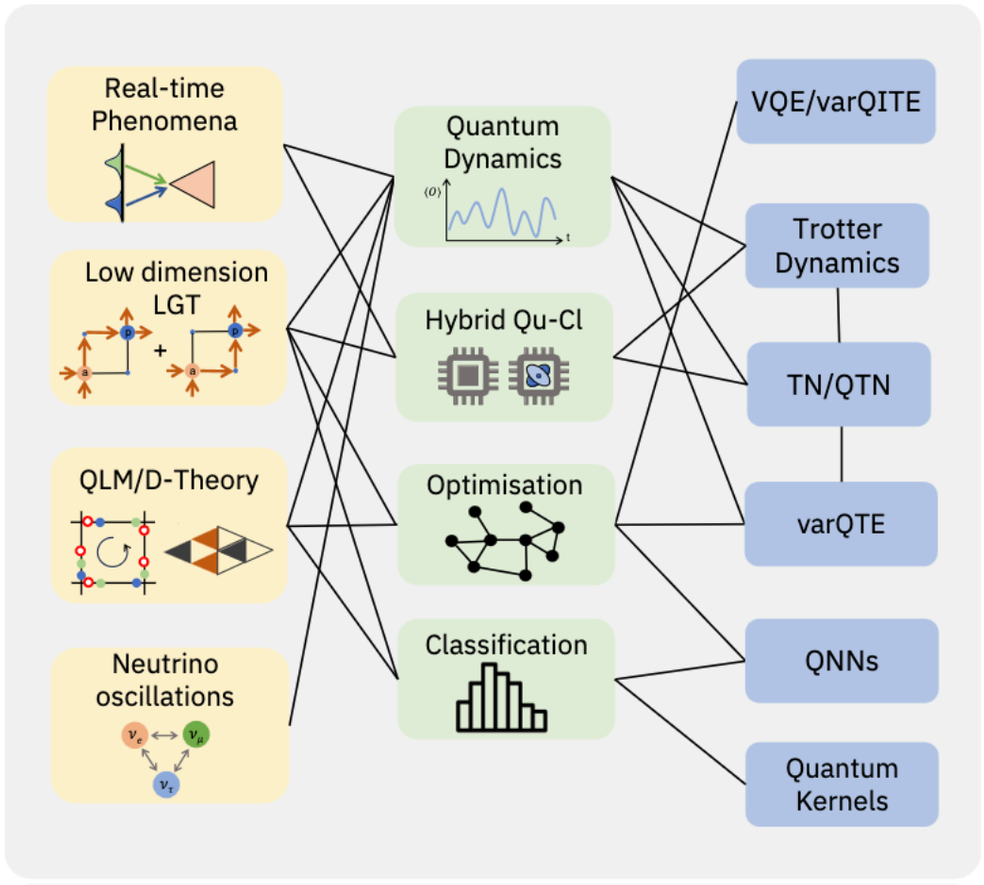
encoding
gauge invariant
degrees of freedom

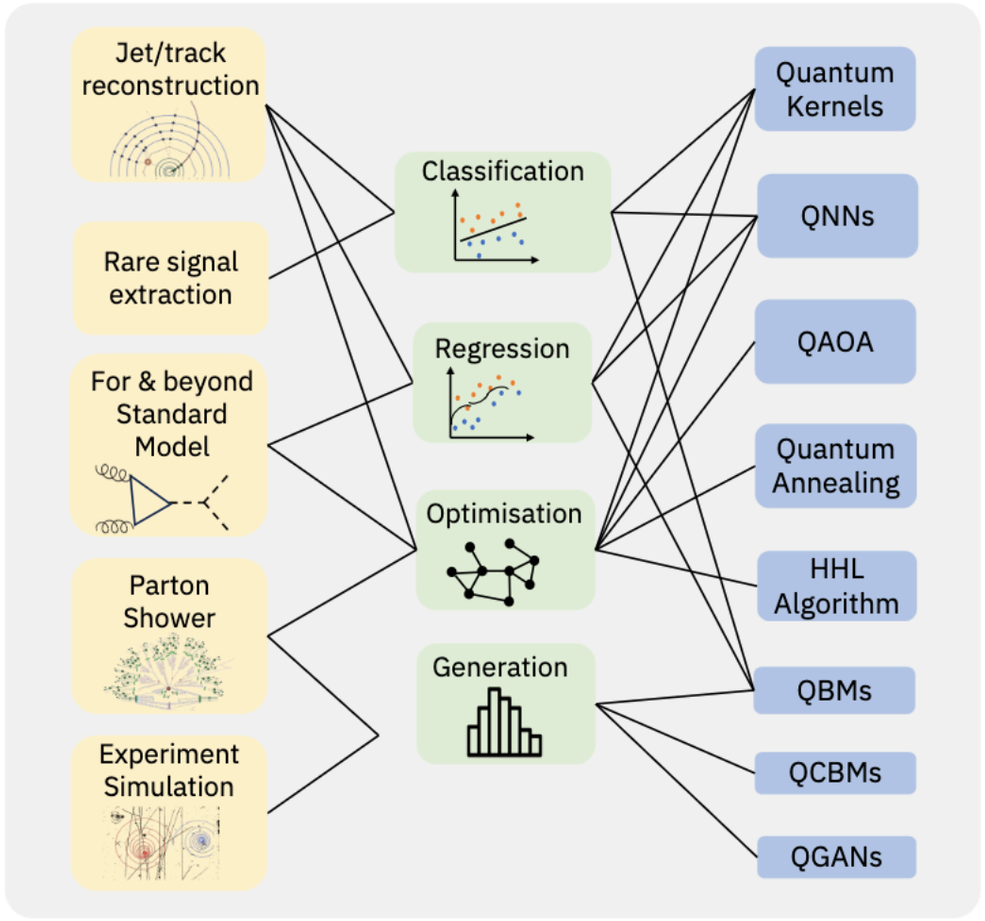
Quantum Computing for High-Energy Physics: State of the Art and Challenges

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[3,5] Srinivasan Arunachalam,[6] Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[1,10] Arianna Crippa,[2,11] Vincent Croft,[12] Roland de Putter,[6] Andrea Delgado,[13] Vedran Dunjko,[12] Daniel J. Egger,[4] Elias Fernández-Combarro,[14] Elina Fuchs,[1,15,16] Lena Funcke,[17] Daniel González-Cuadra,[18,19] Michele Grossi,[1] Jad C. Halimeh,[20,21] Zoë Holmes,[22] Stefan Kühn,[2] Denis Lacroix,[23] Randy Lewis,[24] Donatella Lucchesi,[1,25] Miriam Lucio Martinez,[26,27] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[1,25] Lento Nagano,[28] Vincent R. Pascuzzi,[6] Voica Radescu,[29] Enrique Rico Ortega,[30,31,32,33] Alessandro Roggero,[34,35] Julian Schuhmacher,[4] Joao Seixas,[36,37,38] Pietro Silvi,[1,25] Panagiotis Spentzouris,[39] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[28] Jordi Tura,[12,40] Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[41] Shinjae Yoo,[42] and Jinglei Zhang[43,44]

Roadmap

PRX QUANTUM **5,** 037001 (2024)





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Roadmap

PRX QUANTUM **5,** 037001 (2024)

Reviews:

Quantum Computer Systems for Scientific Discovery, PRX Quantum (2021)
Cold atoms meet lattice gauge theory, Philos Trans A Math Phys Eng Sci (2022)
Quantum Simulation for High-Energy Physics, PRX Quantum (2023)
Quantum Computing for High-Energy Physics: State of the Art and Challenges, PRX Quantum (2024)
Cold-atom quantum simulators of gauge theories, Nat. Phys. (2025)
…

First experimental realizations:

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer, Nature (2016)
Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator, Nature (2020)
Realizing topologically ordered states on a quantum processor, Science (2021)
Probing topological spin liquids on a programmable quantum simulator, Science (2021)
Observation of string breaking on a (2+1)D Rydberg quantum simulator, Nature (2025)
Visualizing dynamics of charges and strings in (2+1)D lattice gauge theories, Nature (2025)
…

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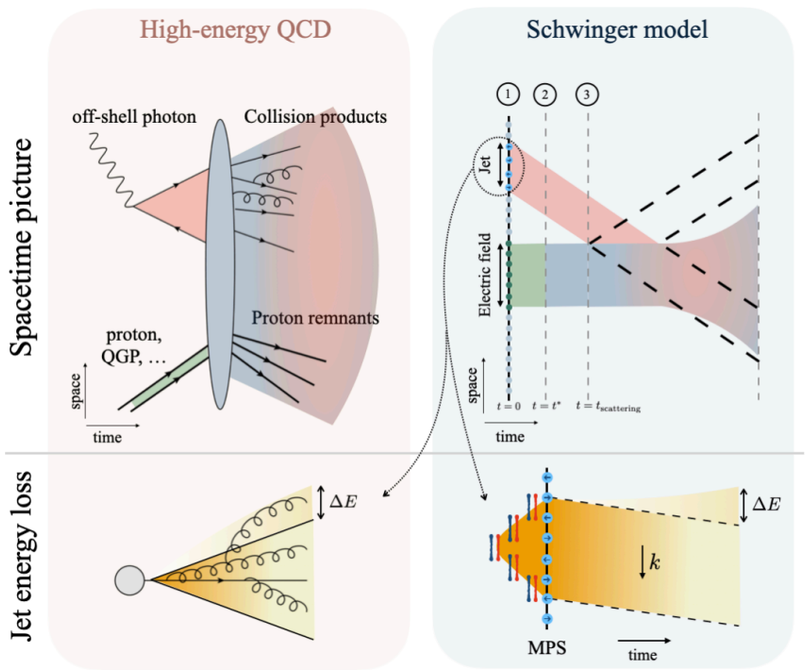
CERN-TH-2025-019

Real-time simulation of jet energy loss and entropy production in high-energy scattering with matter

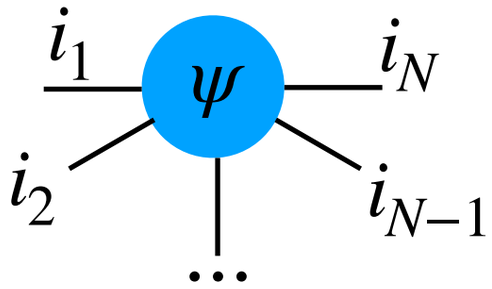
João Barata[1,*] and Enrique Rico[1,†]

[1] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*



$$H(t) = \frac{g^2 a}{2} \sum_{n=1}^{N-1} \left[\frac{1}{2} \sum_{k=1}^{n} (\sigma_k^z + (-1)^k) + \alpha_{\text{ext}}(t,n) \right]^2 + \sum_{n=1}^{N} m(-1)^n \frac{\sigma_n^z}{2} + \frac{1}{2a} \sum_{n=1}^{N-1} \sigma_n^+ \sigma_{n+1}^- + \sigma_{n+1}^+ \sigma_n^- \,,$$

$$|\psi\rangle = \sum_{i_1,i_2,\cdots,i_N=1}^{d} \psi_{i_1,i_2,\cdots,i_N} |\, i_1, i_2, \cdots, i_N\rangle$$



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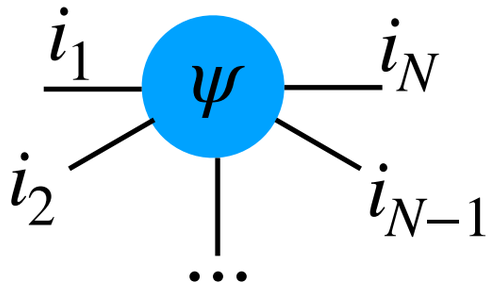
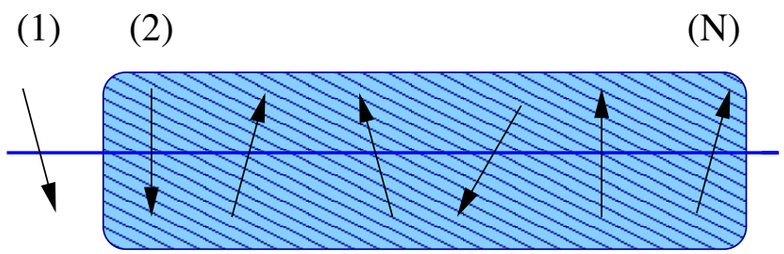


Schmidt decomposition:

$$|\Psi\rangle = \sum_j c_j |\psi_j\rangle_A \otimes |\psi_j\rangle_B \qquad c_j \geq 0; \qquad \sum_j c_j^2 = 1$$



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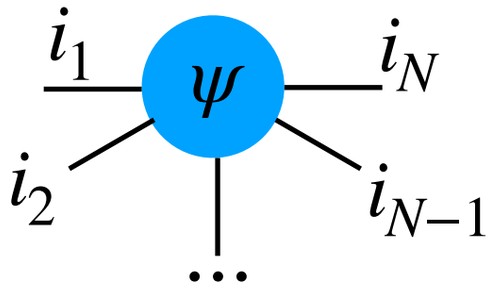

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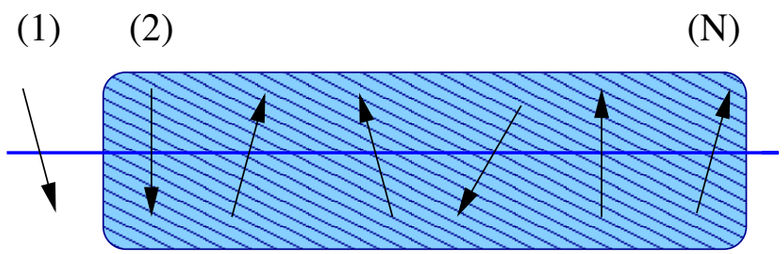
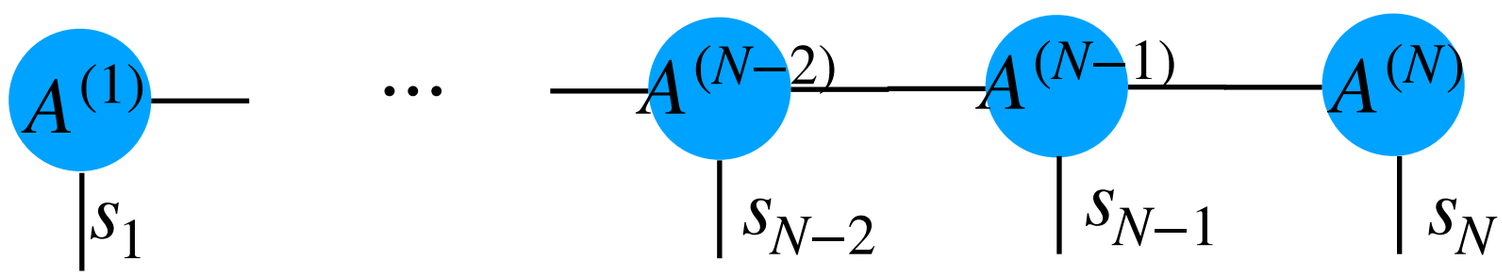
$$|\Psi\rangle = \sum_{a=1}^{D} |\phi_a^{(1)}\rangle \lambda_a^{(1)} |\phi_a^{(2,\ldots,N)}\rangle = \sum_{a=1}^{D} \sum_{s_1=1}^{d} |s_1\rangle\langle s_1|\phi_a^{(1)}\rangle \lambda_a^{(1)} |\phi_a^{(2,\ldots,N)}\rangle$$

$$= \sum_{a=1}^{D} \sum_{s_1=1}^{d} |s_1\rangle A_a[s_1] |\phi_a^{(2,\ldots,N)}\rangle = \sum_{a,b=1}^{D} \sum_{s_1,s_2=1}^{d} |s_1\rangle A_a[s_1] |s_2\rangle A_{ab}[s_2] |\phi_b^{(3,\ldots,N)}\rangle$$

$$= \cdots = \sum_{\{s_j\}=1}^{d} Tr\{A[s_1] \cdots A[s_N]\} |s_1\rangle \cdots |s_N\rangle$$





Matrix Product State (MPS)

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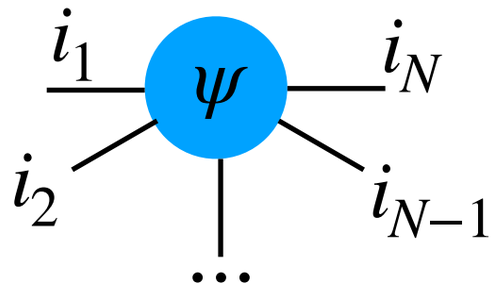

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Parameter count:
NdD^2 vs d^N
Calculation cost:
NdD^3

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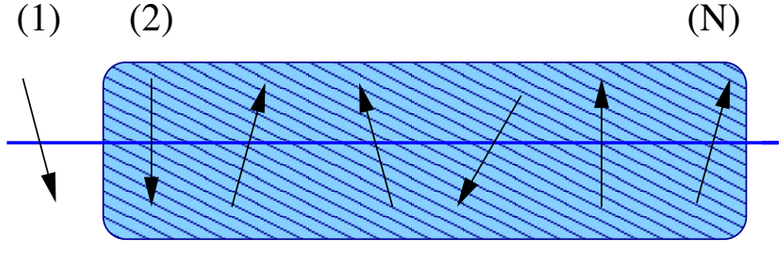
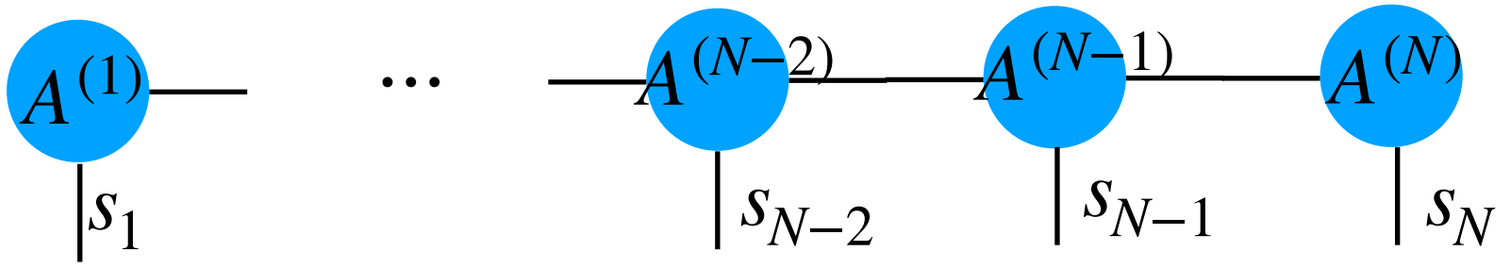
$$= \cdots = \sum_{\{s_j\}=1}^{d} Tr\{A[s_1] \cdots A[s_N]\} |s_1\rangle \cdots |s_N\rangle$$





Matrix Product State (MPS)

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arXiv:2505.23853

CERN-TH-2025-105

Roughening and dynamics of an electric flux string in a (2+1)D lattice gauge theory

