Gauge Physics and Protected Qubits in Superconducting Circuits

Enrique Rico Ortega
Monday 13 April 2026

Apr 13 – 30, 2026
MITP - Mainz Institute for Theoretical Physics, Johannes Gutenberg University Mainz
Europe/Berlin timezone

2413/2-430 - MITP Seminar Room, MITP - Mainz Institute for Theoretical Physics, Johannes Gutenberg University Mainz
10:00 - 11:00

Open Quantum Systems: Dissipation and Decoherence from Subatomic to Cosmic Scales

Hardware-native dynamical gauge simulation and protected qubits

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

Jesús Cobos, Joana Fraxanet, César Benito, Francesco di Marcantonio, Pedro Rivero, Kornél Kapás, Miklós Antal Werner, Örs Legeza, Alejandro Bermudez, Enrique Rico

arXiv:2507.08088

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

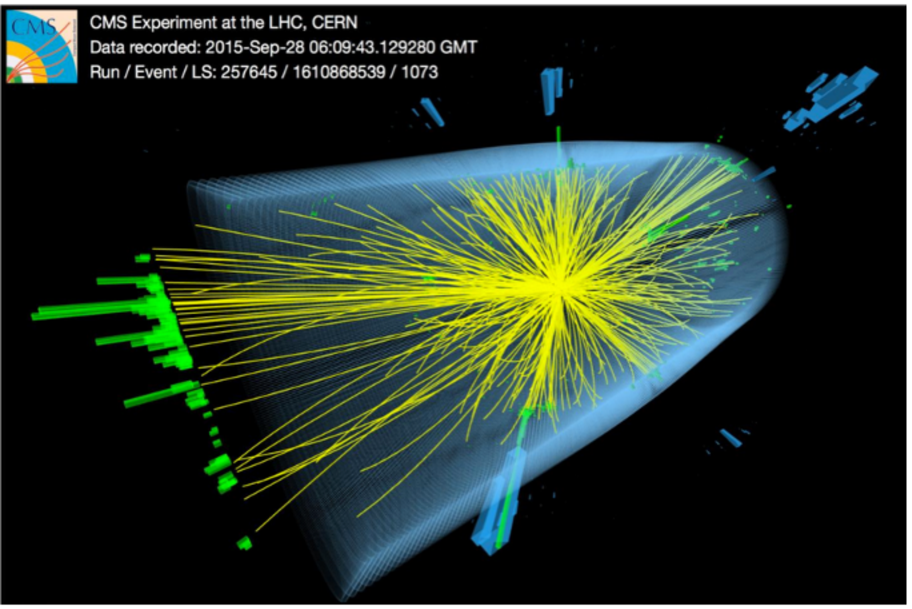
J. M. Alcaine-Cuervo, S. Pradhan, E. Rico, Z. Shi, C. M. Wilson

arXiv:2601.23150

Role of anomalous symmetry in 0-π qubits

I.L. Egusquiza, A. Iñiguez, E. Rico, A. Villarino

arXiv:2109.11824

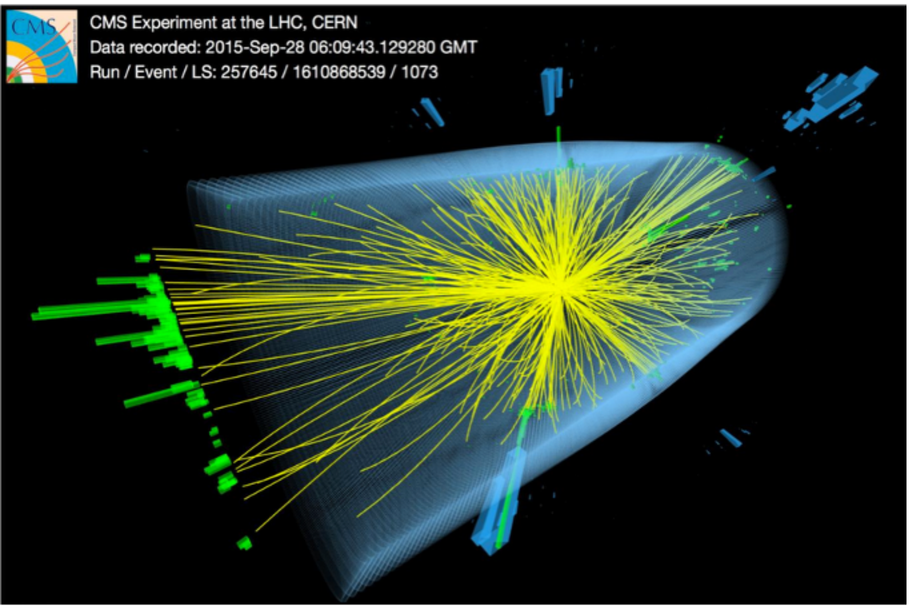


The Grand Challenge:
Simulating the strong force (QCD)

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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BlueGene & QCDOC
Classical Co-Design for QCD
Solved static properties
(e.g., hadron masses)
Non-efficient for real-time dynamics.

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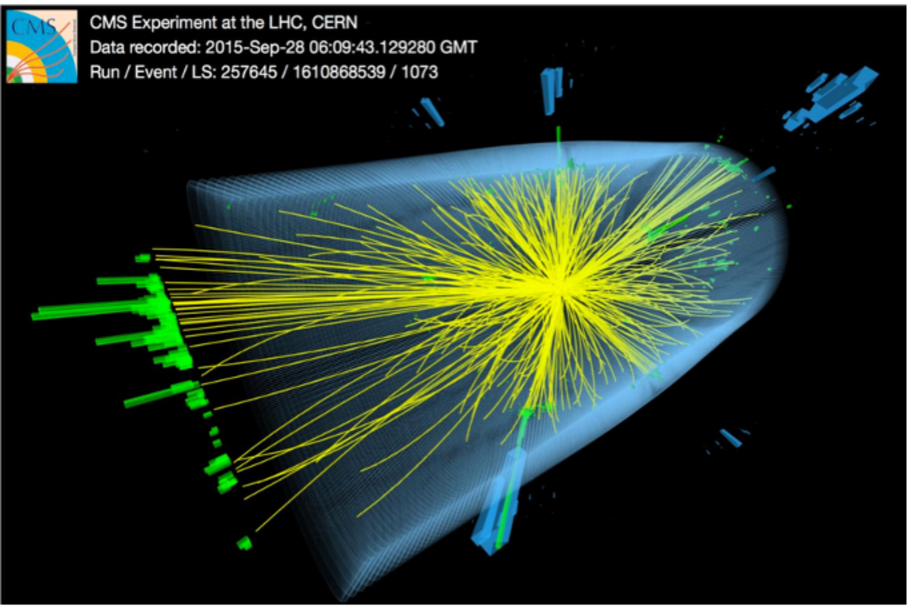

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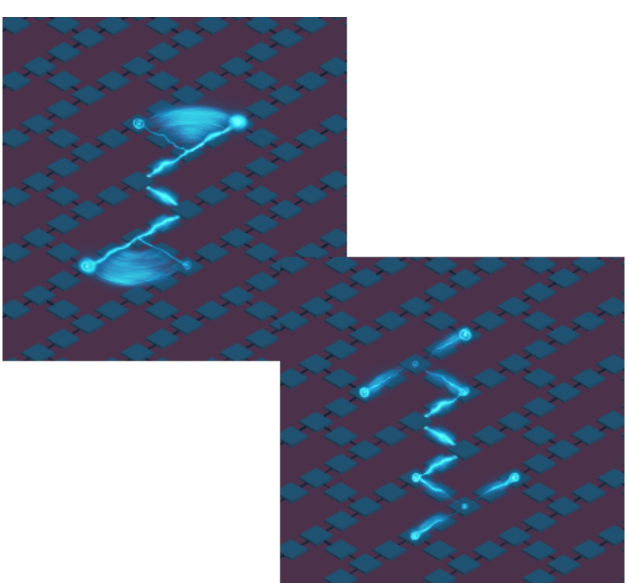
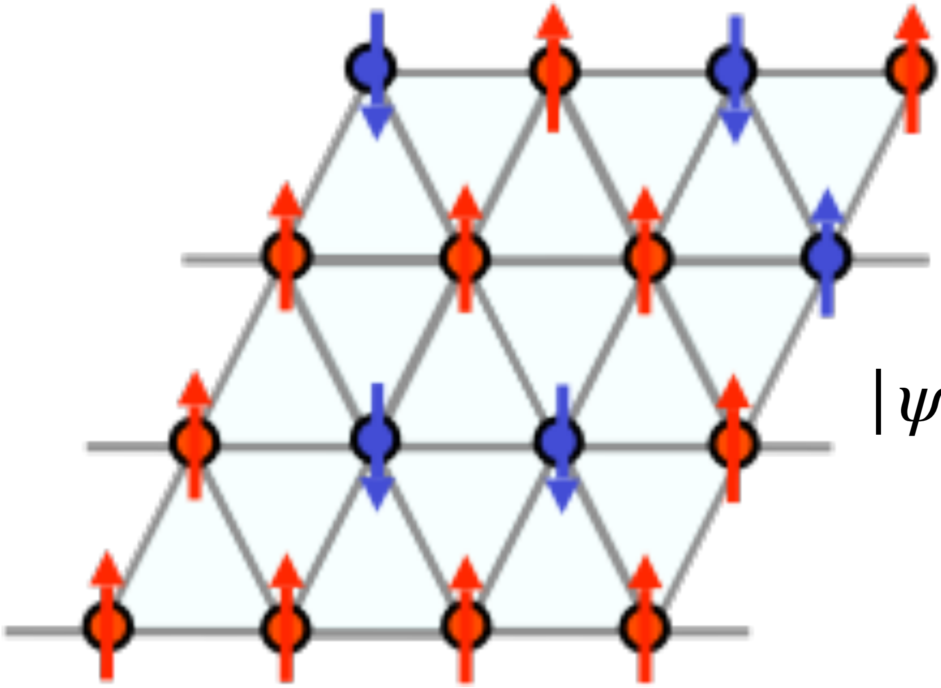


TODAY
Quantum Co-Design for QCD
Solved dynamical properties
(e.g., string dynamics)

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

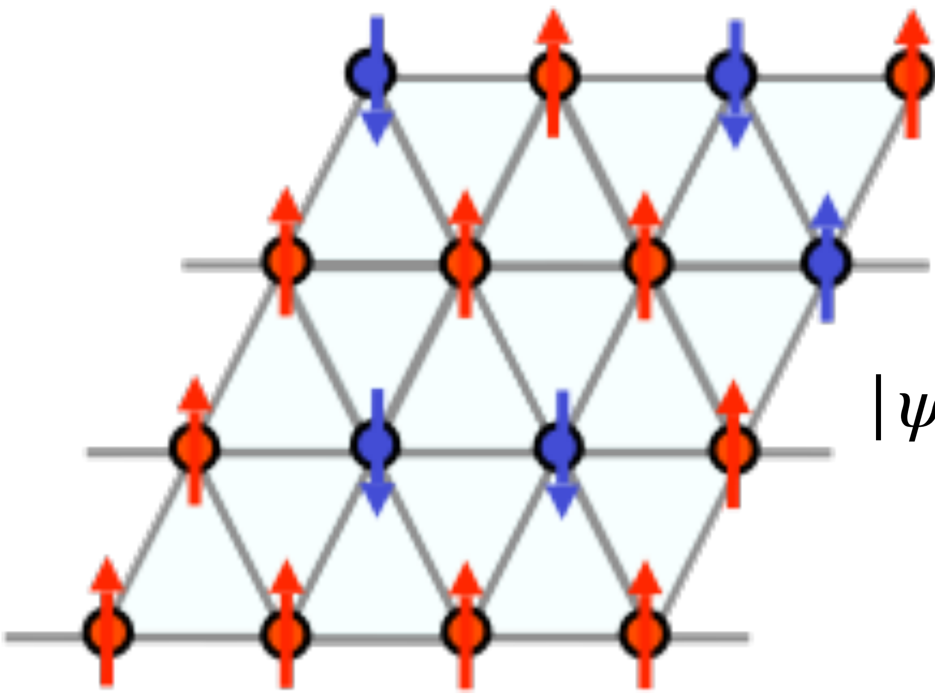


Preparation of a general quantum state

$$|\psi\rangle = c_1 |\uparrow\uparrow\cdots\uparrow\rangle + c_2 |\uparrow\uparrow\cdots\downarrow\rangle + \cdots + c_{2^N} |\downarrow\downarrow\cdots\downarrow\rangle$$

quantum correlations = entanglement

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



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$$|\psi(t)\rangle = U(t)|\psi\rangle$$

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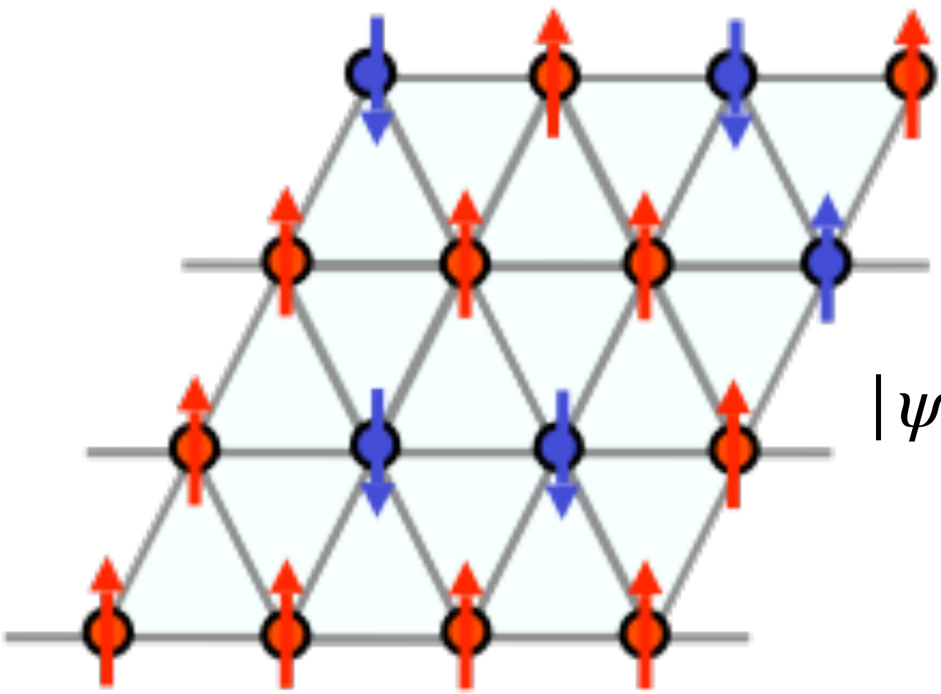

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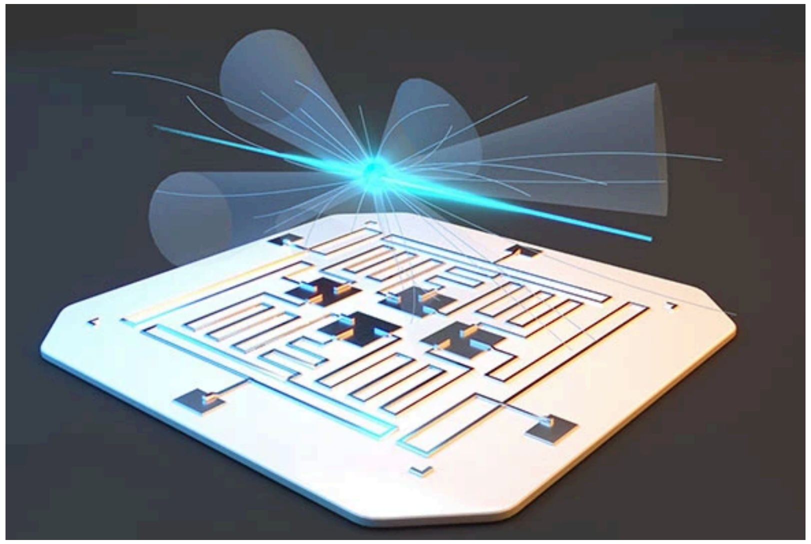
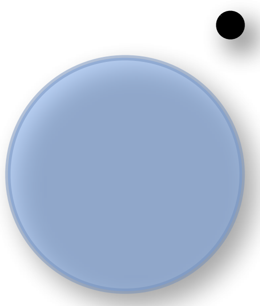