Francesco Di Marcantonio,[1,*] Sunny Pradhan,[1,†] Sofia Vallecorsa,[2,‡]
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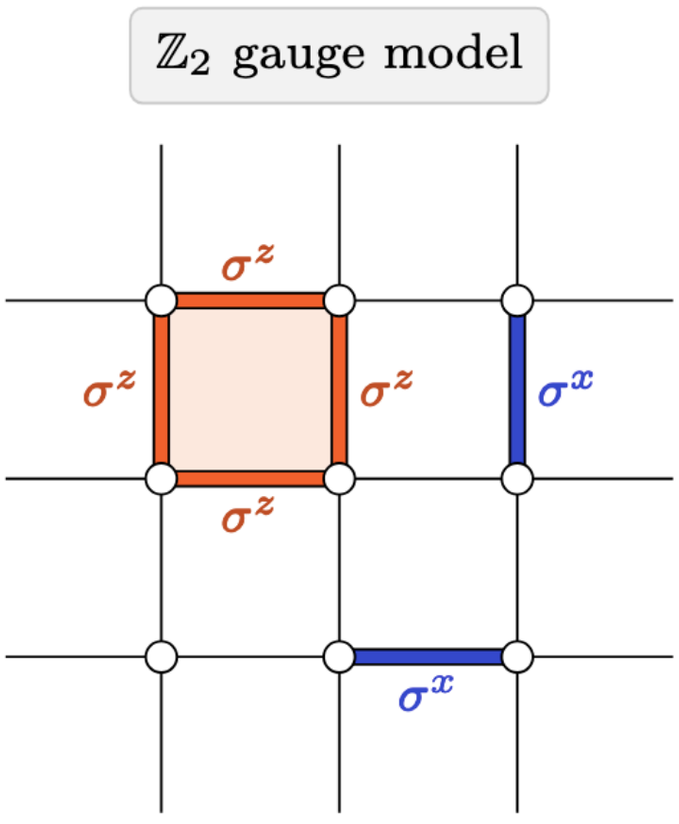

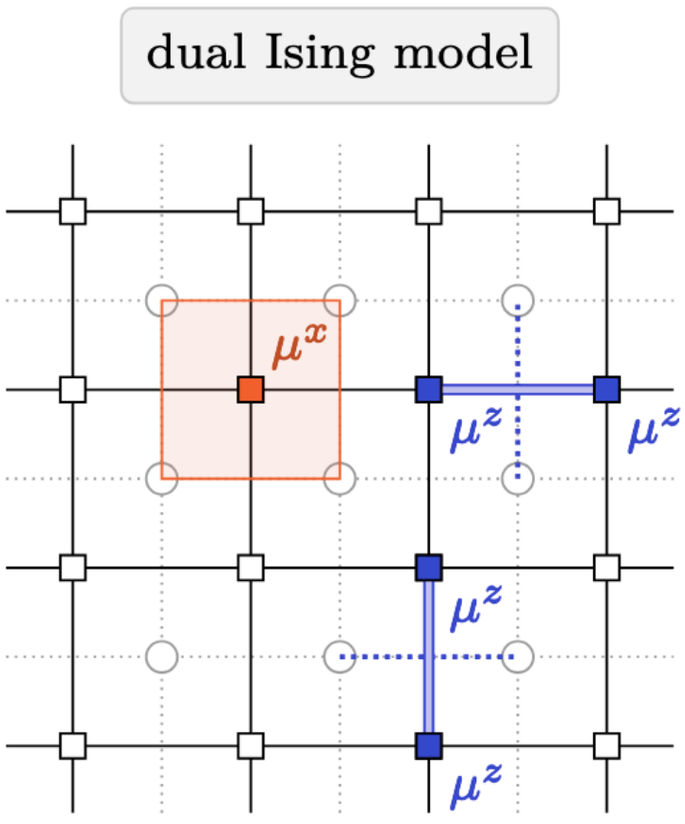

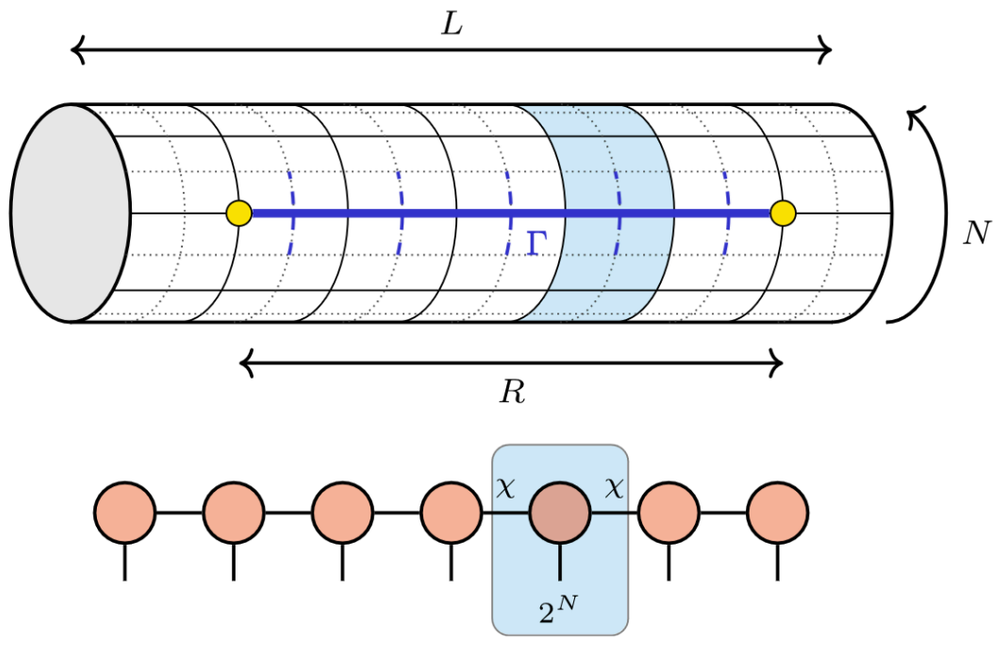

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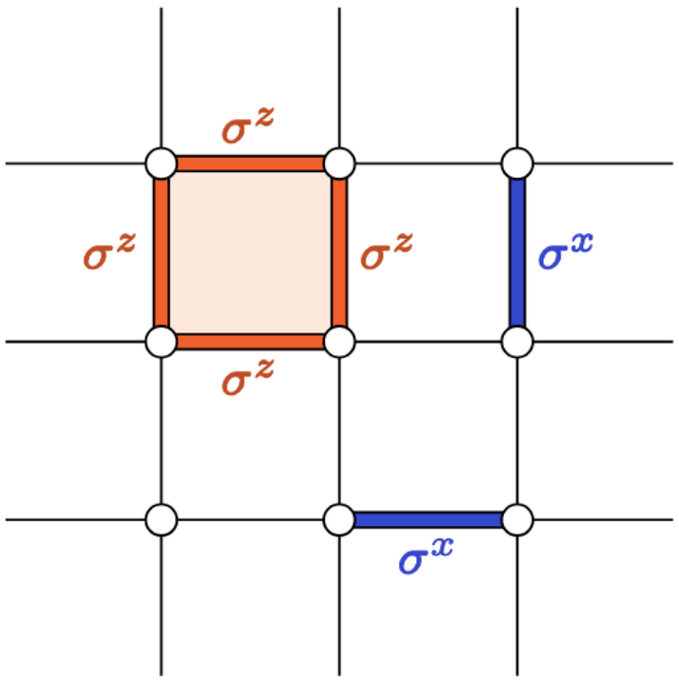
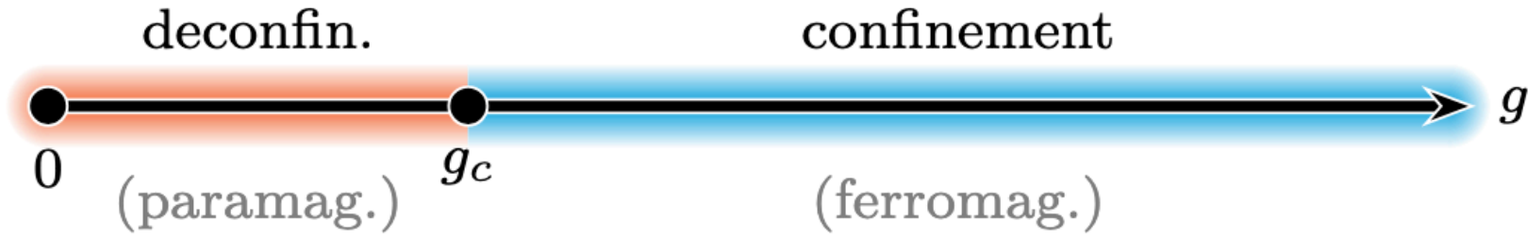
$\mathbb{Z}_2$ gauge model

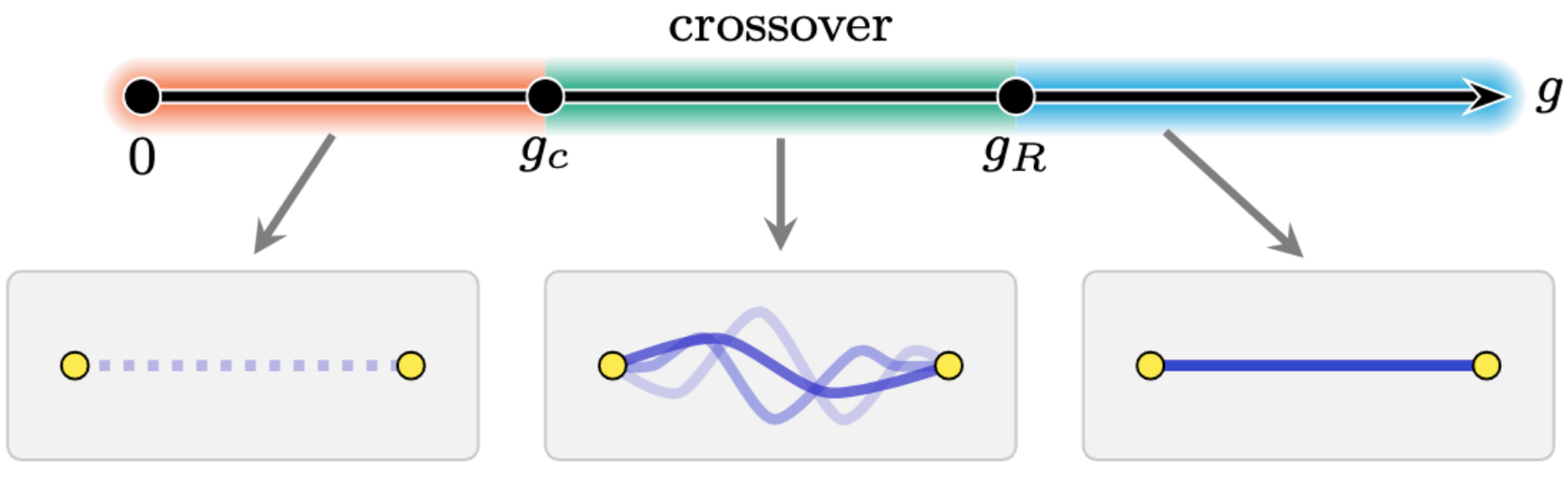


direct lattice

$\mathbb{Z}_2$ vacuum



$\mathbb{Z}_2$ 2-particle



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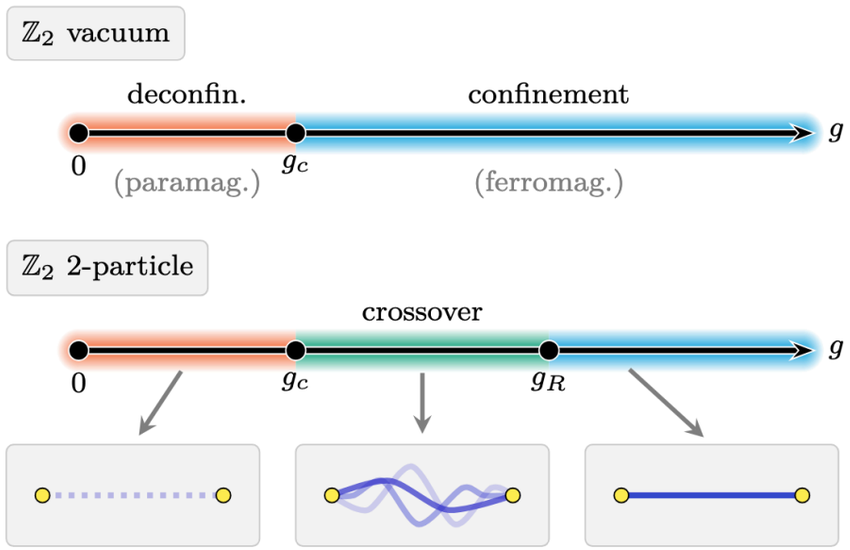

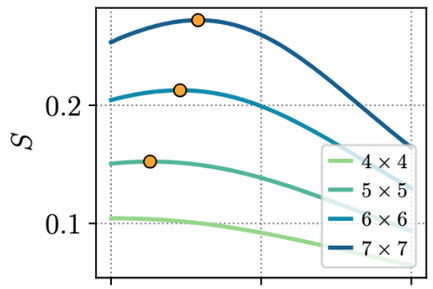

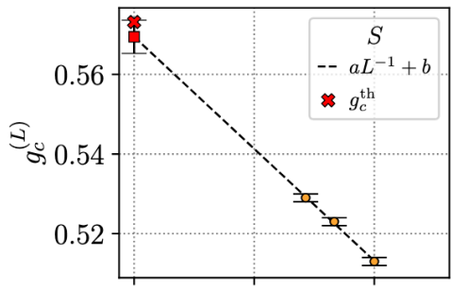

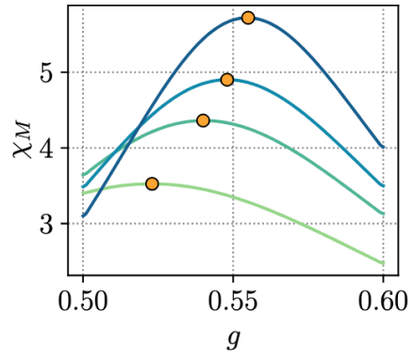

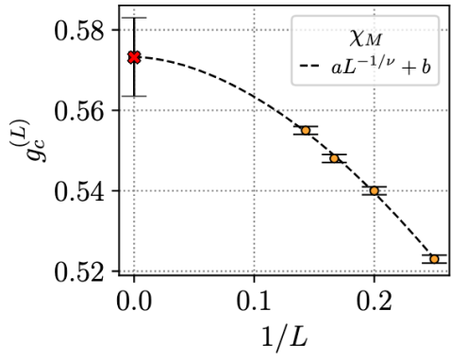

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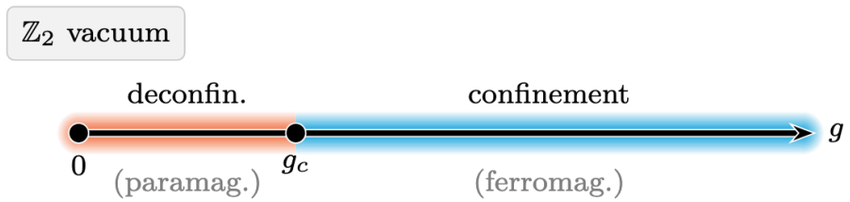

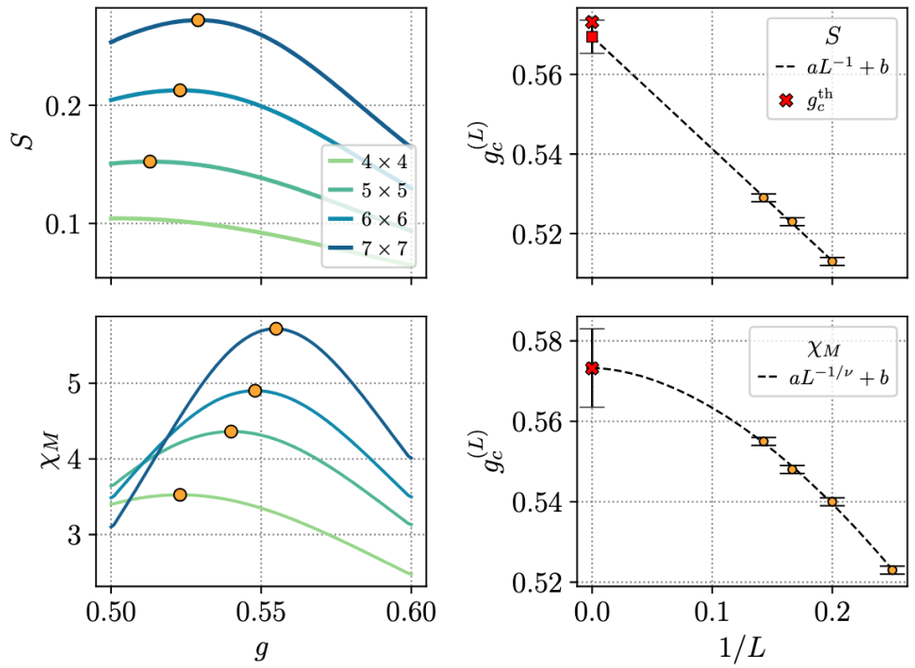

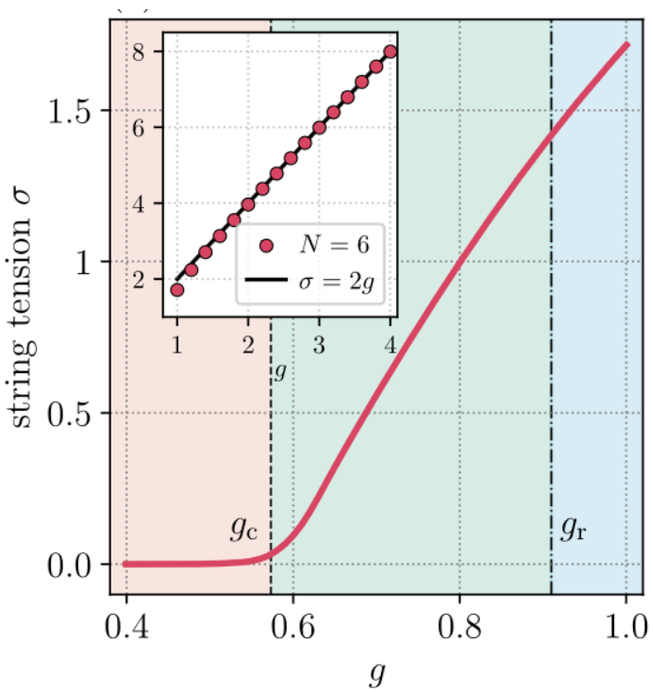

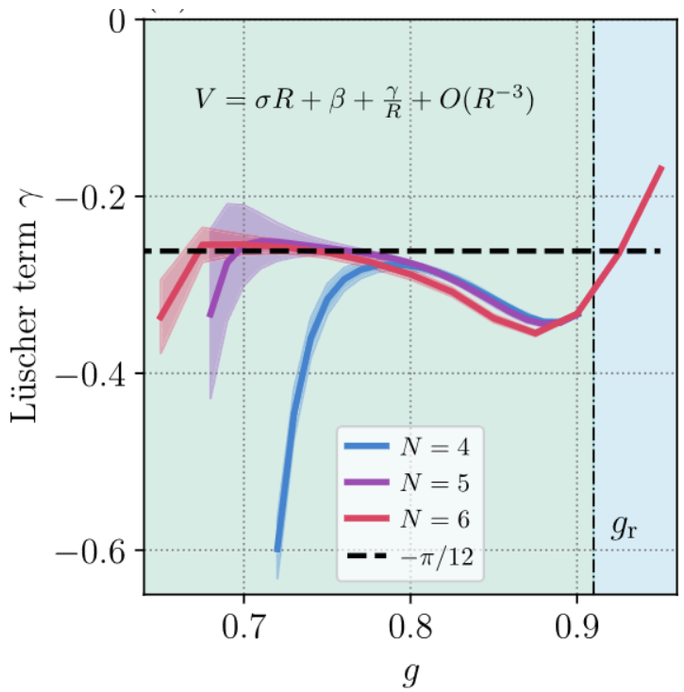

$$V(R,g) = \langle \Omega_{2p} | H^{2p}(g) | \Omega_{2p} \rangle - \langle \Omega_{vac} | H^{vac}(g) | \Omega_{vac} \rangle$$