Quantum Simulators

Three ingredients to describe Nature

Three ingredients to describe Nature

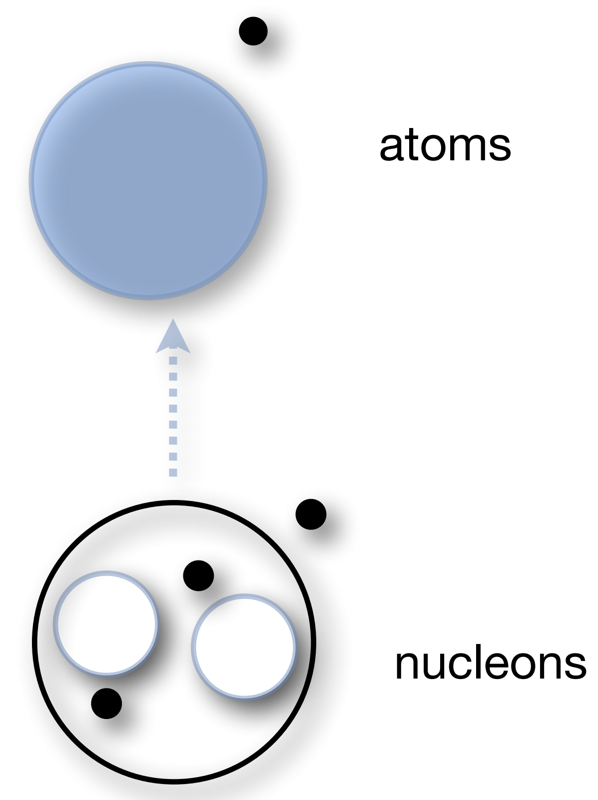
- Quantum matter as the basic building block



Three ingredients to describe Nature

- Quantum matter as the basic building block

- Gauge symmetry as a fundamental principle and at the origin of every force

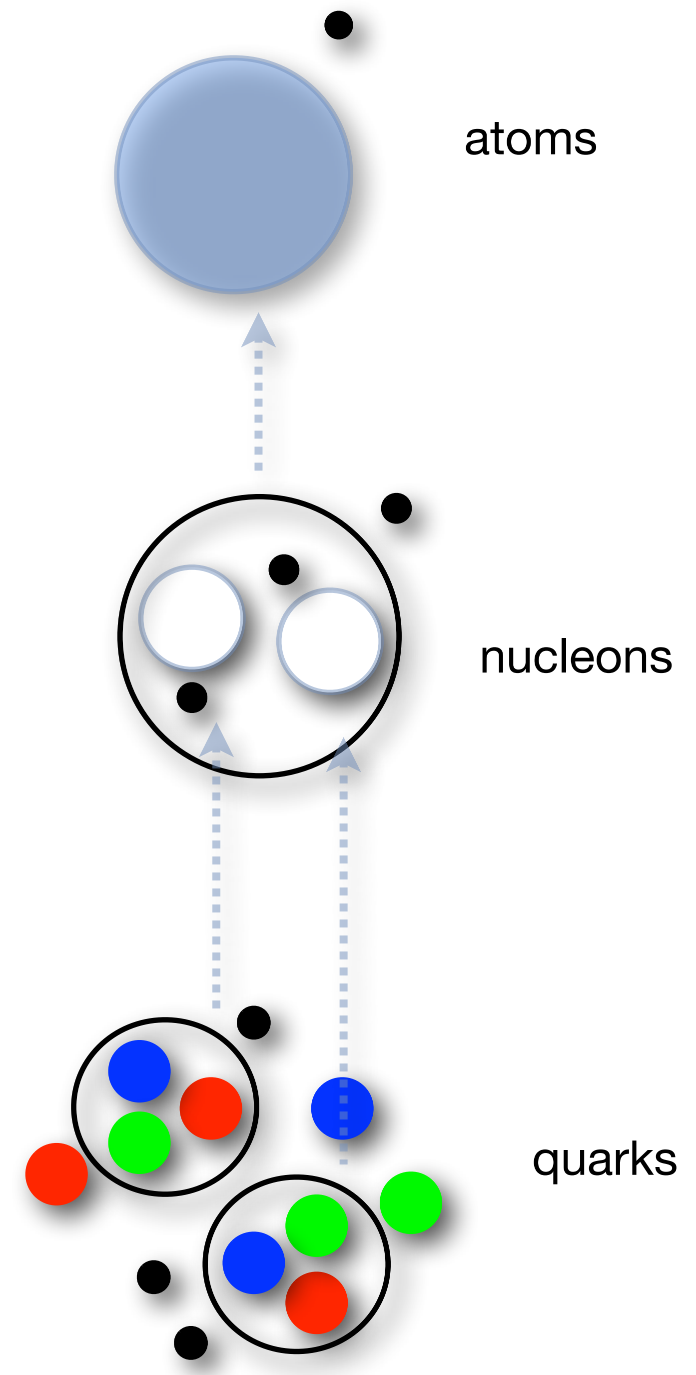


Three ingredients to describe Nature

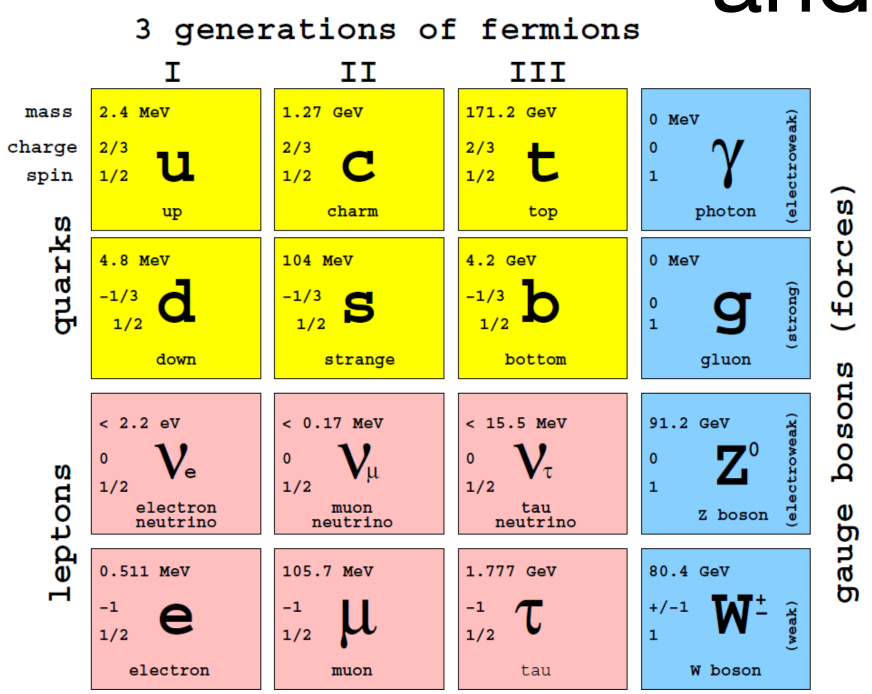
- Quantum matter as the basic building block

- Gauge symmetry as a fundamental principle and at the origin of every force

- Renormalisation group as a tool to study Nature at different scales



Gauge symmetry as a fundamental principle and at the origin of every force



Standard model: for every force there is a gauge boson

The photon is the “carrier” of the electromagnetic force.
The W_+, W_- and Z_0 are the “carriers” of the weak force.
The gluons are the “carriers” of the strong force.

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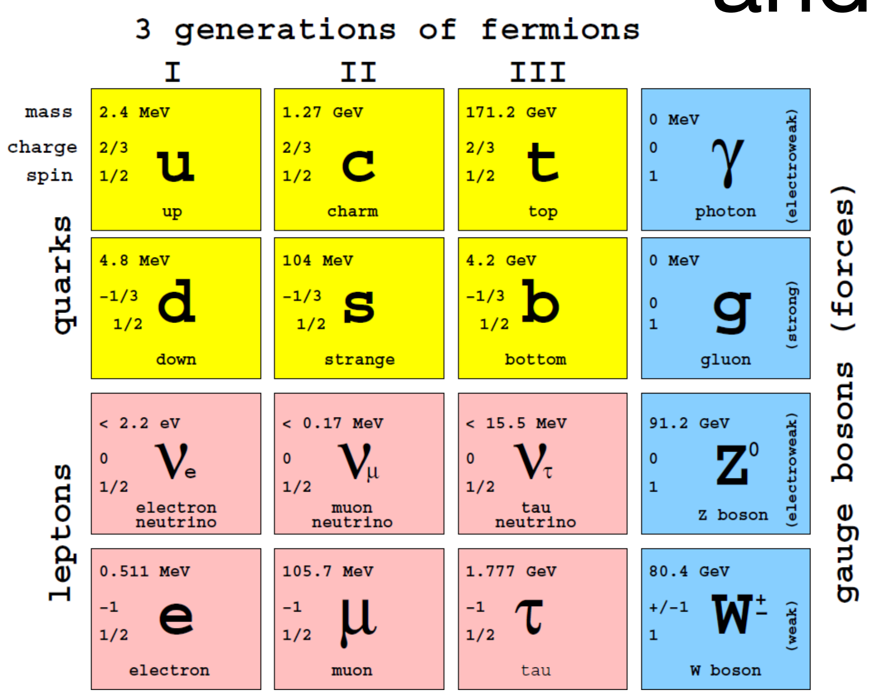

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Standard model: a successful story

Non-abelian quantum chromodynamics (QCD) responsible for mass in every-day life
50+ years success story of parton model
40 years success story of (p)QCD (1979: discovery of gluon in e+e- at PETRA)

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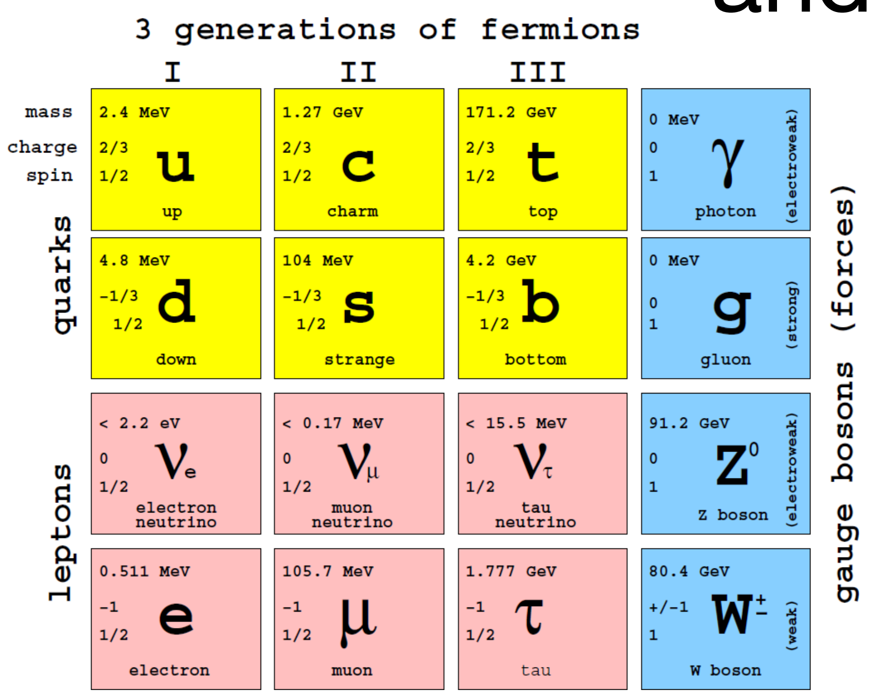

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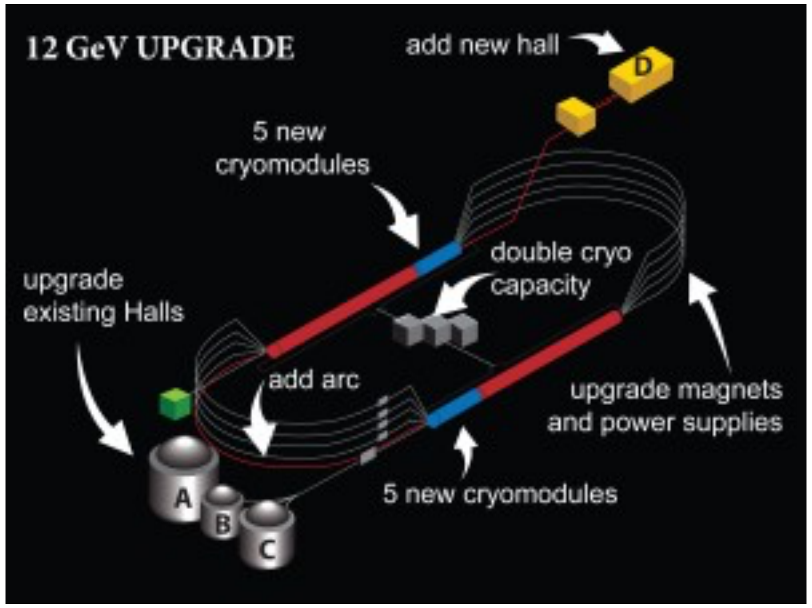
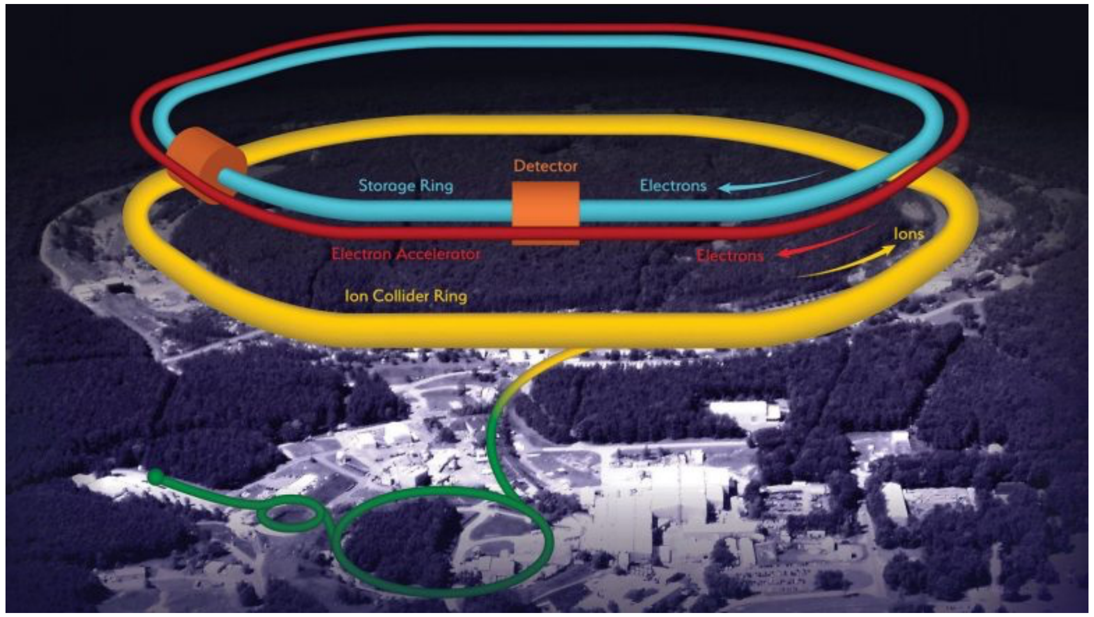
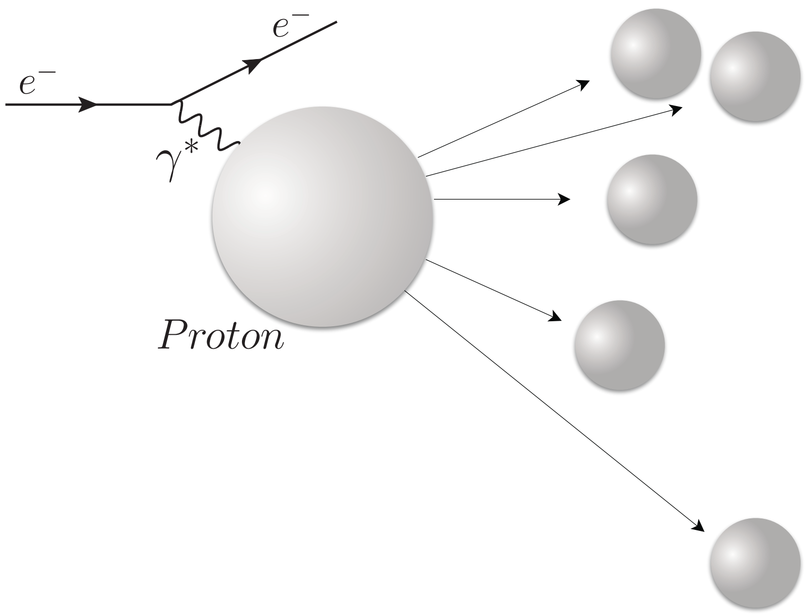
but non-perturbative part (hadron structure and formation) still a vast, partly unexplored field