$$V(R) = \sigma R + c + \frac{\gamma}{R} + O(R^{-3})$$

$$\gamma = -\frac{(d-2)\pi}{24}$$

Universal Luscher term

arXiv:2505.23853

CERN-TH-2025-105

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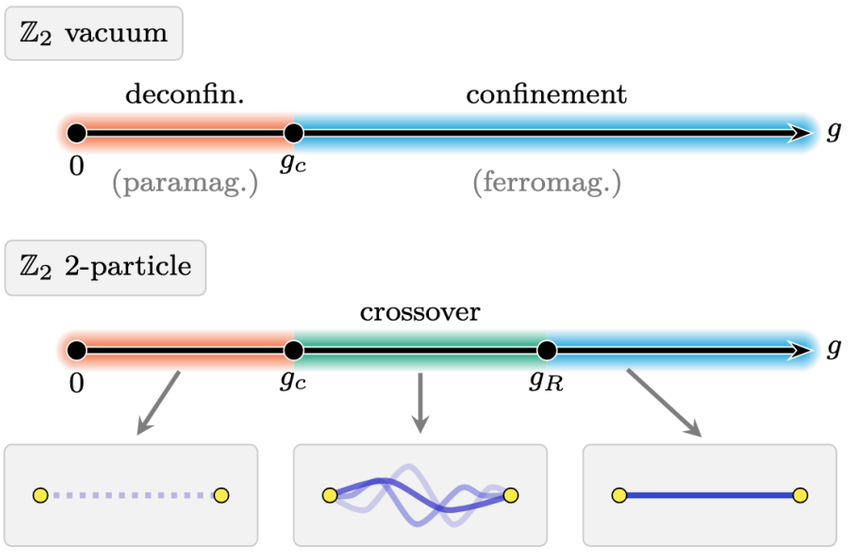
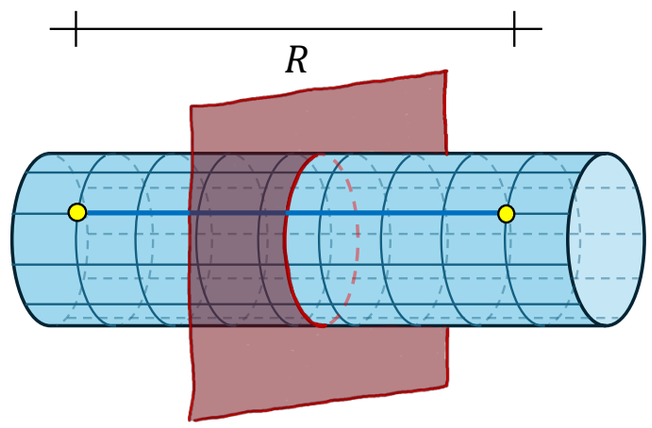
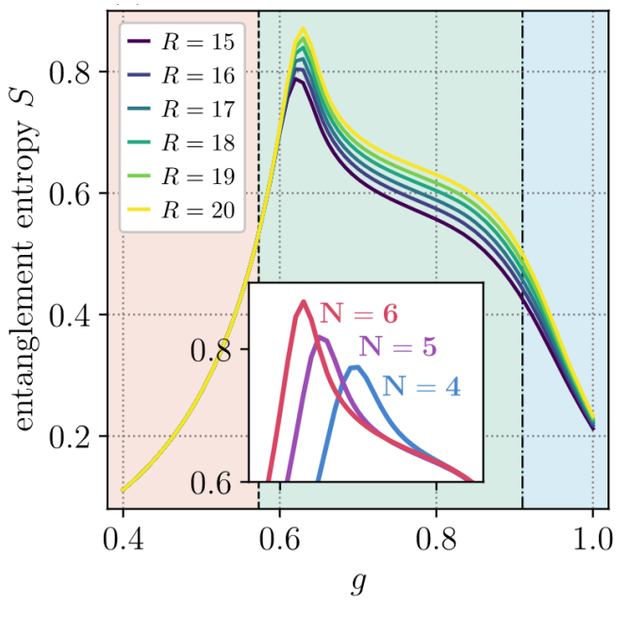
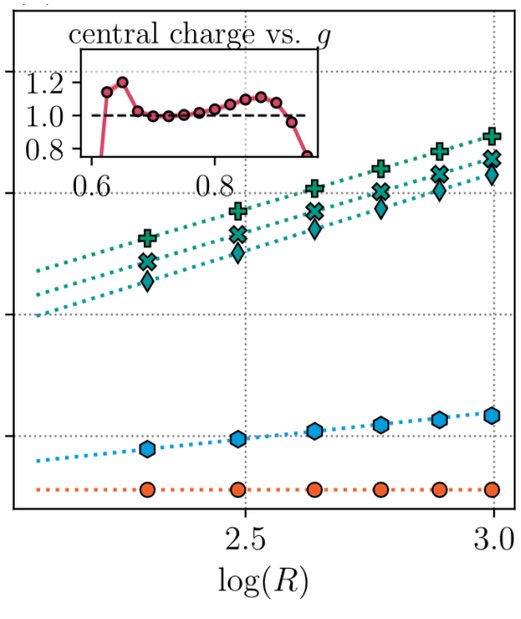


$$|\psi(t,g,R)\rangle = e^{-itH^{2p}(g)}|\Omega_{vac}(g)\rangle$$



$$S_{vn}(t) = \sum_i \alpha^2_{i,L/2} \log \alpha^2_{i,L/2}$$





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CERN-TH-2025-105

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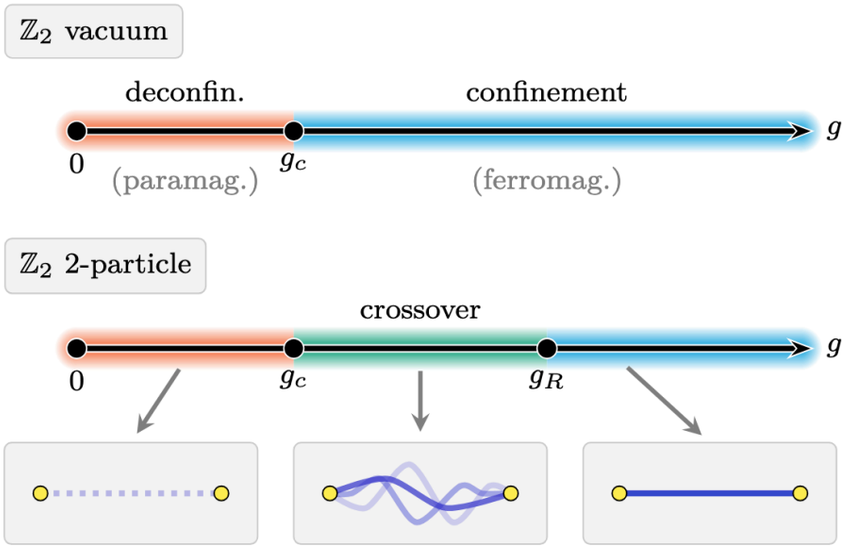

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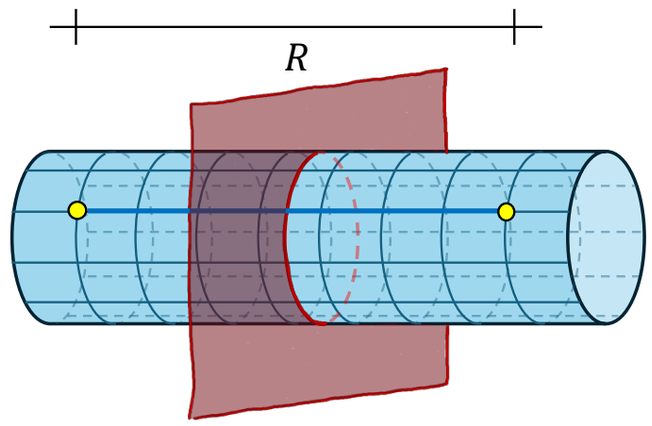

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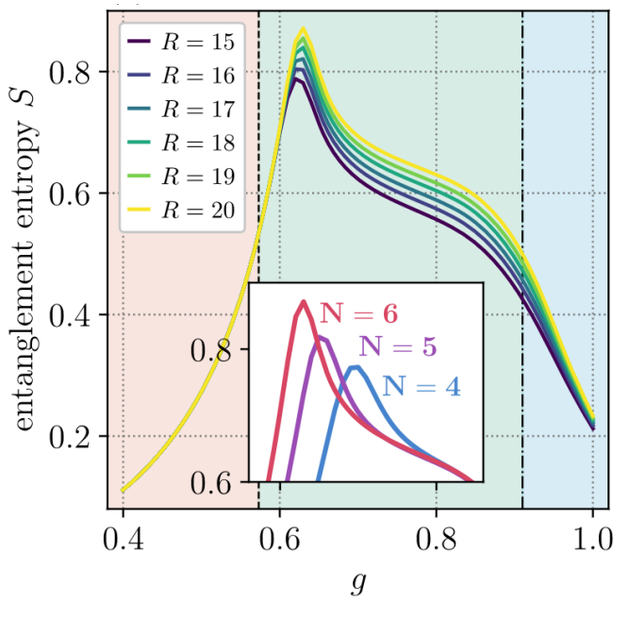
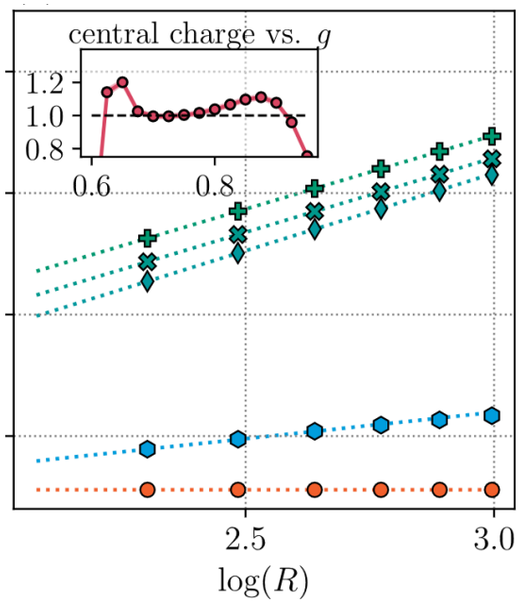
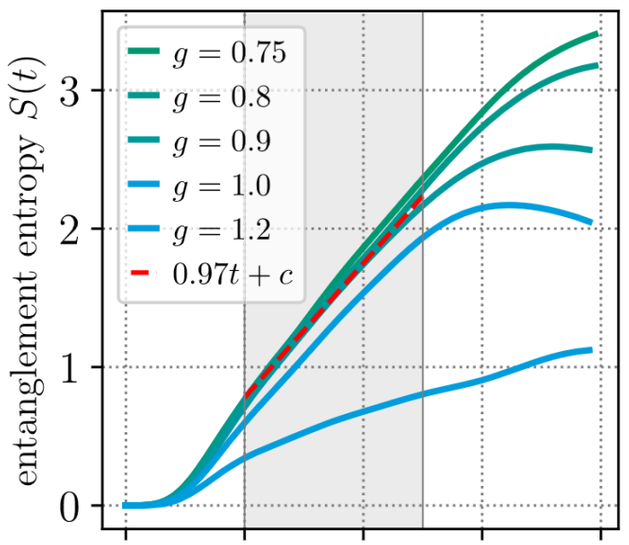
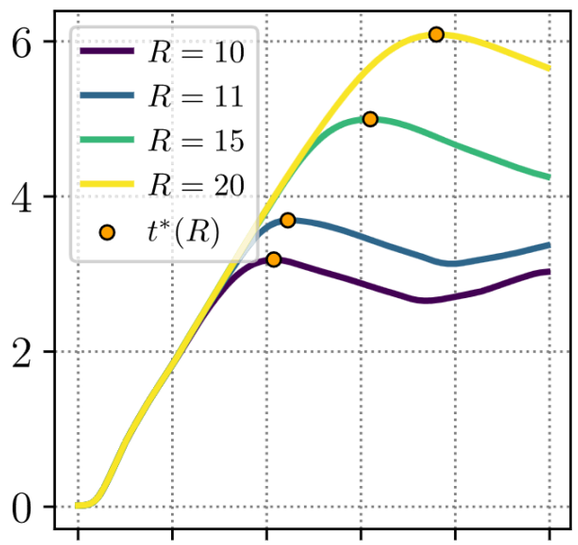
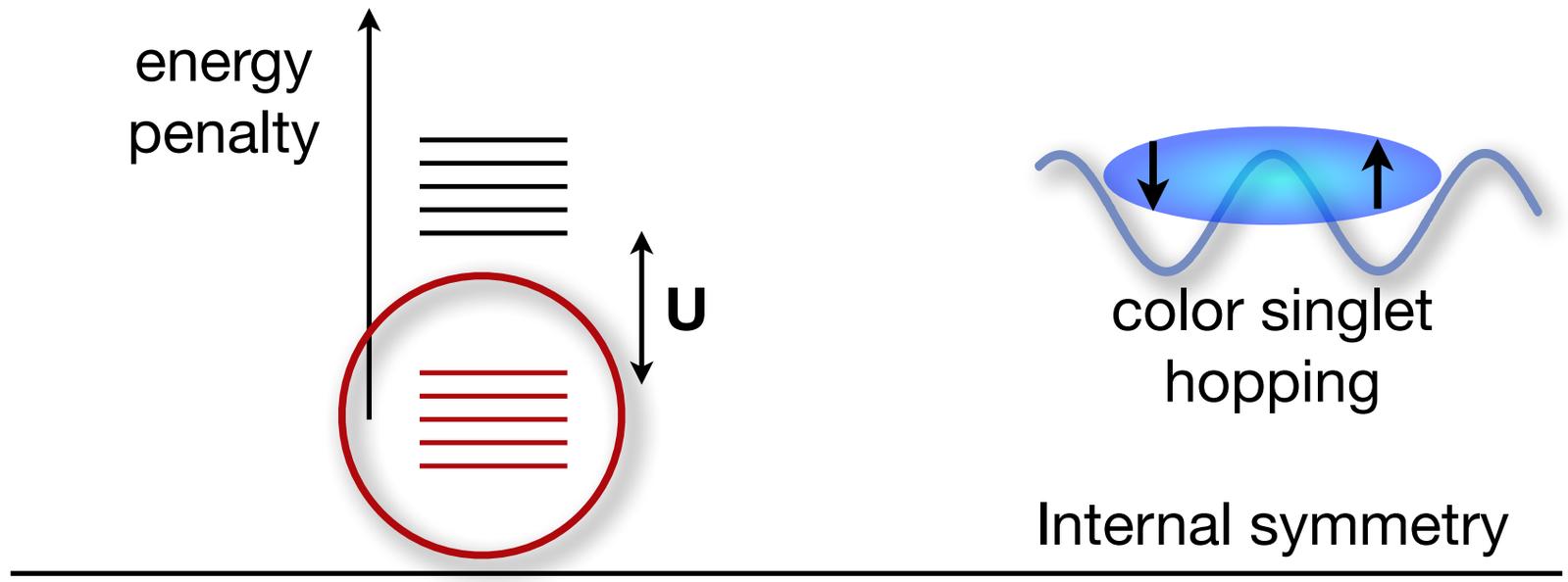










CERN-TH-2025-111

Real-Time Dynamics in a (2+1)-D Gauge Theory: The Stringy Nature on a Superconducting Quantum Simulator

Jesús Cobos,[1,*] Joana Fraxanet,[2] César Benito,[3] Francesco di Marcantonio,[1] Pedro Rivero,[2] Kornél Kapás,[4] Miklós Antal Werner,[4] Örs Legeza,[4,5,6] Alejandro Bermudez,[3] and Enrique Rico[1,7,8,9]

arXiv:2507.08088

CERN-TH-2026-003

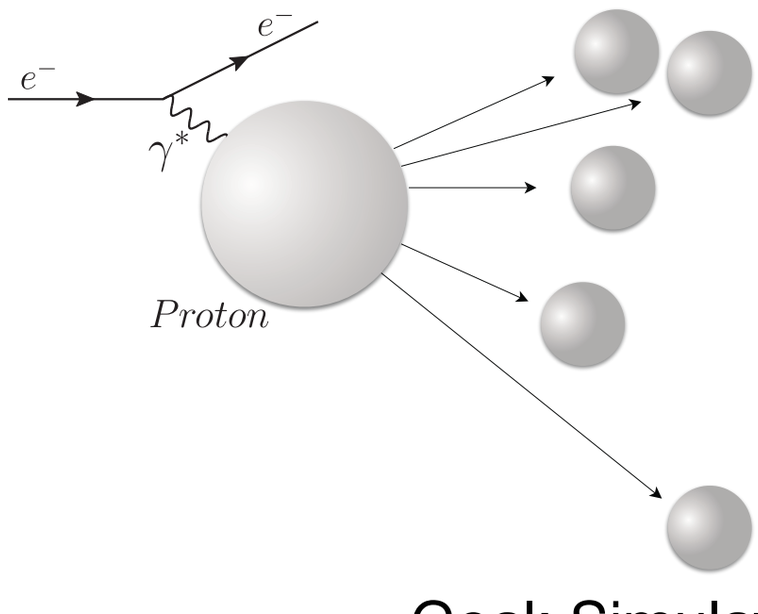
Compact U(1) Lattice Gauge Theory in Superconducting Circuits with Infinite-Dimensional Local Hilbert Spaces