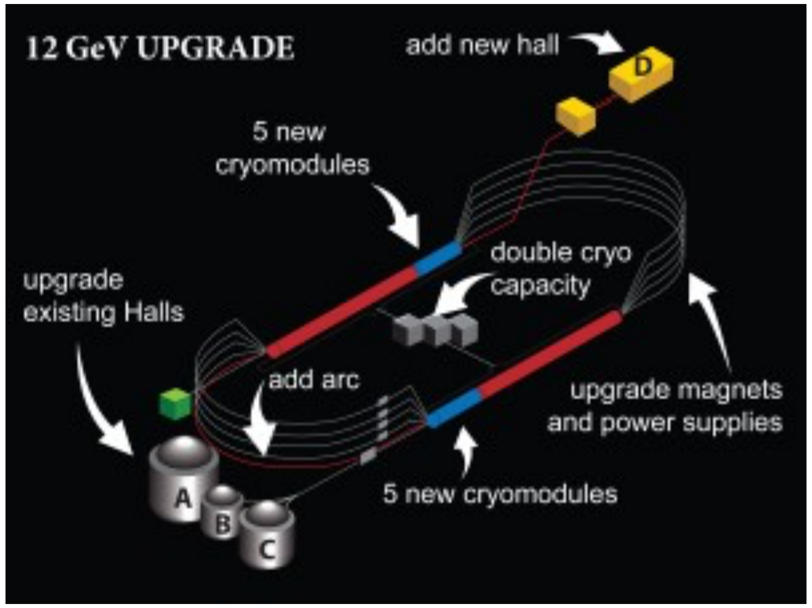


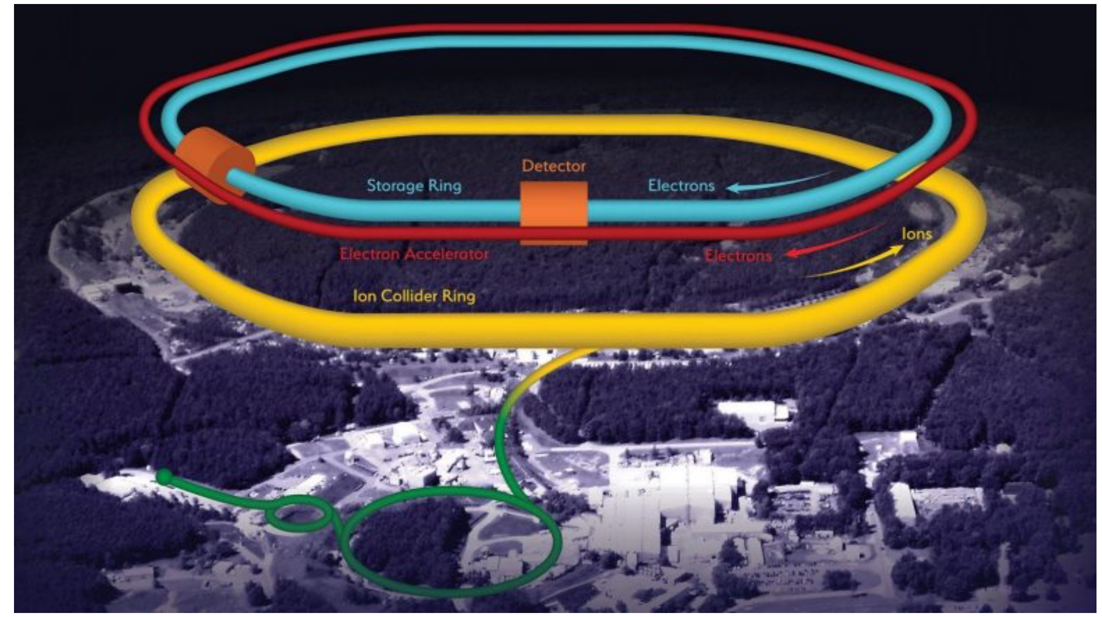


modern microscopes



(semi-inclusive)
deep-inelastic lepton scattering





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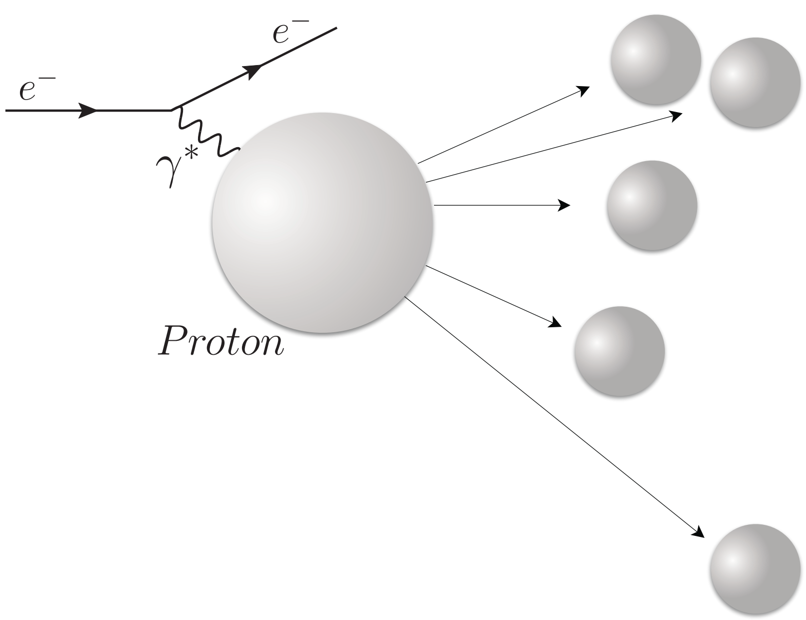
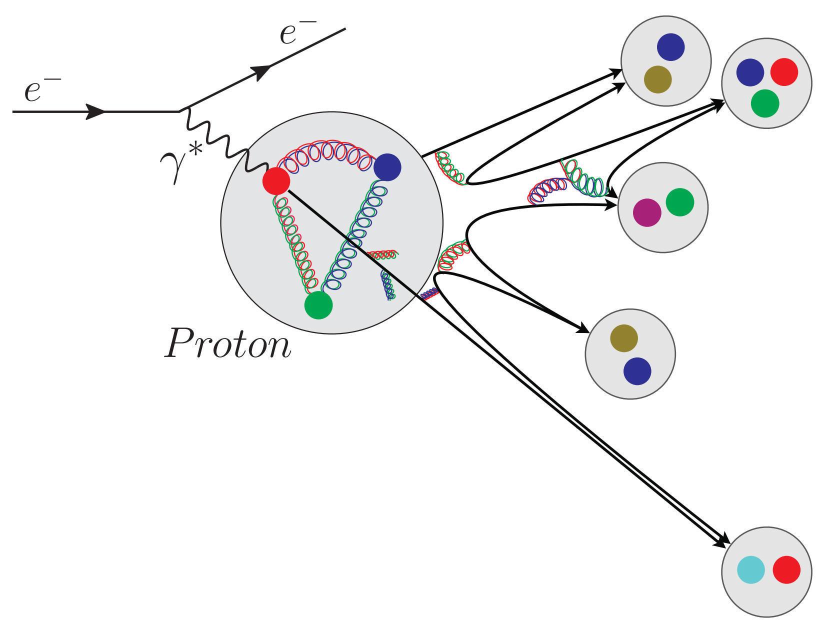
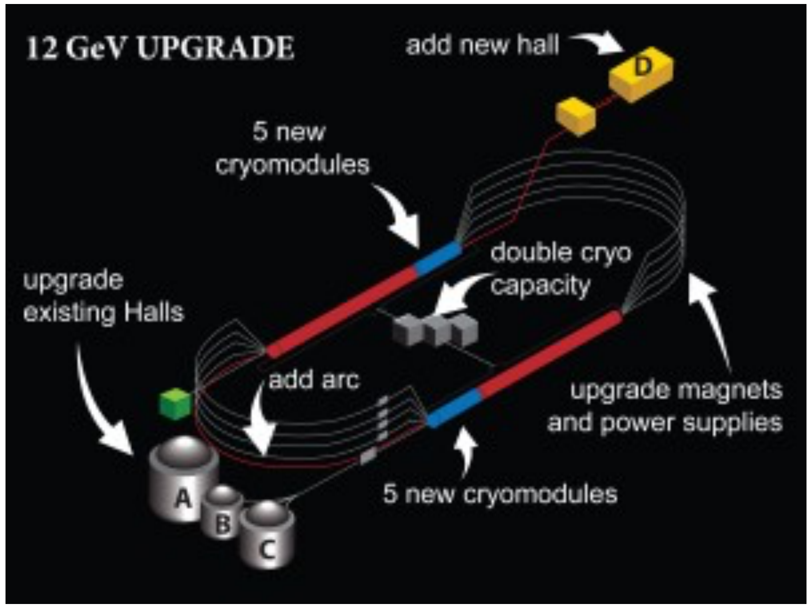
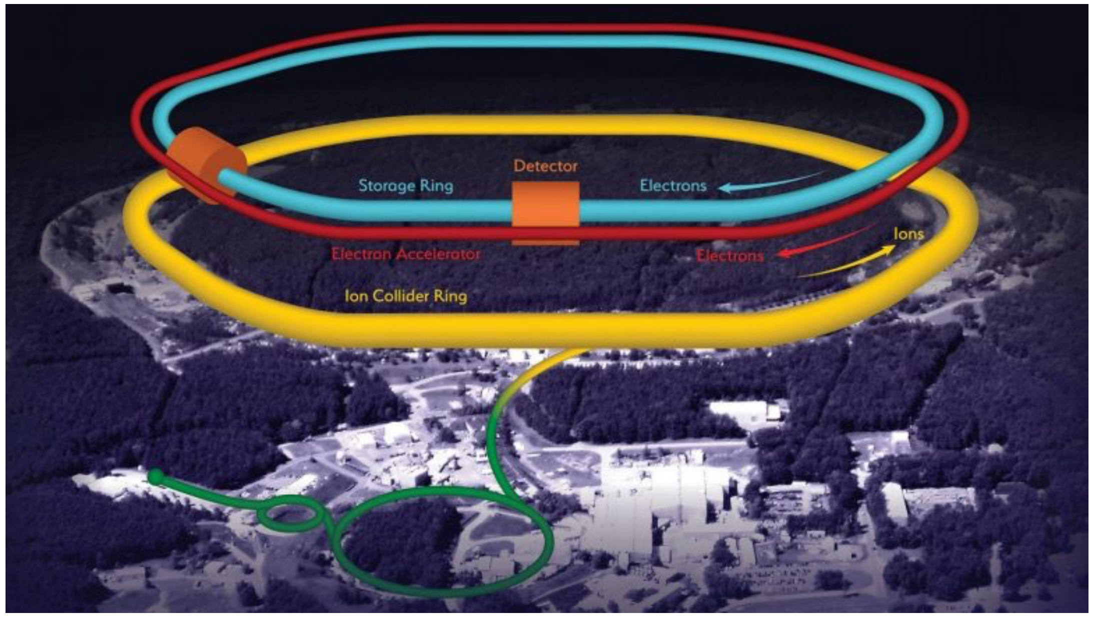