J. M. Alcaine-Cuervo,[1,2,*] S. Pradhan,[1,3,†] E. Rico,[1,3,4,5,‡] Z. Shi,[6,§] and C.M. Wilson[6,¶]

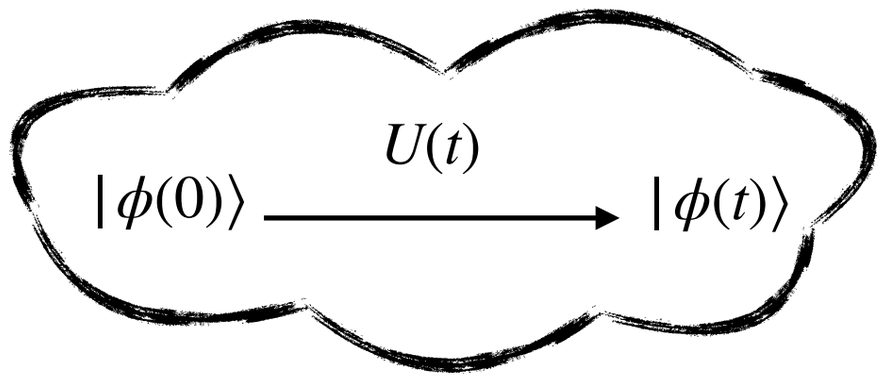
arXiv:2601.23150

Quantum Simulation

Problem to compute



Quantum system

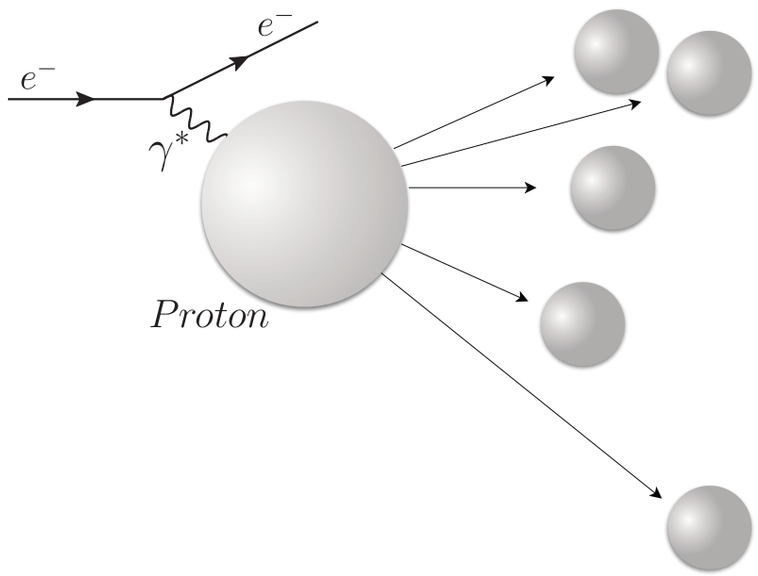


Goal: Simulate the physics of a quantum system of interest by another quantum device that is easier to control and to measure

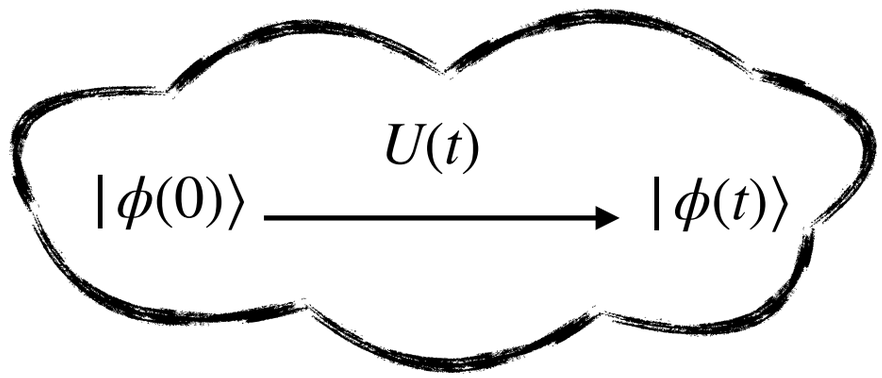
Quantum Simulation,
Rev. Mod. Phys (2014)

Quantum Simulation

Problem to compute



Quantum system



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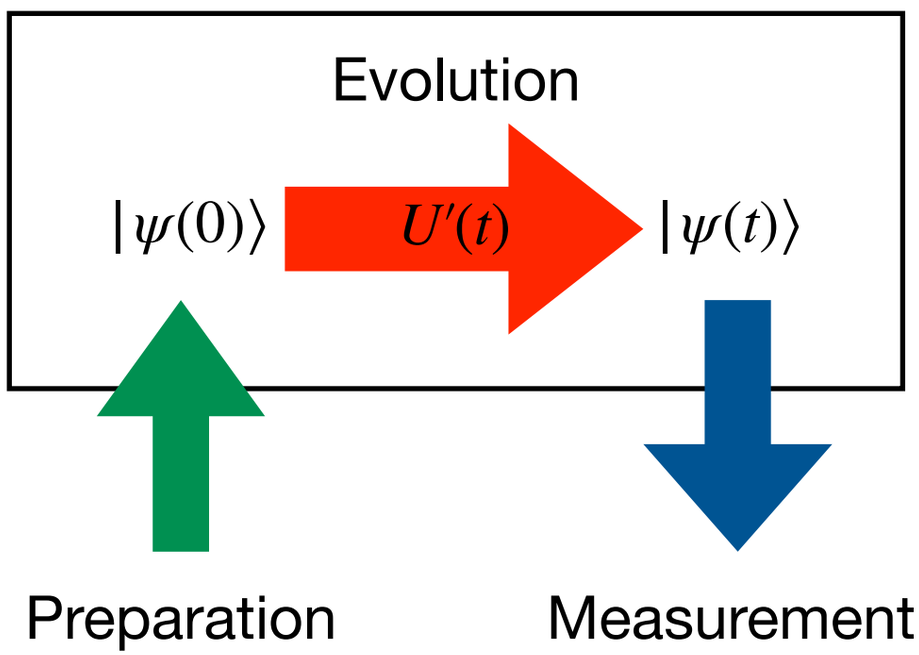
Quantum simulator



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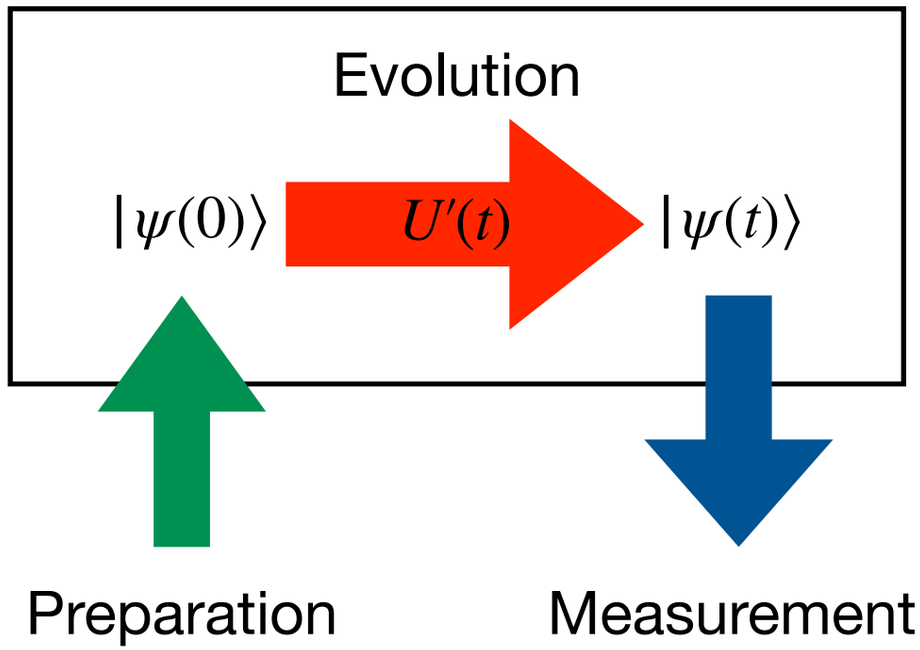
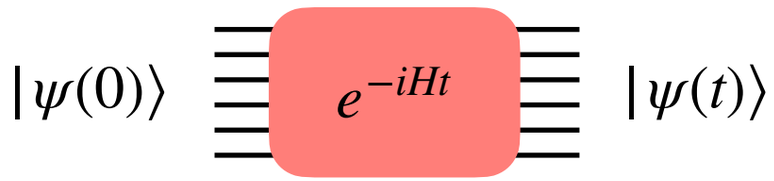
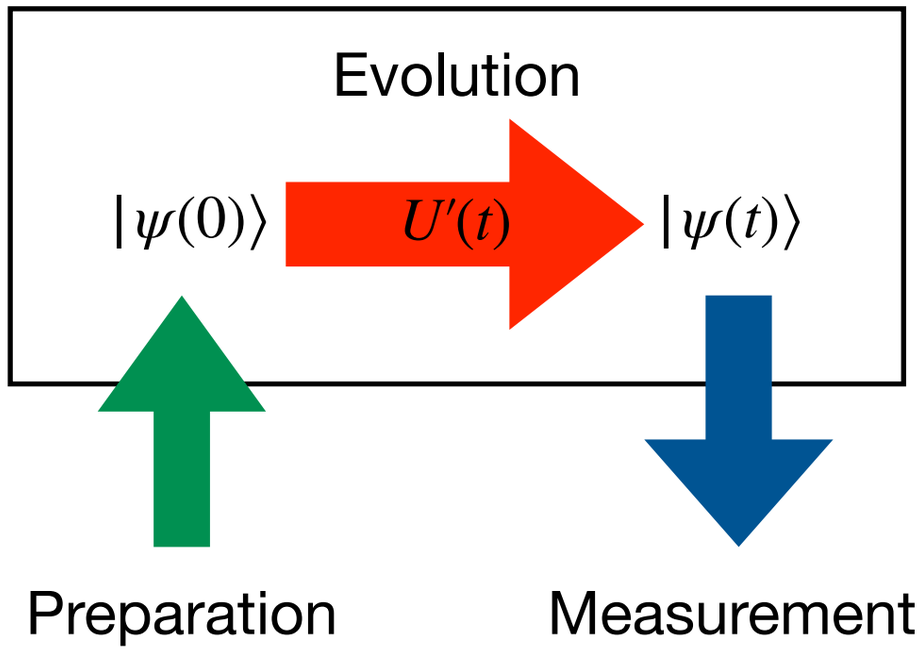


Analog simulation:
Single-purpose simulator



Engineer the interactions to
emulate the Hamiltonian of the model

Quantum Simulation



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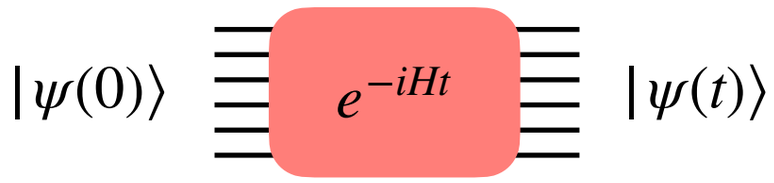

Engineer the interactions to
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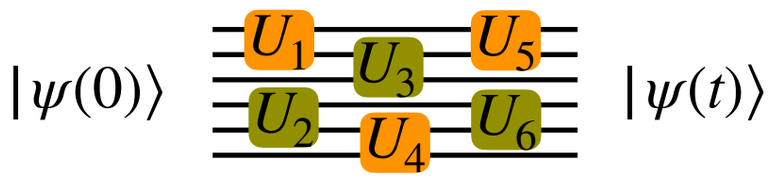
Digital simulation:
Universal simulator



Decompose dynamics into
sequence of quantum gates

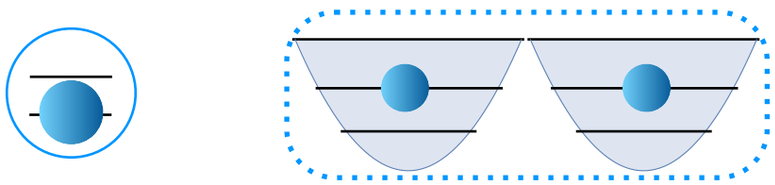
Superconducting circuits implementation

We need:

Tuneable (spectrum) device

two-level atom (anharmonic)
cavity (harmonic)

Coherent dynamics (low dissipation)



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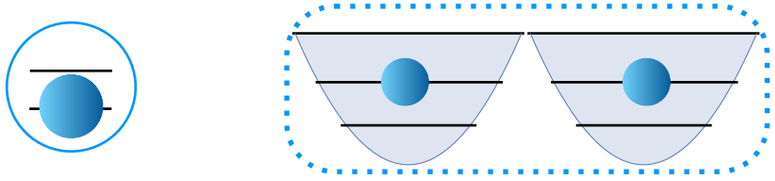
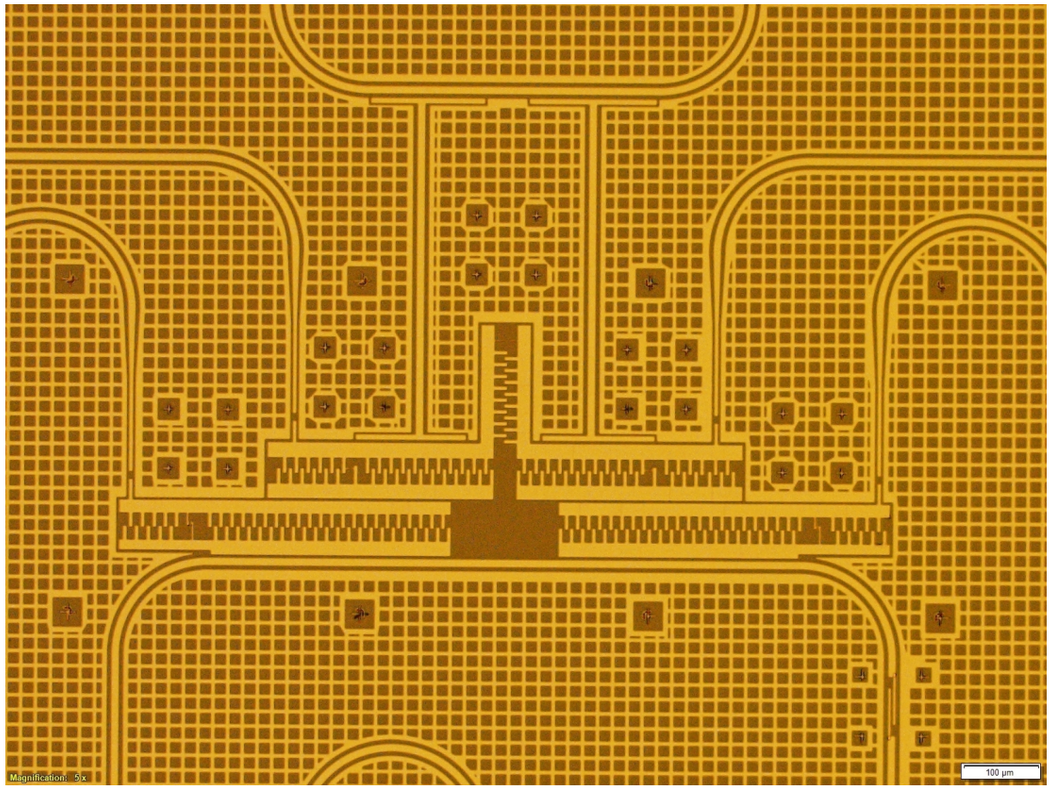




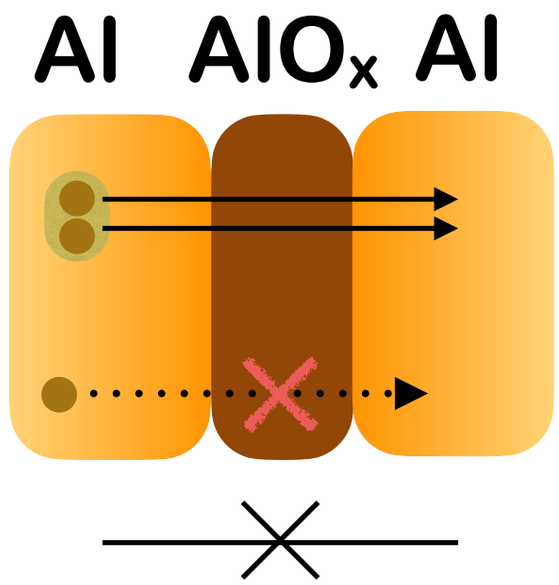
Chris Wilson



Superconducting circuits ingredients

Josephson tunnelling:

- couple two superconductors via an oxide layer
- The oxide layer acts as a tunnelling barrier
- The superconducting gap inhibits electron tunnelling



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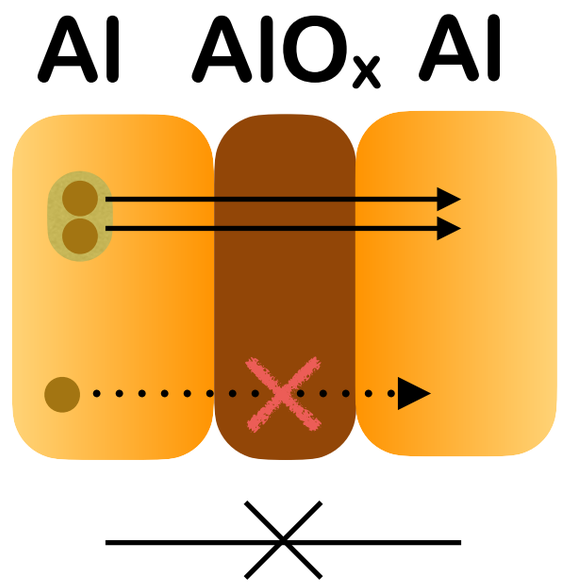

Josephson Hamiltonian:

$$H_J = -\frac{E_J}{2}\sum_n \left[|n\rangle\langle n+1| + |n+1\rangle\langle n|\right]$$

Superconducting circuits ingredients

Josephson tunnelling:

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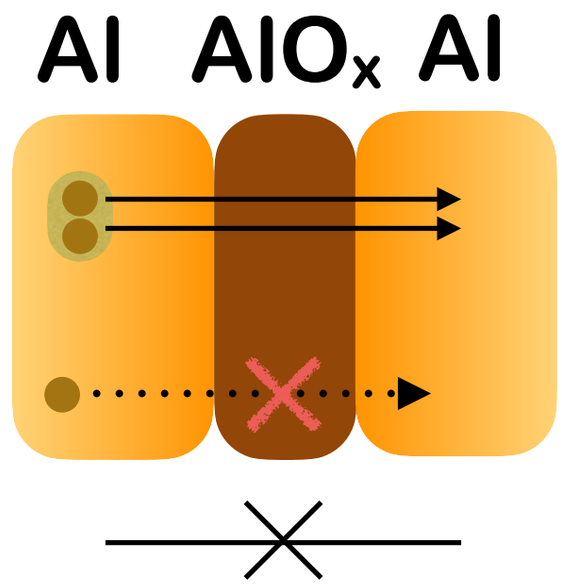


Josephson Hamiltonian:

$$H_J = -\frac{E_J}{2}\sum_n \left[|n\rangle\langle n+1| + |n+1\rangle\langle n|\right]$$

$$= -E_J \cos\phi$$

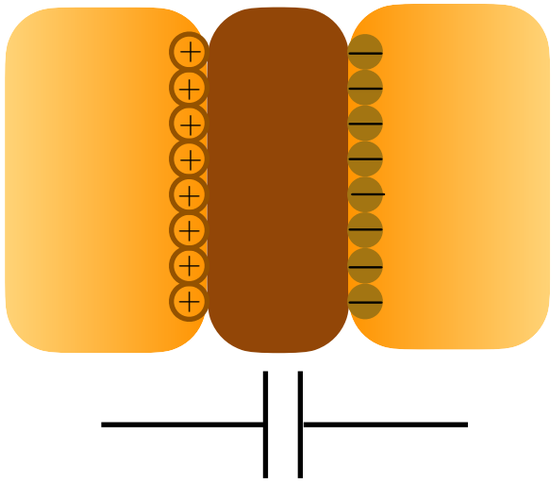
written in terms of the conjugate variable
(Fourier transform)
Physically: difference of the SC phases

$$[\phi, n] = i$$

Superconducting circuits ingredients

Charging hamiltonian of the SC: Junction also acts as a capacitor

$$H = \frac{(2e)^2}{2C} n^2 = 4E_C n^2$$



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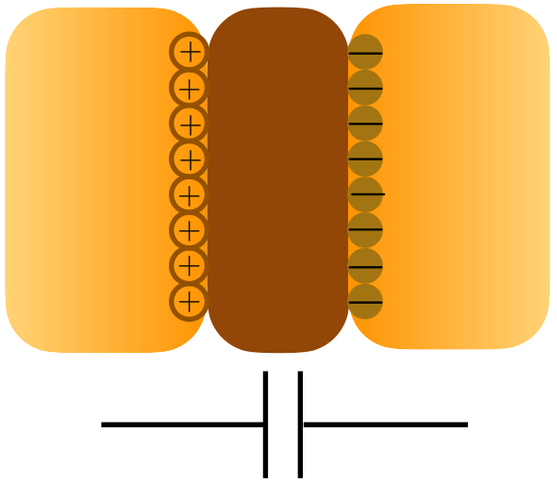
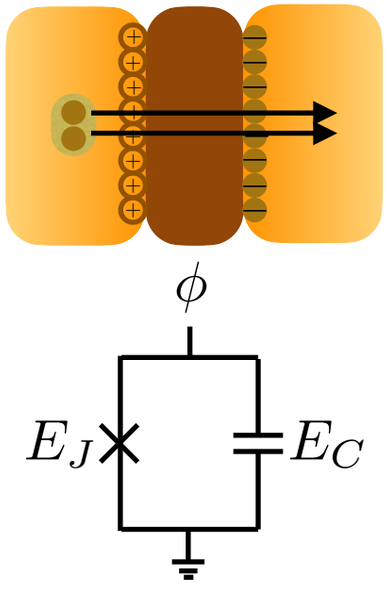
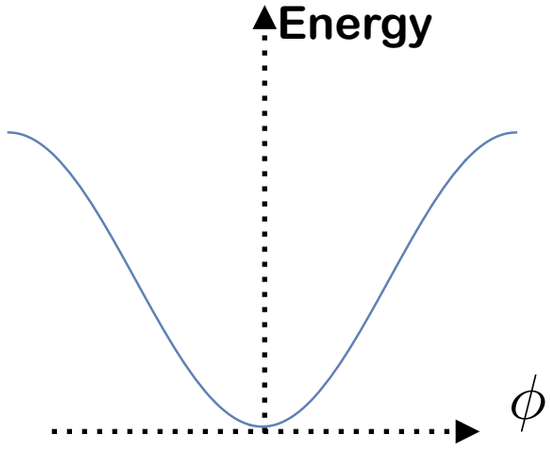


Non-linear oscillator - anharmonic cavity - Josephson junction:



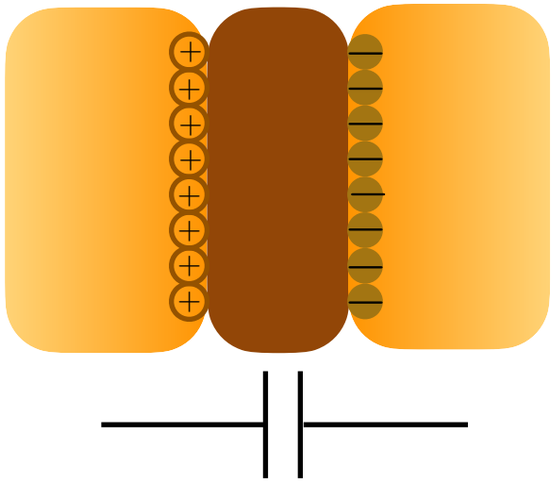
$$H = 4E_C n^2 - E_J \cos\phi$$



Superconducting circuits ingredients

Charging hamiltonian of the SC: Junction also acts as a capacitor

$$H = \frac{(2e)^2}{2C} n^2 = 4E_C n^2$$



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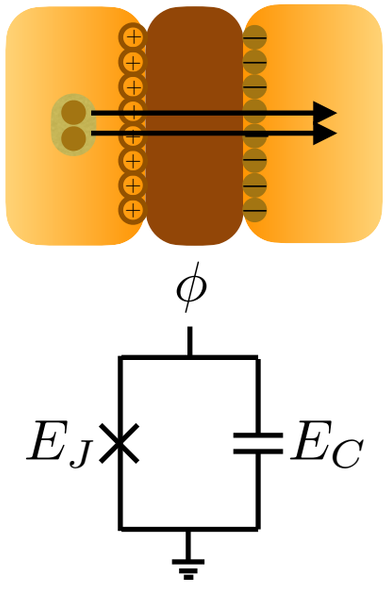
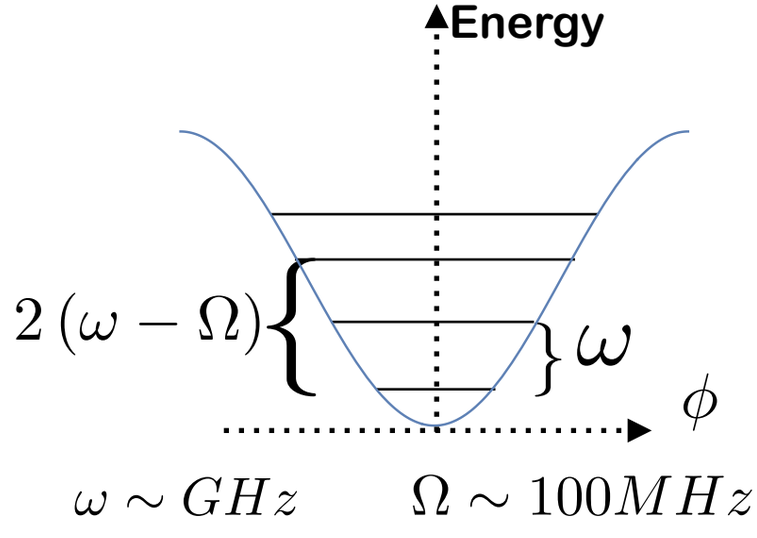


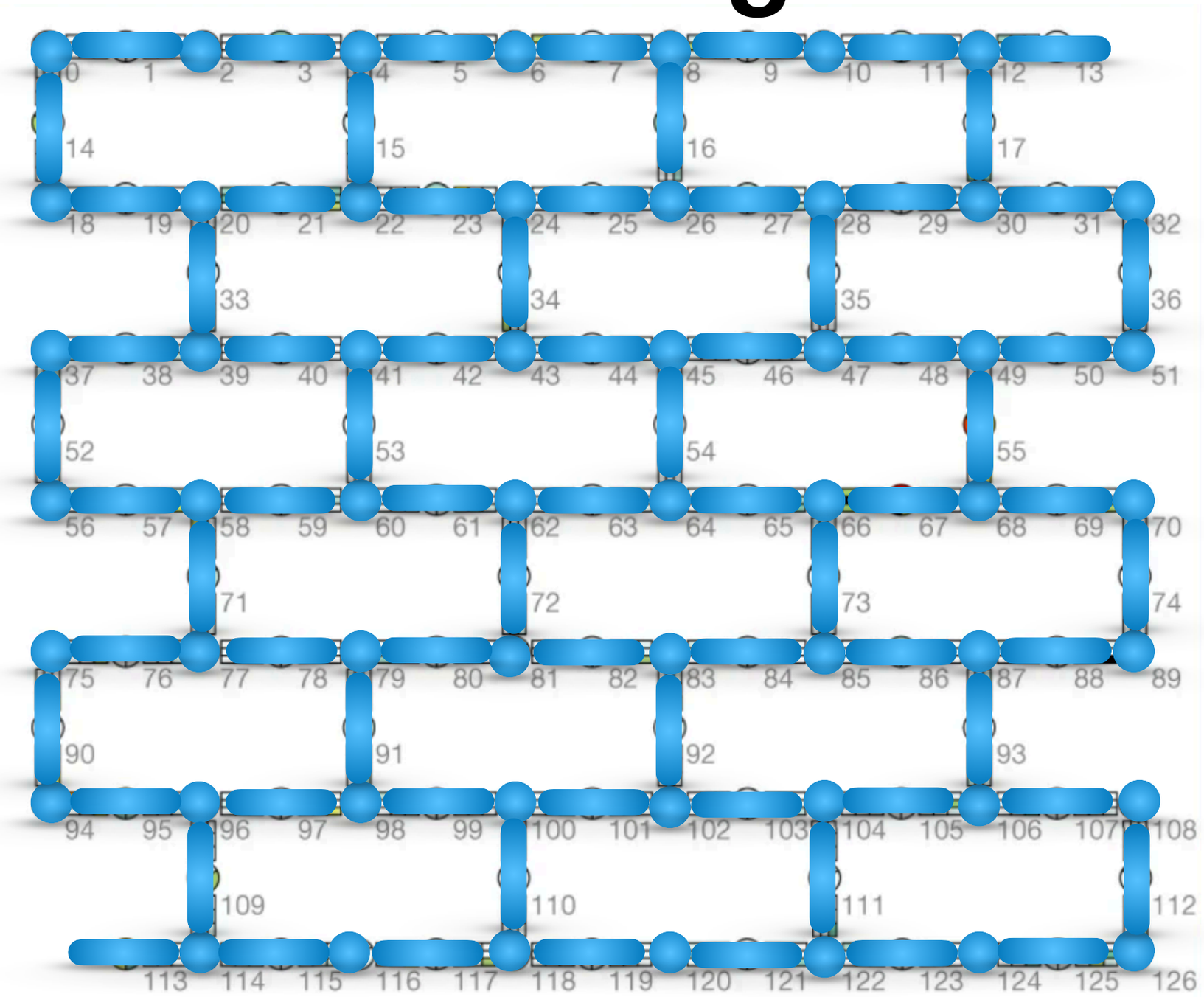
$$H = 4E_C n^2 - E_J \cos\phi$$
$$= \omega b^\dagger b - \Omega b^{\dagger 2} b^2$$



String on a chip



String on a chip



$\hat{\tau}^x_{\vec{r}}$ $\hat{\sigma}^x_{\vec{r},\vec{r}+\breve{\mu}}$ $\hat{\tau}^x_{\vec{r}+\breve{\mu}}$

$\vec{r}$ $\vec{r}+\breve{\mu}$

minimal coupling

$-m\hat{\tau}^z_{\vec{r}}$

$\vec{r}$

mass-term

$-g\hat{\sigma}^z_{\vec{r},\vec{r}+\breve{\mu}}$

$\vec{r}$ $\vec{r}+\breve{\mu}$

electric energy

$$\hat{H} = -m\sum_v \hat{\tau}^z_v - g\sum_l \hat{\sigma}^z_{i,j} + \sum_l \hat{\tau}^x_i \hat{\sigma}^x_{i,j} \hat{\tau}^x_j$$

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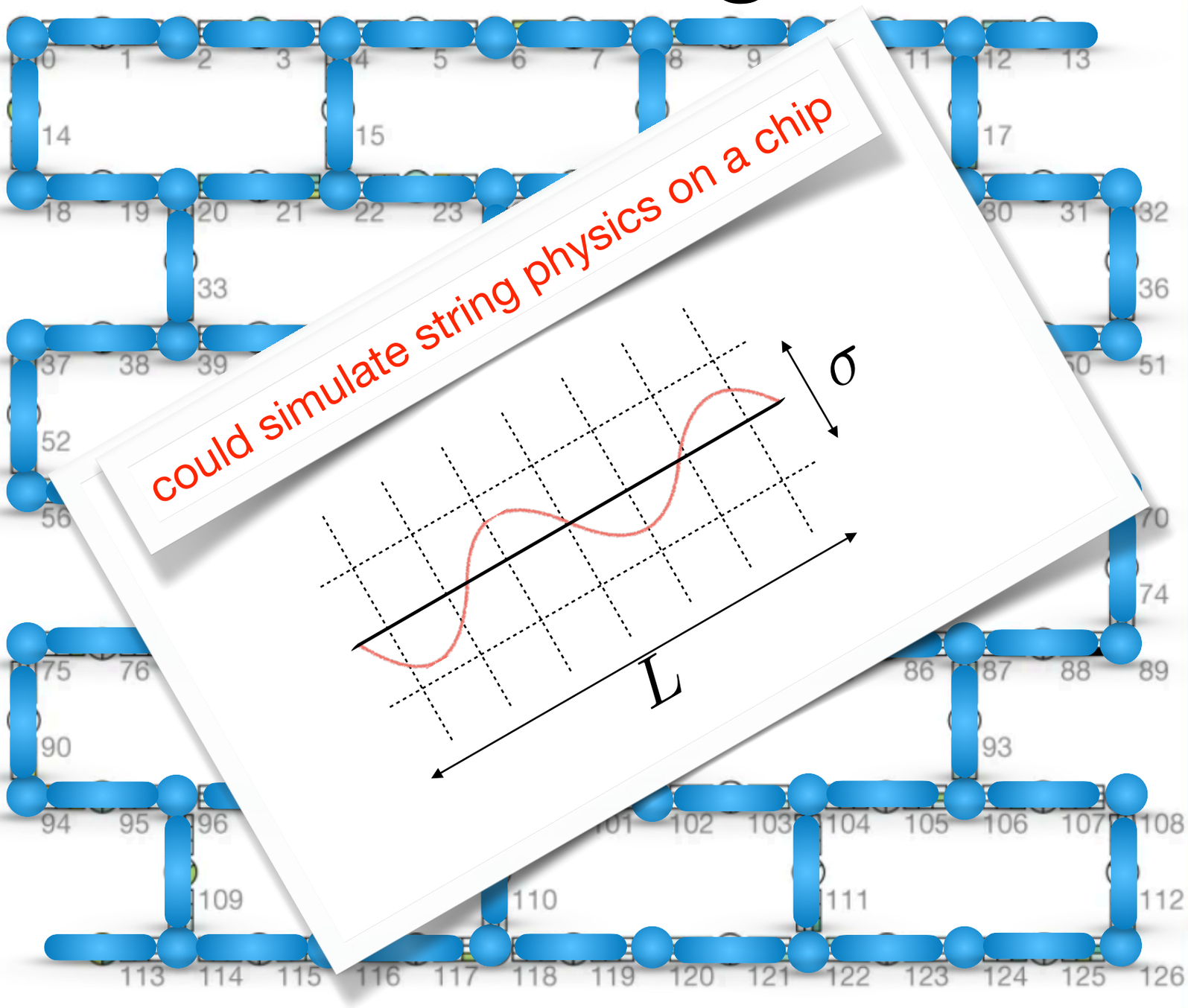

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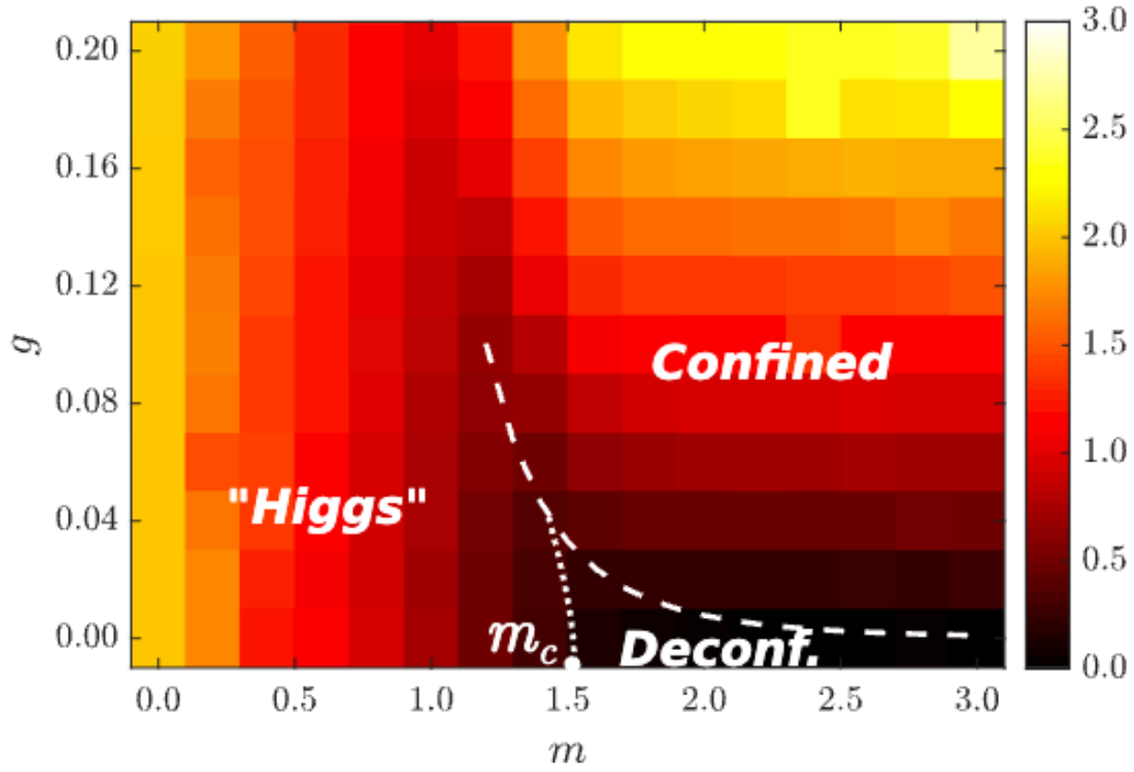
Quantum Real-Time Dynamics of the $\mathbb{Z}_2$ Higgs model