(semi-inclusive)
deep-inelastic lepton scattering

highly virtual photons resolve
inner (partonic) structure





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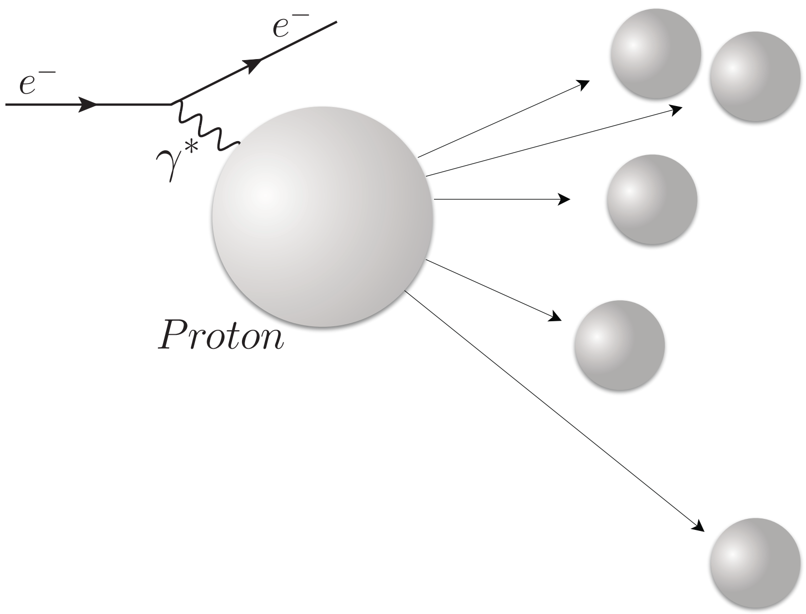
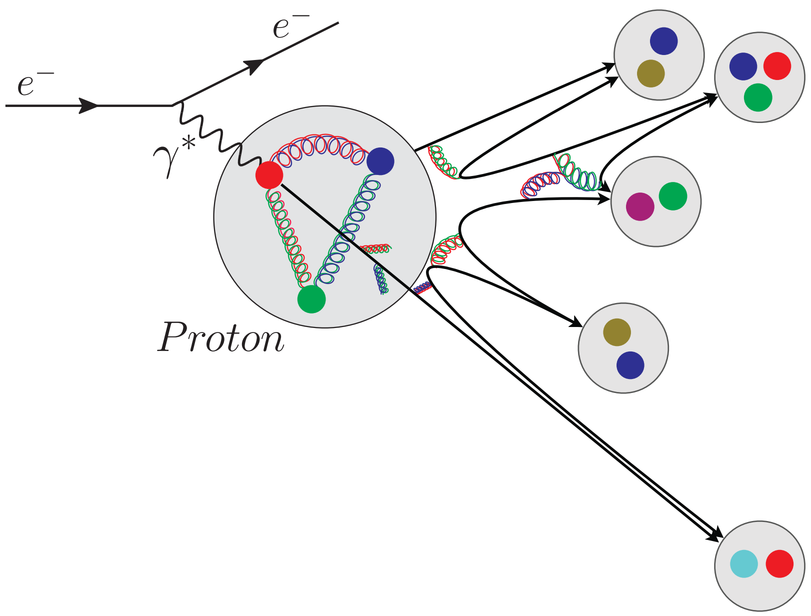
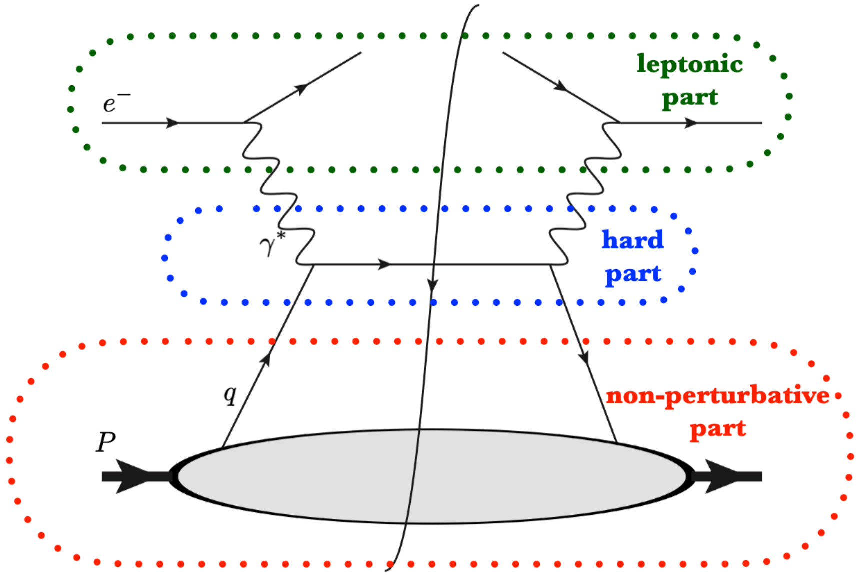






(semi-inclusive)
deep-inelastic lepton scattering

highly virtual photons resolve
inner (partonic) structure

factorization theorems
separate non-calculable from
calculable parts

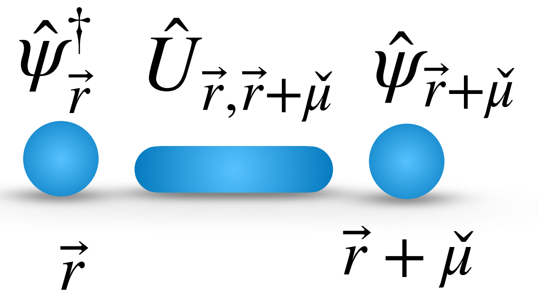
Eur. Phys. J. D (2020) 74: 165
https://doi.org/10.1140/epjd/e2020-100571-8

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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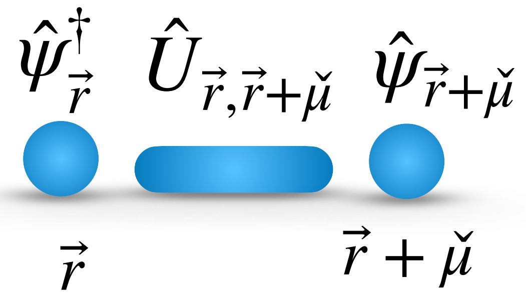
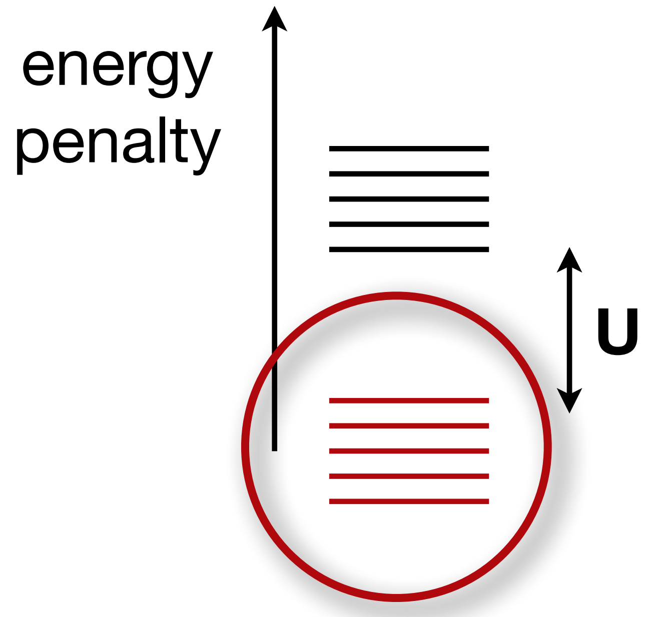
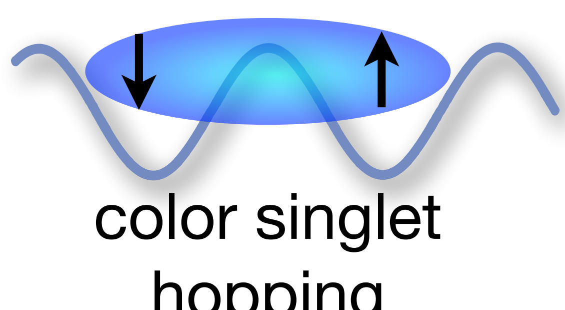
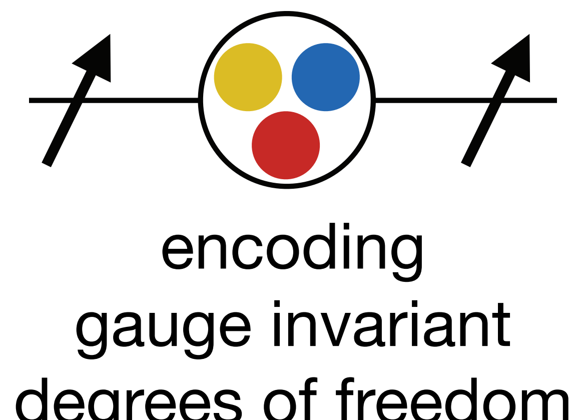


- Implementing the gauge invariant dynamics





Internal symmetry



PRX QUANTUM **2**, 017001 (2021)

Roadmap

Quantum Computer Systems for Scientific Discovery

Yuri Alexeev,[1] Dave Bacon,[2] Kenneth R. Brown,[3,4,5] Robert Calderbank,[3,6] Lincoln D. Carr,[7] Frederic T. Chong,[8] Brian DeMarco,[9] Dirk Englund,[10] Edward Farhi,[11,12] Bill Fefferman,[8] Alexey V. Gorshkov,[13,14] Andrew Houck,[15] Jungsang Kim,[3,5,16] Shelby Kimmel,[17] Michael Lange,[18] Seth Lloyd,[19] Mikhail D. Lukin,[20] Dmitri Maslov,[21] Peter Maunz,[22] Christopher Monroe,[13,16,*] John Preskill,[23] Martin Roetteler,[24] Martin J. Savage,[25] and Jeff Thompson[15]

PRX QUANTUM **4**, 027001 (2023)

Roadmap

Quantum Simulation for High-Energy Physics

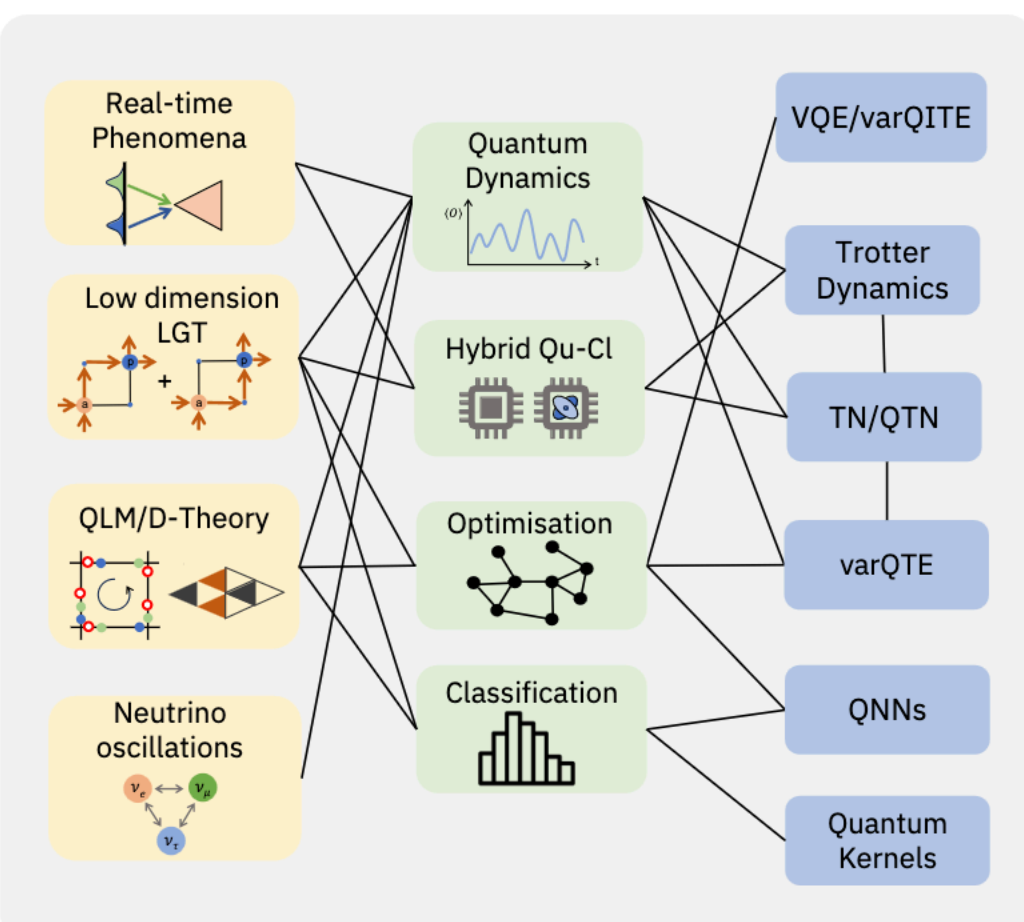
Christian W. Bauer,[1,*] Zohreh Davoudi,[2,†] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[14,15] Junyu Liu,[16,17] Mikhail Lukin,[18] Yannick Meurice,[19] Christopher Monroe,[20,21,22,23] Benjamin Nachman,[1] Guido Pagano,[24] John Preskill,[25] Enrico Rinaldi,[26,27,28] Alessandro Roggero,[29,30] David I. Santiago,[31,32] Martin J. Savage,[33] Irfan Siddiqi,[31,32,34] George Siopsis,[35] David Van Zanten,[5] Nathan Wiebe,[36,37] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[38] and Silvia Zorzetti[6]