Ground-state phase diagram with tensor networks:



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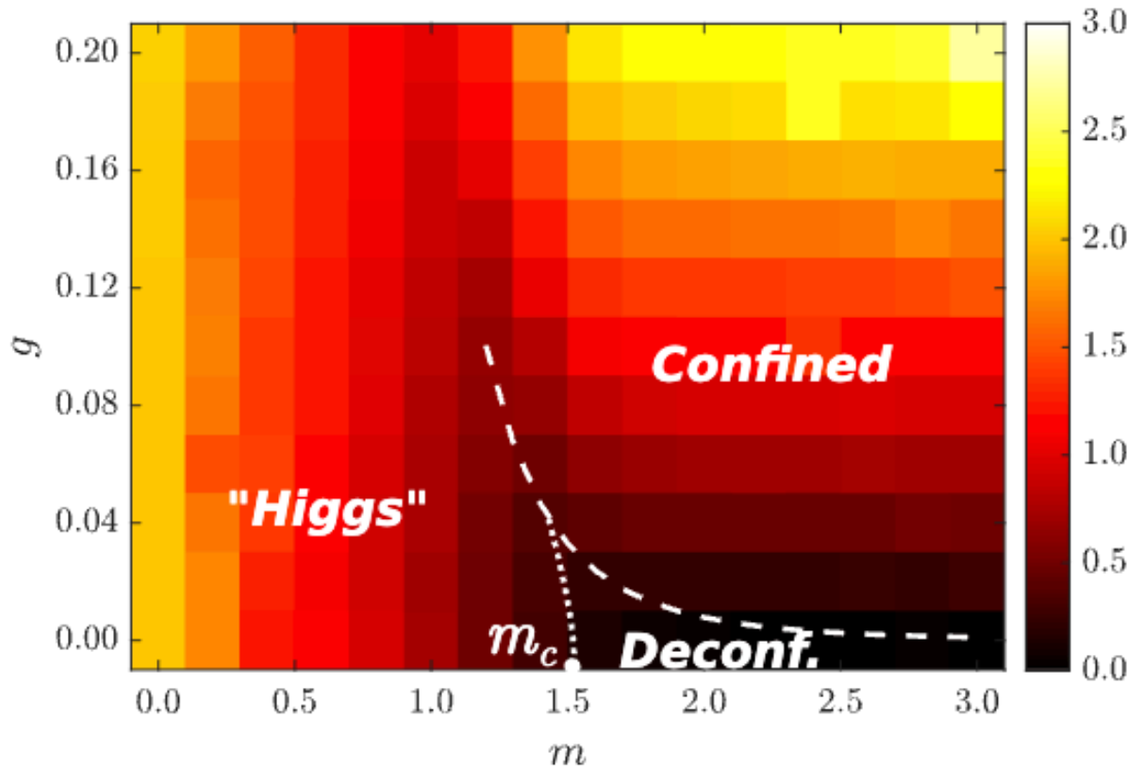
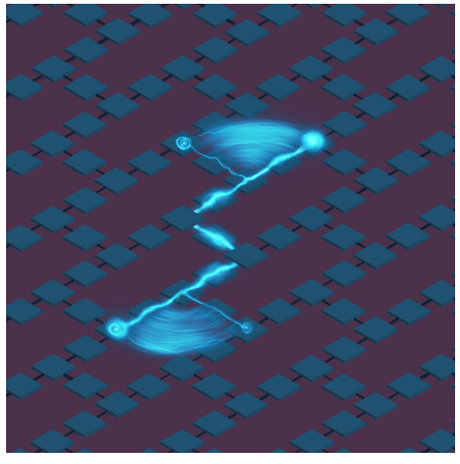
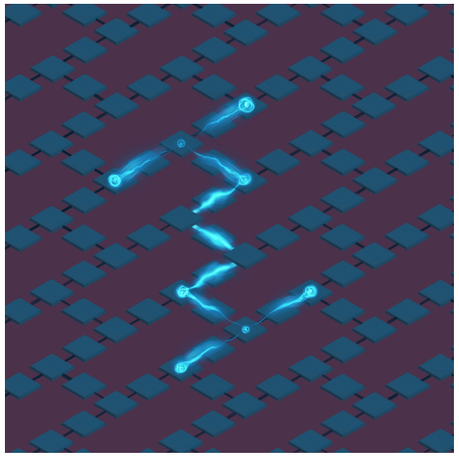


String dynamics: bending mode



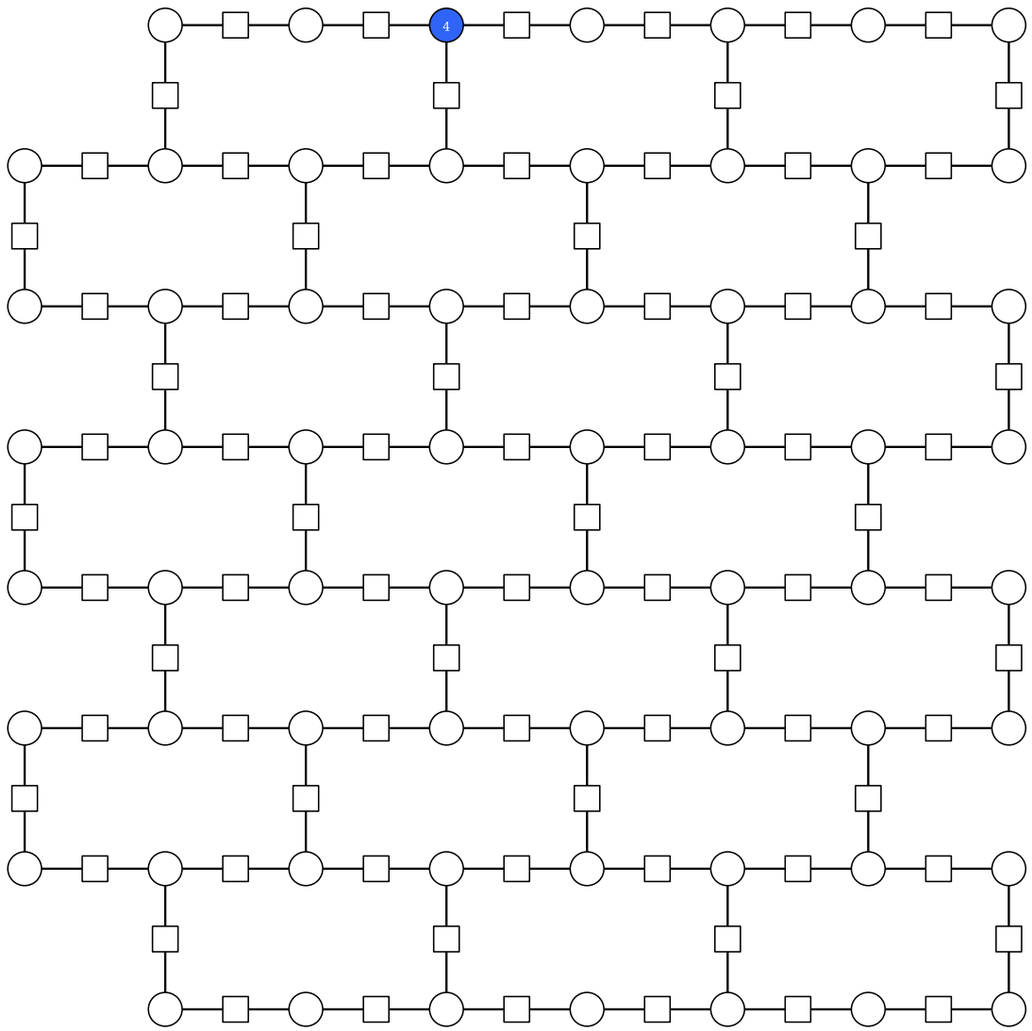
String dynamics: io-io mode

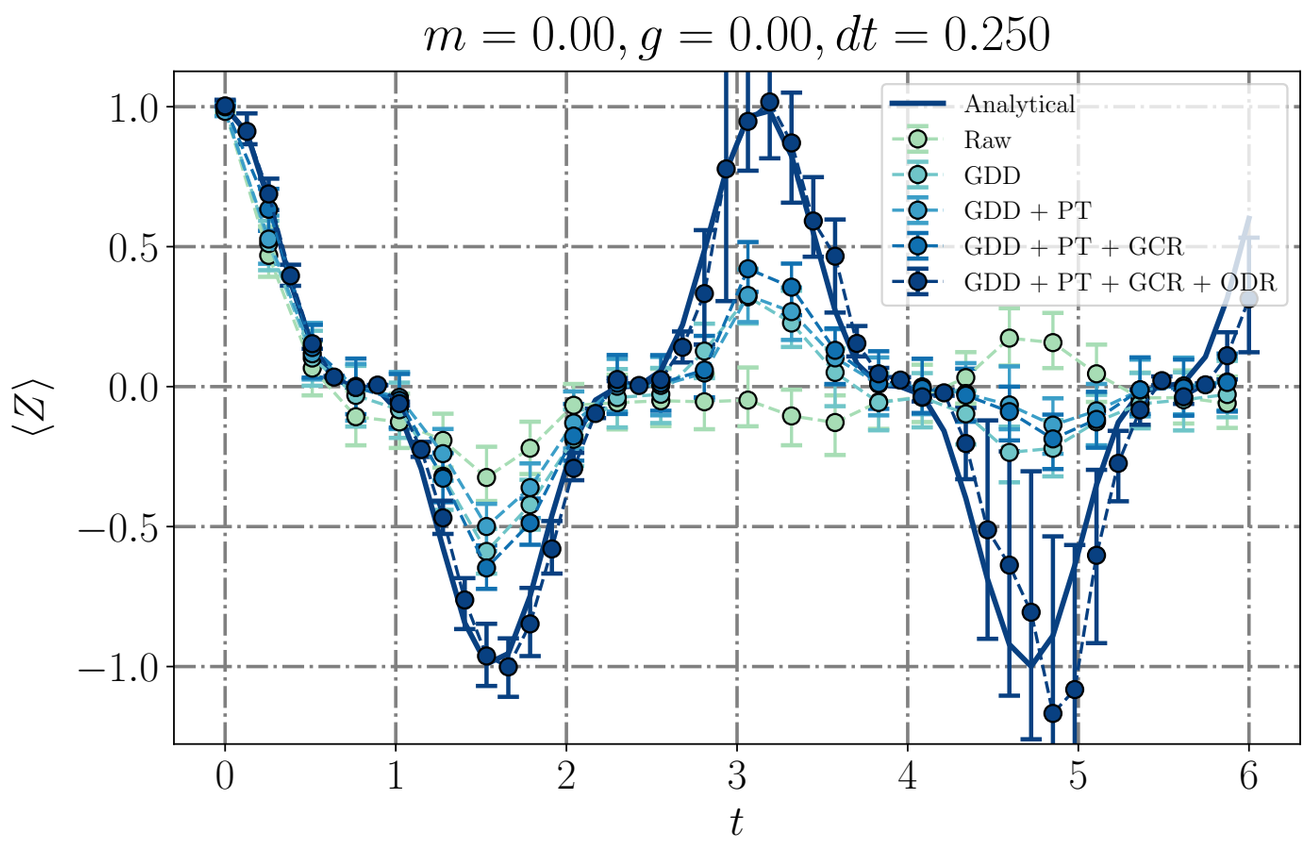


Quantum Real-Time Dynamics of the $\mathbb{Z}_2$ Higgs model

Customized error mitigation techniques:

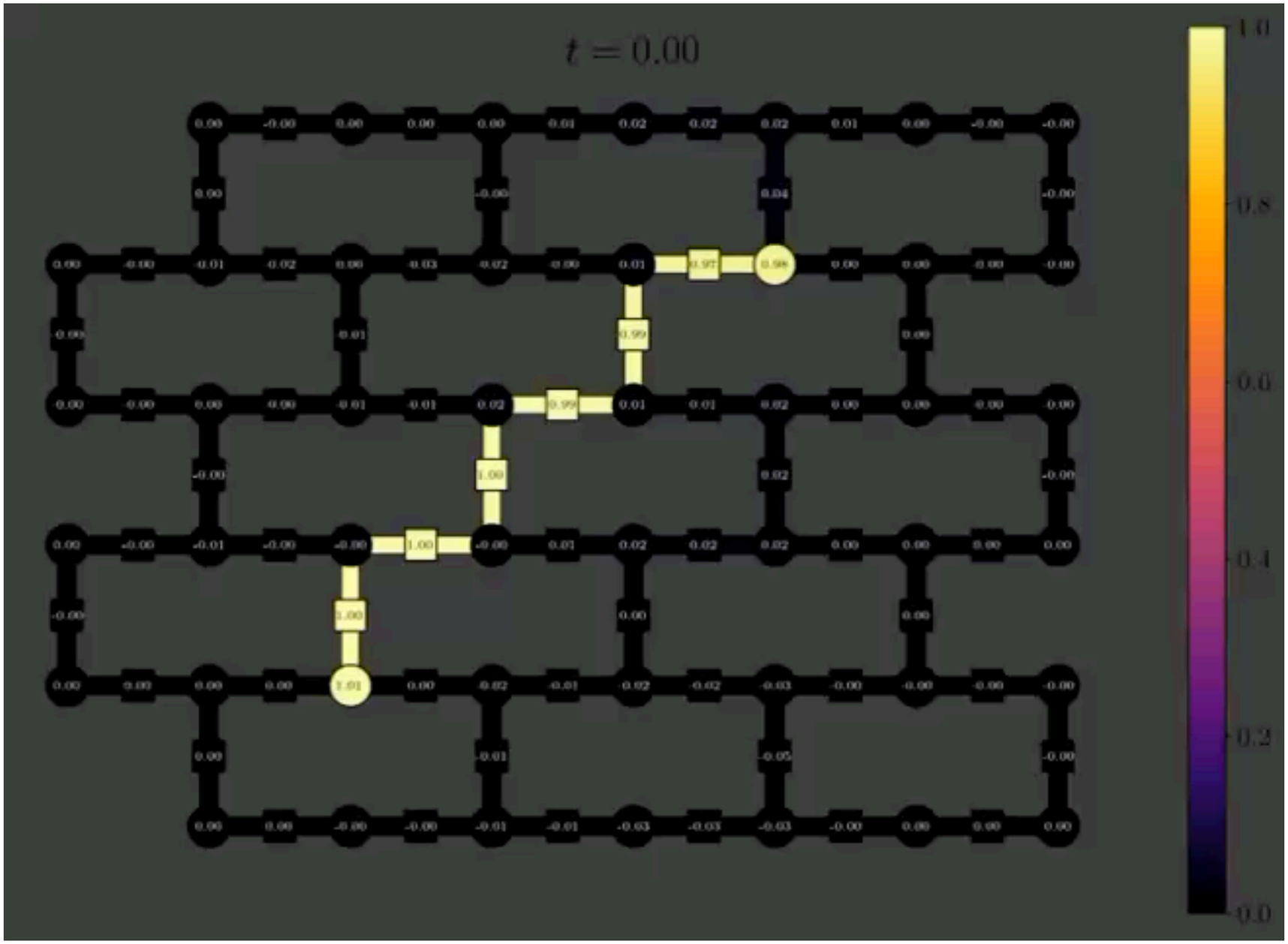
Gauge dynamical decoupling (GDD)
Pauli Twirling (PT)
Gauge configuration recovery (GCR)
Operator decoherence renormalization (ODR)





Quantum Real-Time Dynamics of the $\mathbb{Z}_2$ Higgs model

Single string oscillations at m = 0, g = 0 point:



Max. 2Q depth: 192
Num qubits: 144
Total 2Q gates: 7872

Device: ibm_aachen

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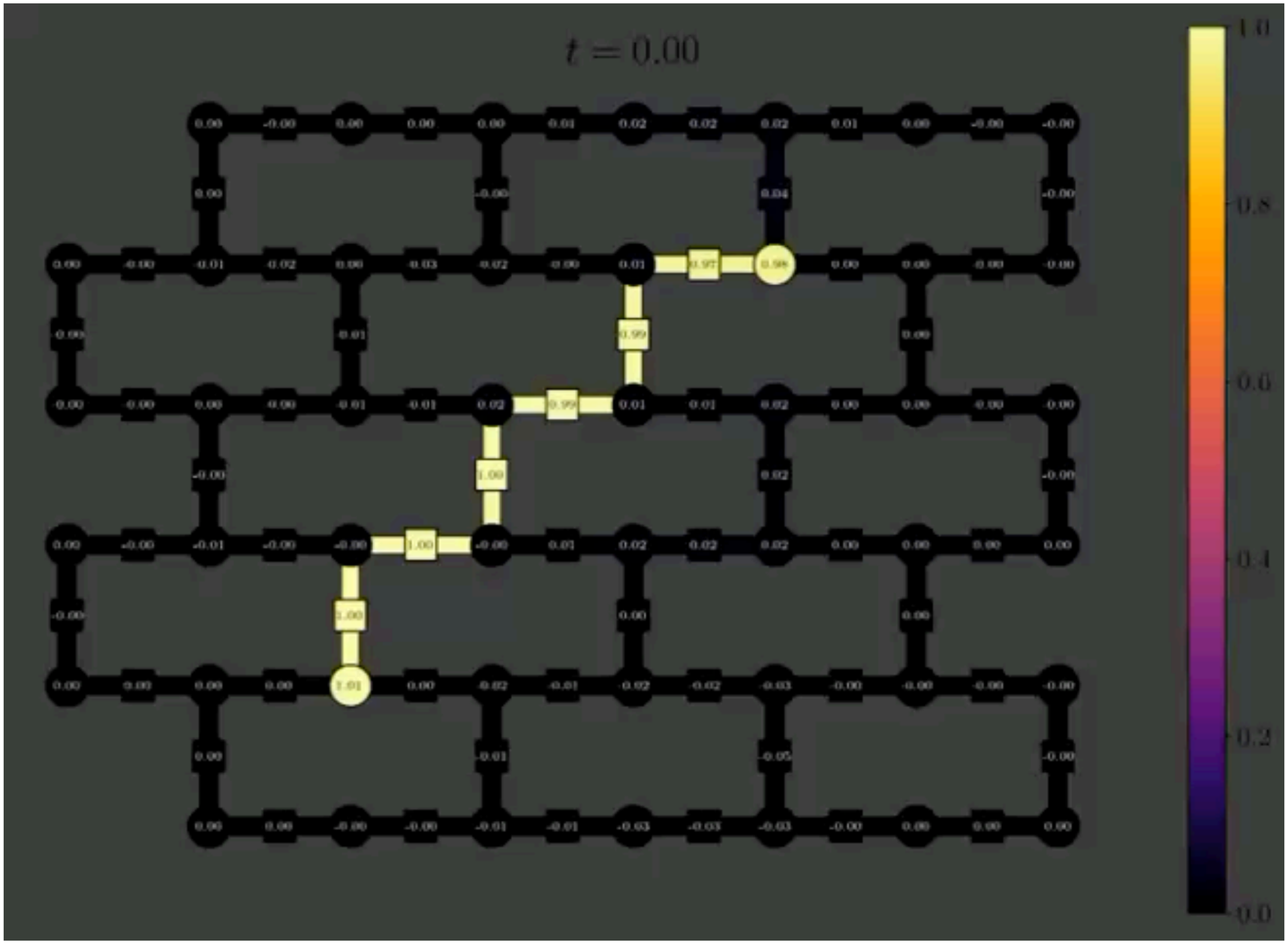

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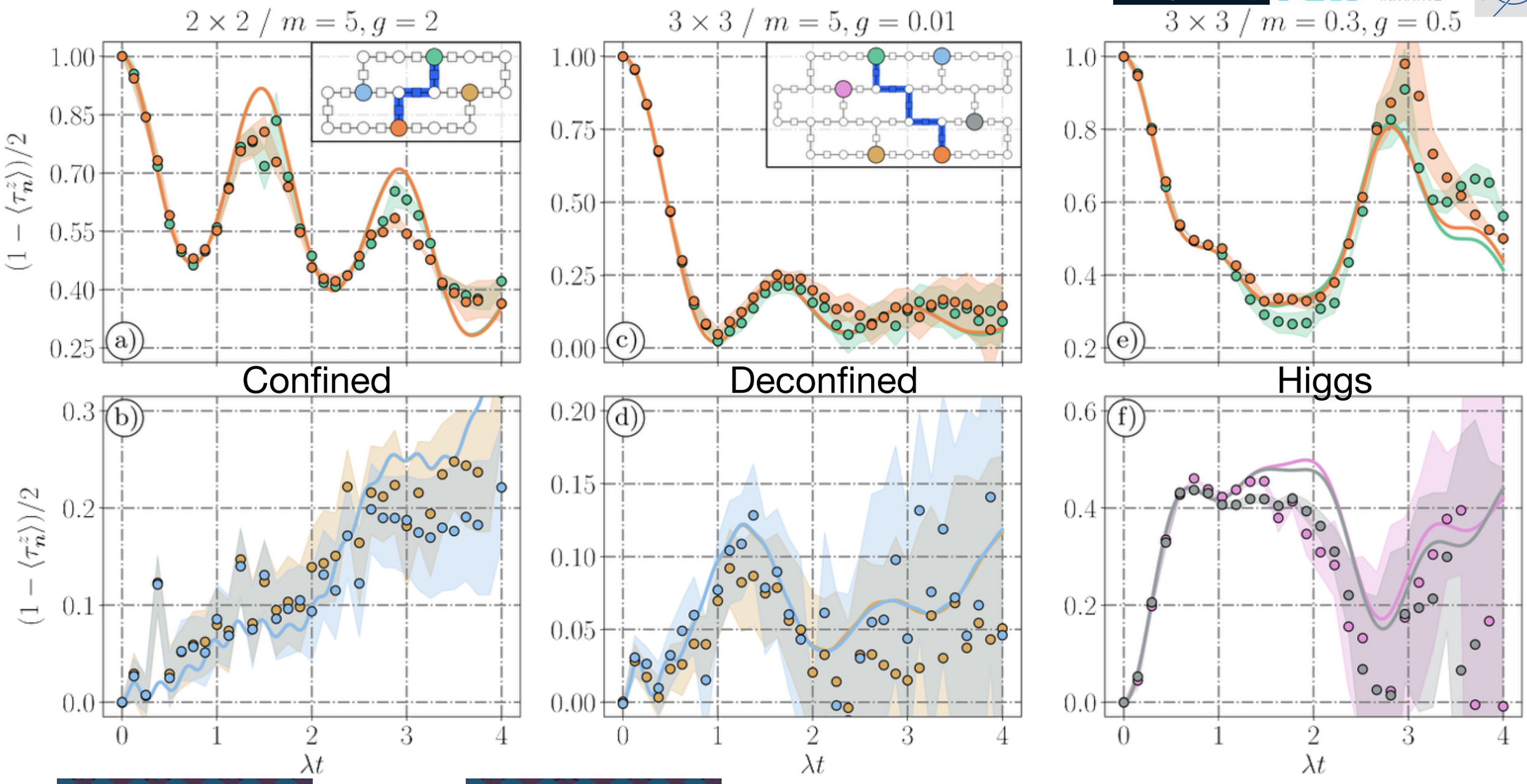

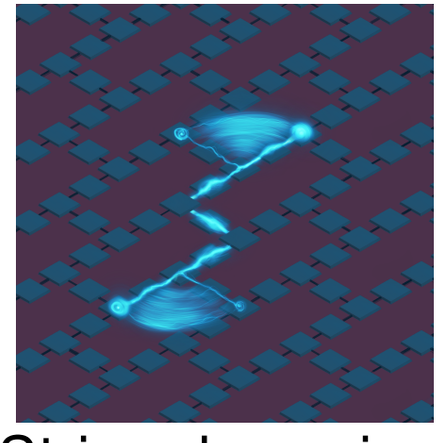

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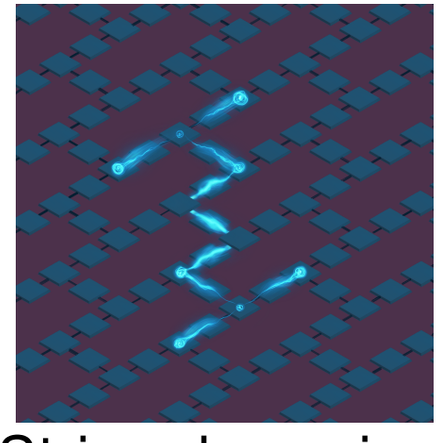
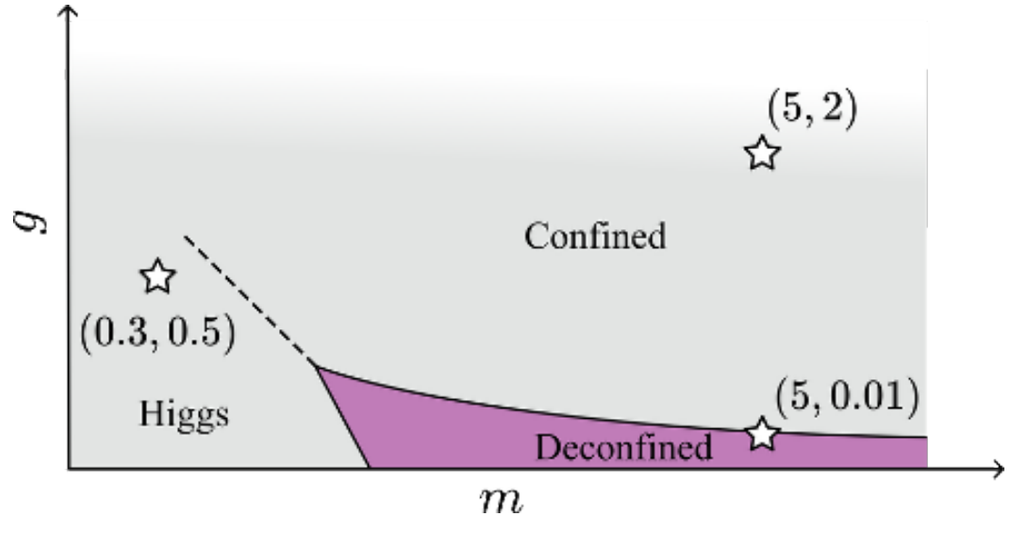
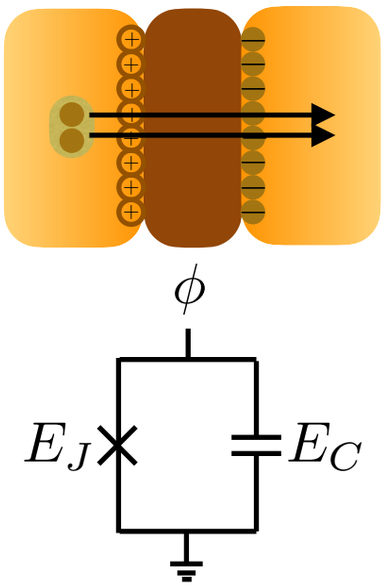


String dynamics: io-io mode



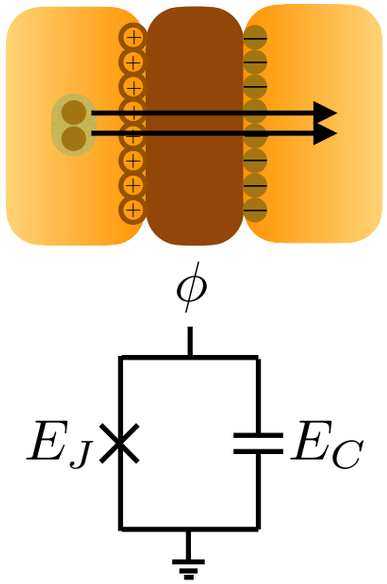
Superconducting circuits ingredients



A capacitor in parallel with a Josephson Junction

$$H = 4E_C n^2 - E_J \cos\phi \qquad [\phi, n] = i$$

Superconducting circuits ingredients



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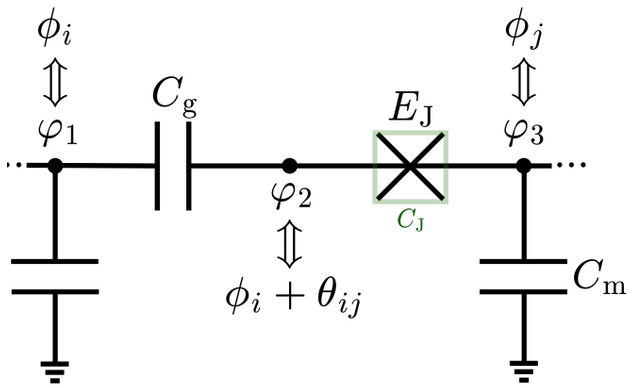
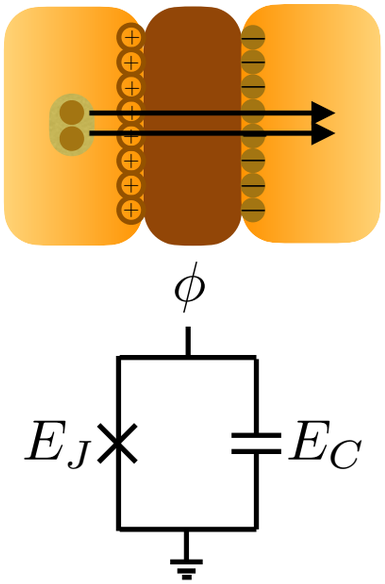


A capacitor in series with a Josephson Junction

$$\hat{H} = m \sum_i \hat{n}_i^2 + g \sum_{<i,j>} \hat{n}_{ij}^2 - \lambda \sum_{<i,j>} \cos(\hat{\phi}_i + \hat{\theta}_{ij} - \hat{\phi}_j)$$

mass (on-site energy) — Electric term (on-site energy) — Matter-gauge coupling (correlated hopping)

Superconducting circuits ingredients



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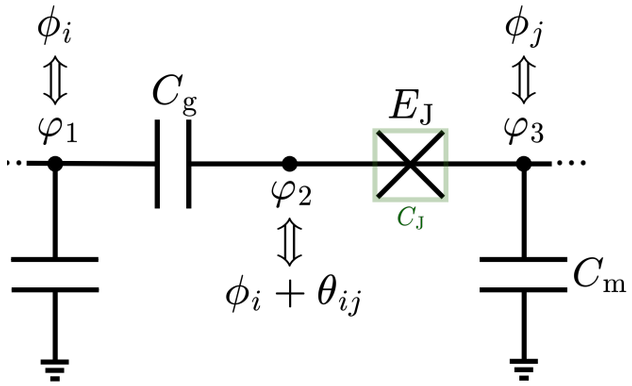


A capacitor in series with a Josephson Junction

Quantum Electrodynamics !!!

matter (vertex) degrees of freedom

gauge (link) degrees of freedom

$$\hat{H} = m \sum_i \hat{n}_i^2 + g \sum_{<i,j>} \hat{n}_{ij}^2 - \lambda \sum_{<i,j>} \cos(\hat{\phi}_i + \hat{\theta}_{ij} - \hat{\phi}_j)$$

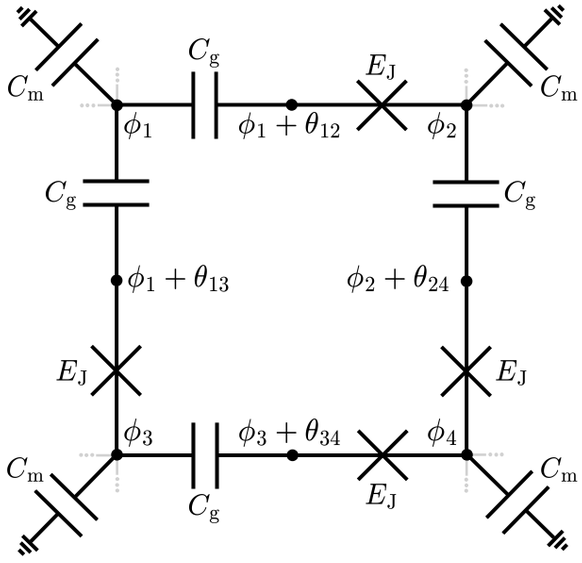
mass (on-site energy)

Electric term (on-site energy)

Matter-gauge coupling (correlated hopping)

Native U(1) gauge theory

$$\hat{H} = m \sum_i \hat{n}_i^2 + g \sum_{<i,j>} \hat{n}_{ij}^2 - \lambda \sum_{<i,j>} \cos(\hat{\phi}_i + \hat{\theta}_{ij} - \hat{\phi}_j)$$



Native interactions, exactly gauge invariants !!!

No fine-tuning, no approximation, no perturbation

Native U(1) gauge theory

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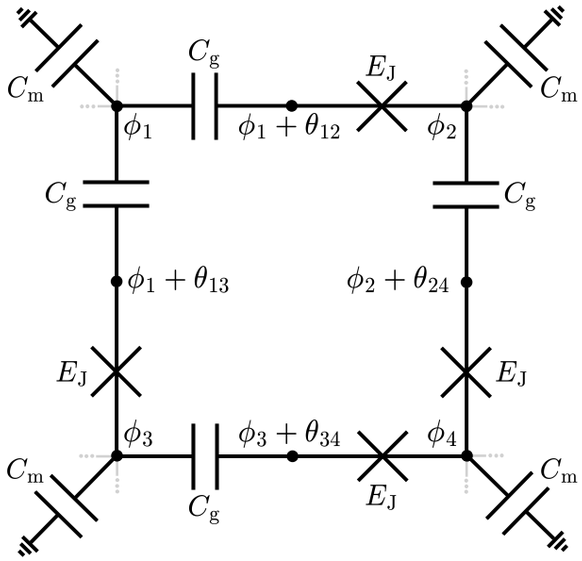

Native interactions, exactly gauge invariants !!!

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$$\hat{\square} = \cos\left(\hat{\theta}_{12} + \hat{\theta}_{24} - \hat{\theta}_{13} - \hat{\theta}_{34}\right)$$

Perturbative magnetic term
(plaquette interaction)

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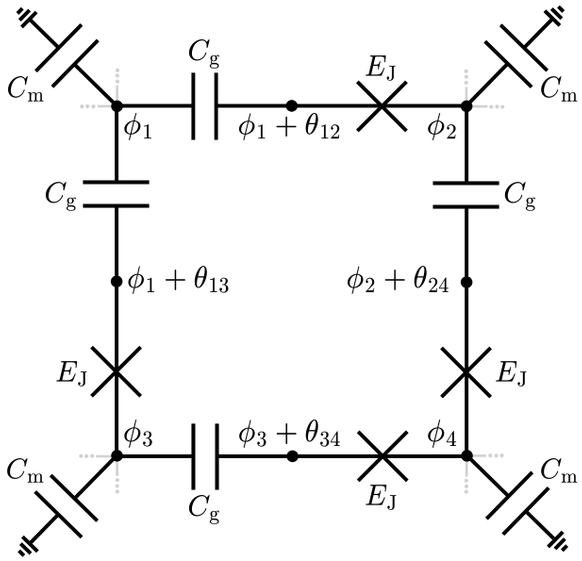

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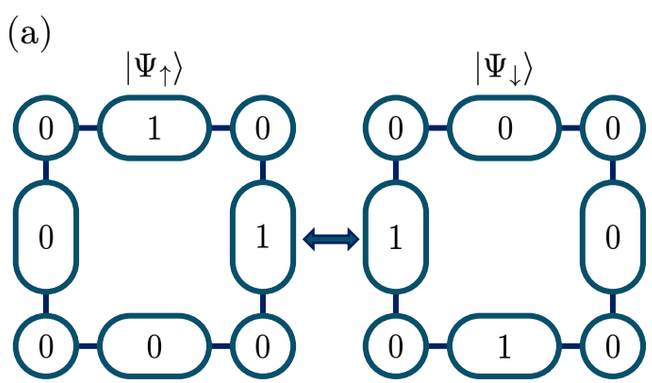
Perturbative magnetic term
(plaquette interaction)

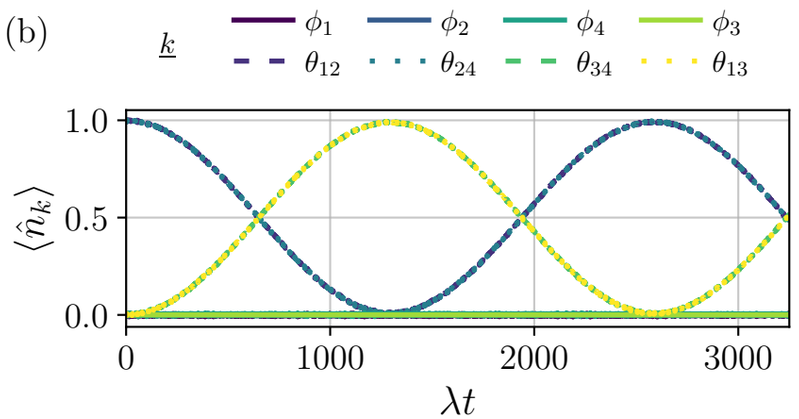
Pure Quantum Electrodynamics:

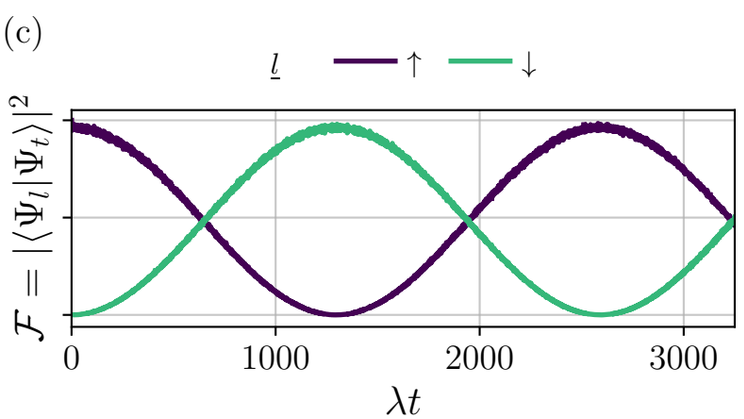
Electric + magnetic interaction

$$\hat{H}_{\text{eff}} = g \sum_{\langle ij \rangle} \hat{n}_{ij}^2 + J_{\square} \cos\left(\hat{\theta}_{12} + \hat{\theta}_{24} - \hat{\theta}_{13} - \hat{\theta}_{34}\right)$$

$$J_{\square} = -5\lambda^4/(16m^3)$$







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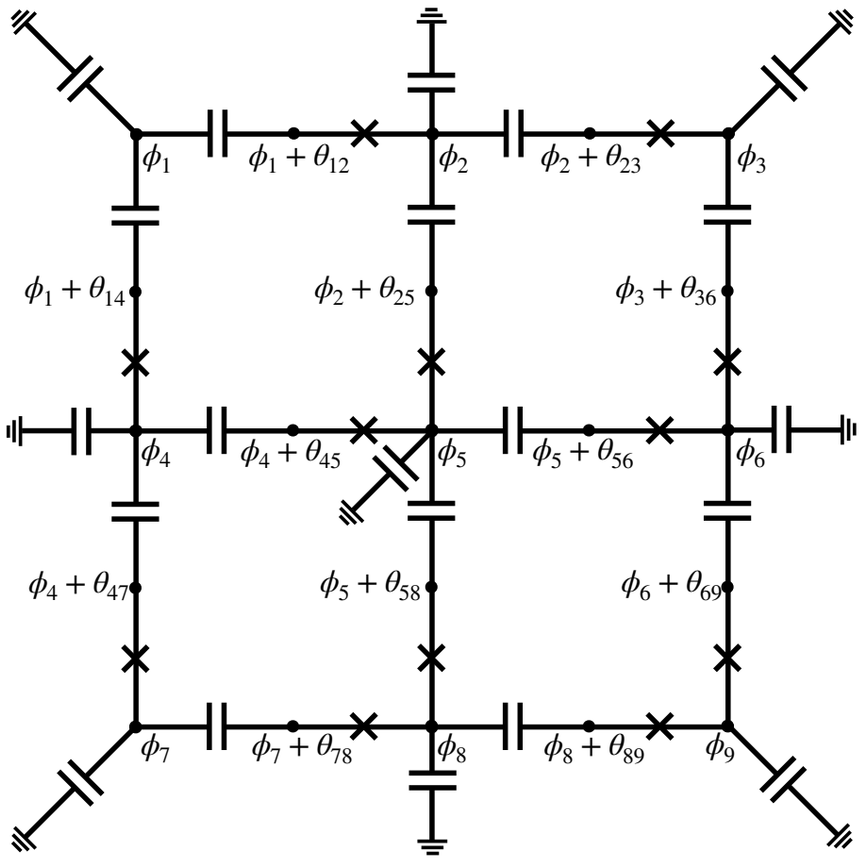

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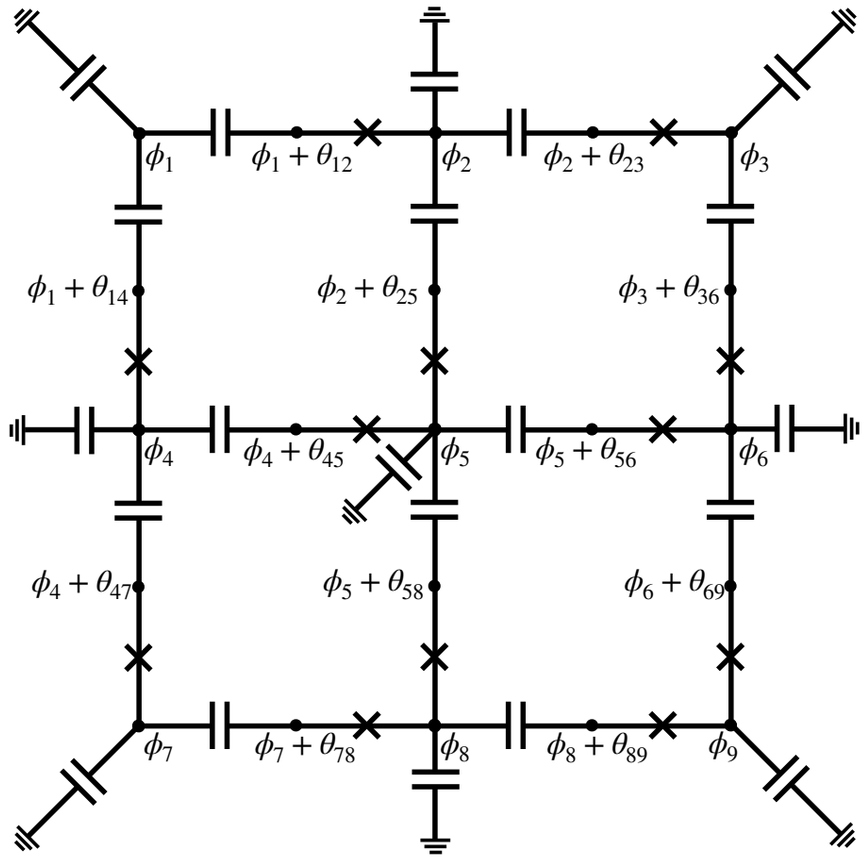

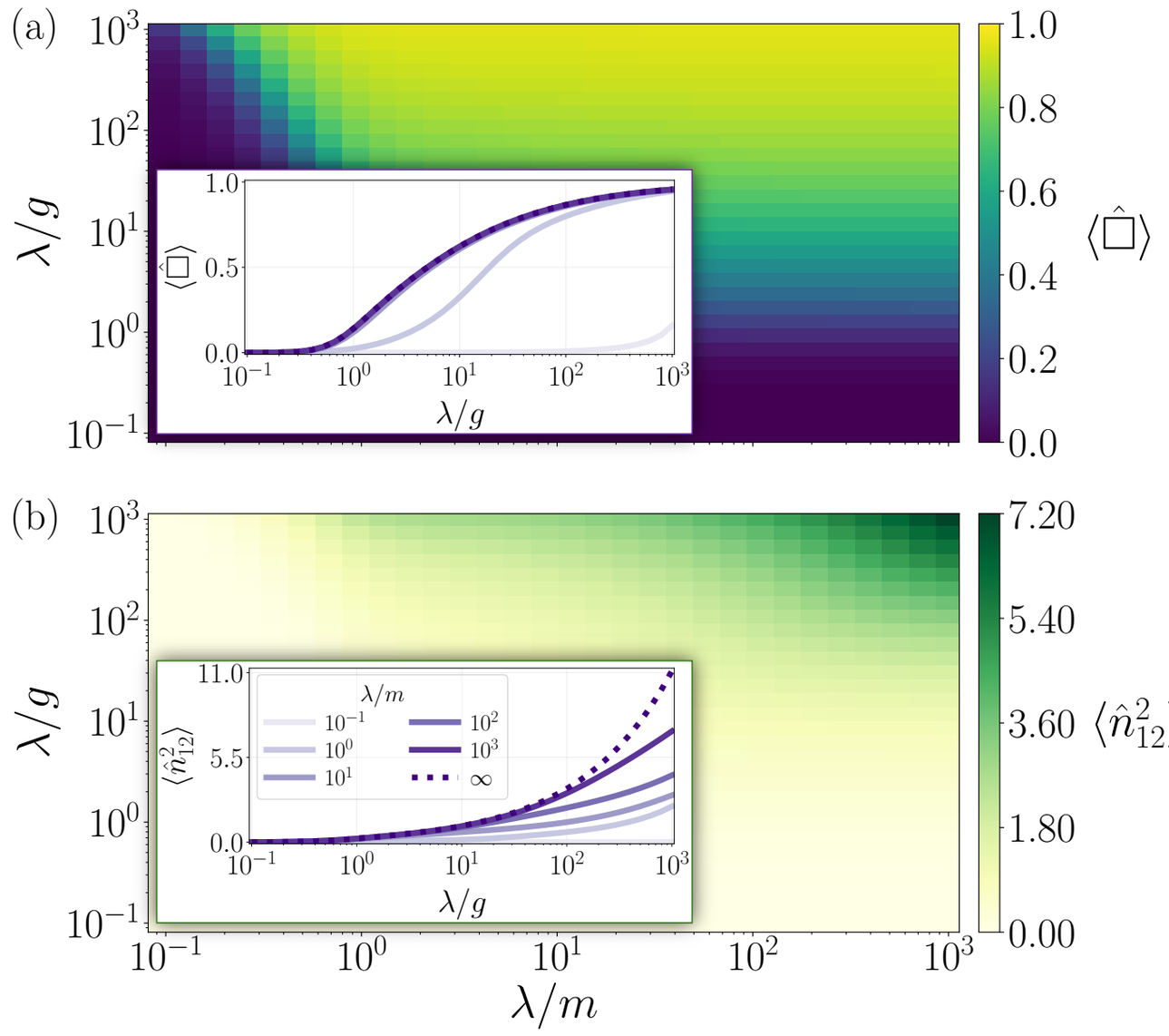

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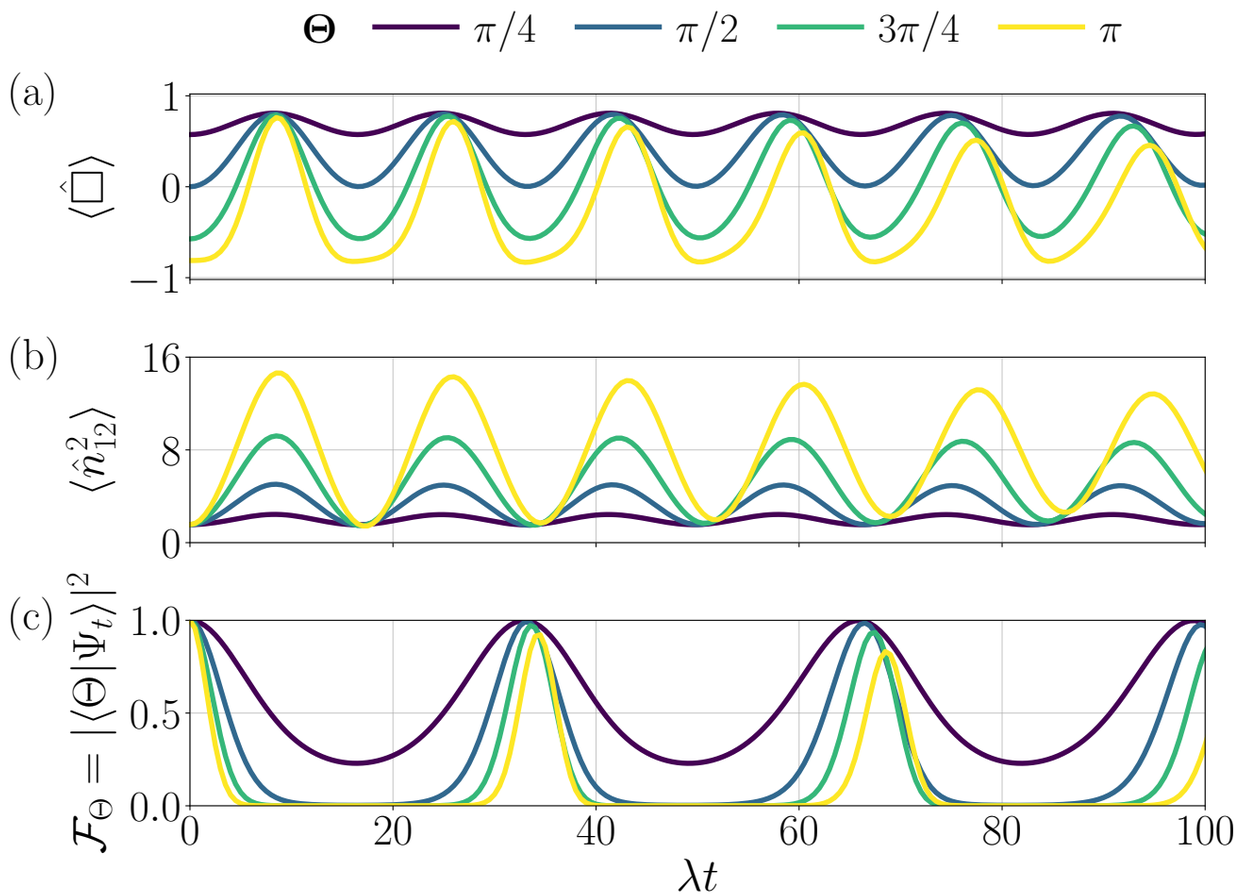

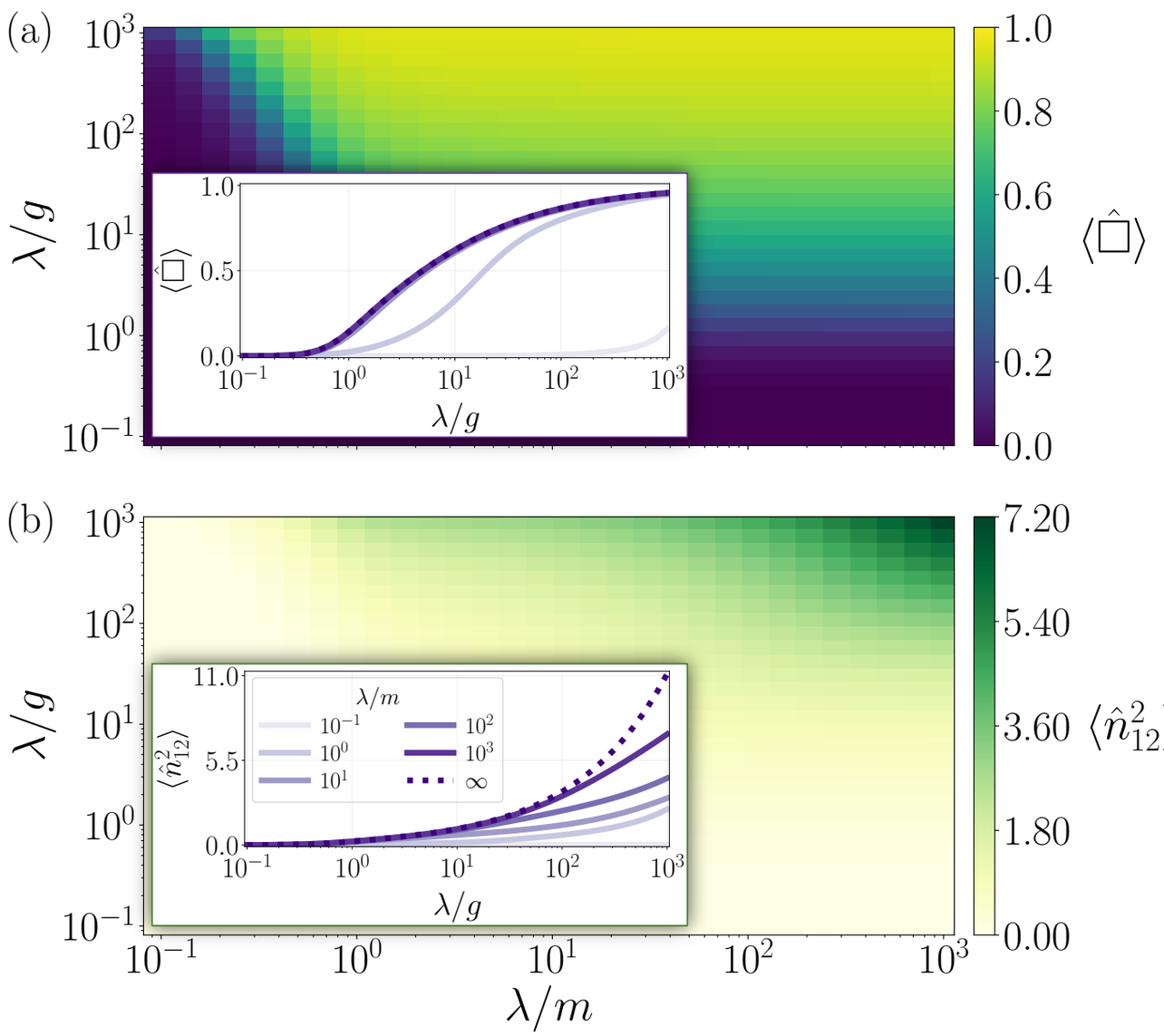

Vortex operator:

$$\hat{U}_{\text{vortex}}(\Theta) = \exp\left(\frac{i\Theta}{4}(\hat{n}_{12} + \hat{n}_{24} - \hat{n}_{34} - \hat{n}_{13})\right)$$

Hamiltonian methods from Quantum Information Technologies: from Z2 String Dynamics to Continuous U(1) Electrodynamics

Tensor network states can encode quantum features within a classical framework.

Quantum simulation and co-design (Hardware + Physics + Error Handling).

Digital quantum simulators: 144-qubit digital processor to track the real-time evolution/ vibrations of electric flux tubes in a (2+1)-D.

Analog quantum simulators: In analog architectures, Gauss's law can appear exactly from fundamental circuit topology.

Continuum limit: Exploiting the intrinsic infinite-dimensional Hilbert space of superconducting circuit variables (phase/charge) to simulate continuous gauge fields naturally.

CERN-TH-2025-105

Roughening and dynamics of an electric flux string in a (2+1)D lattice gauge theory

Francesco Di Marcantonio,[1,*] Sunny Pradhan,[1,†] Sofia Vallecorsa,[2,‡]
Mari Carmen Bañuls,[3,4,§] and Enrique Rico Ortega[1,2,5,6,¶]

arXiv:2505.23853

CERN-TH-2025-111

Real-Time Dynamics in a (2+1)-D Gauge Theory: The Stringy Nature on a Superconducting Quantum Simulator

Jesús Cobos,[1,*] Joana Fraxanet,[2] César Benito,[3] Francesco di Marcantonio,[1] Pedro Rivero,[2] Kornél Kapás,[4] Miklós Antal Werner,[4] Örs Legeza,[4,5,6] Alejandro Bermudez,[3] and Enrique Rico[1,7,8,9]

arXiv:2507.08088

CERN-TH-2026-003

Compact U(1) Lattice Gauge Theory in Superconducting Circuits with Infinite-Dimensional Local Hilbert Spaces

J. M. Alcaine-Cuervo,[1,2,*] S. Pradhan,[1,3,†] E. Rico,[1,3,4,5,‡] Z. Shi,[6,§] and C.M. Wilson[6,¶]

arXiv:2601.23150