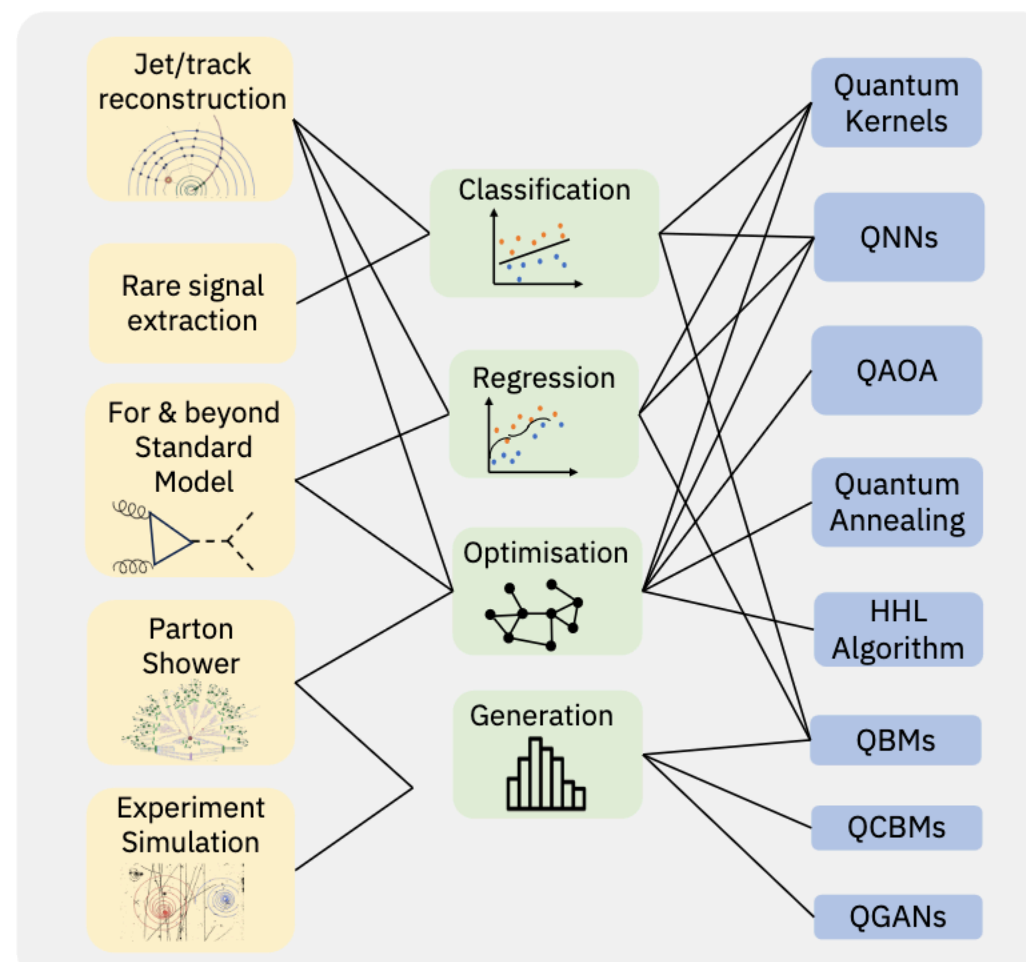
Quantum Computing for High-Energy Physics: State of the Art and Challenges

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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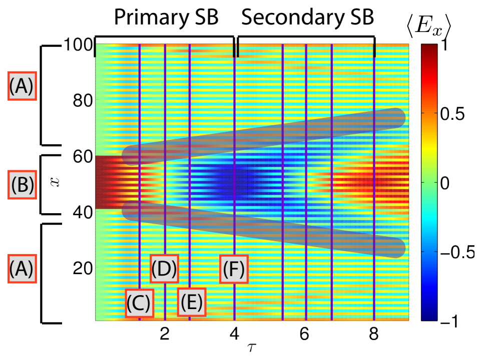

PHYSICAL REVIEW X **6,** 011023 (2016)

Real-Time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks

T. Pichler,[1] M. Dalmonte,[2,3] E. Rico,[4,5,6] P. Zoller,[2,3] and S. Montangero[1]

After a particle collision, pairs of quarks remain confined in color singlet states through a **flux tube (Wilson line)** connecting them.

As the flux tube evolves, it stretches giving rise to the **string** breaking and **string** fragmentation

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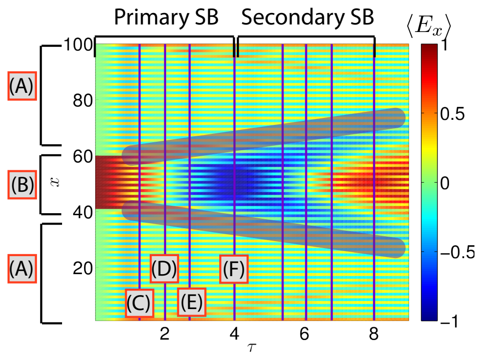

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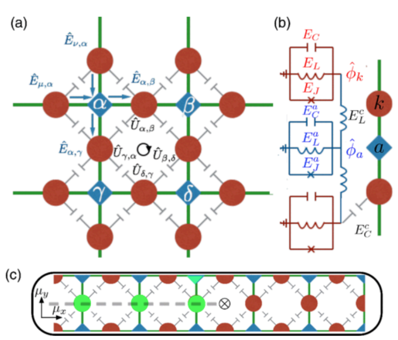
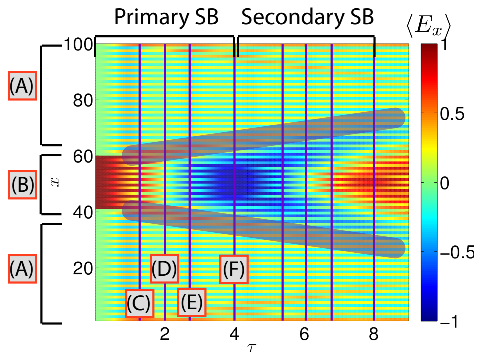


PRL **117,** 240504 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

Loops and Strings in a Superconducting Lattice Gauge Simulator

G. K. Brennen,[1] G. Pupillo,[2] E. Rico,[3,4] T. M. Stace,[5] and D. Vodola[2]

The witnesses to the existence of the predicted confining phase of the model are provided by nonlocal order parameters from **Wilson loops** and disorder parameters from **'t Hooft strings.**



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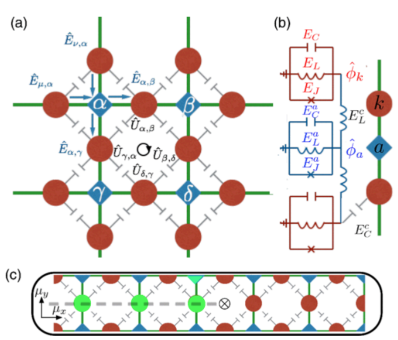

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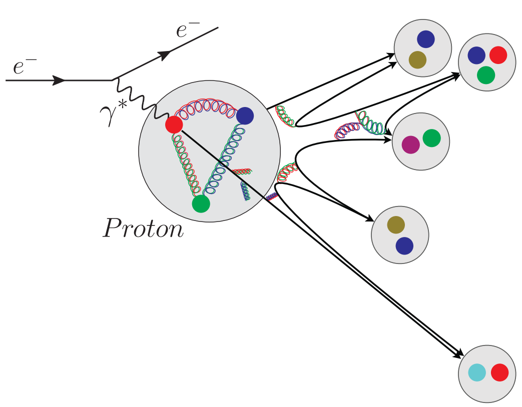


PHYSICAL REVIEW D **104,** 014512 (2021)

Quantum simulation of light-front parton correlators

M. G. Echevarria,[1,*] I. L. Egusquiza,[2,†] E. Rico,[3,4,‡] and G. Schnell[2,4,§]

Hadron structure study requires the measurement of **flux tubes (Wilson lines)** among its constituents (partons) in space and real-time

Superconducting circuits implementation

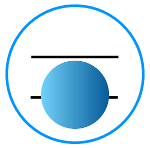
Local degrees of freedom.-

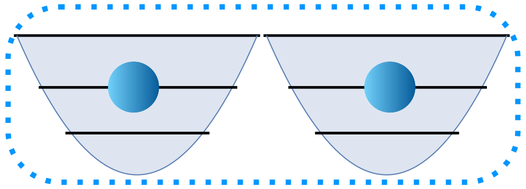
We need:

Tuneable (spectrum) device

two-level atom (anharmonic)
cavity (harmonic)

Coherent dynamics (low dissipation)





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Chris Wilson

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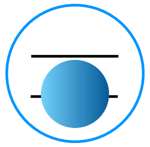

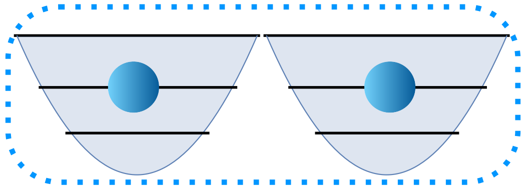

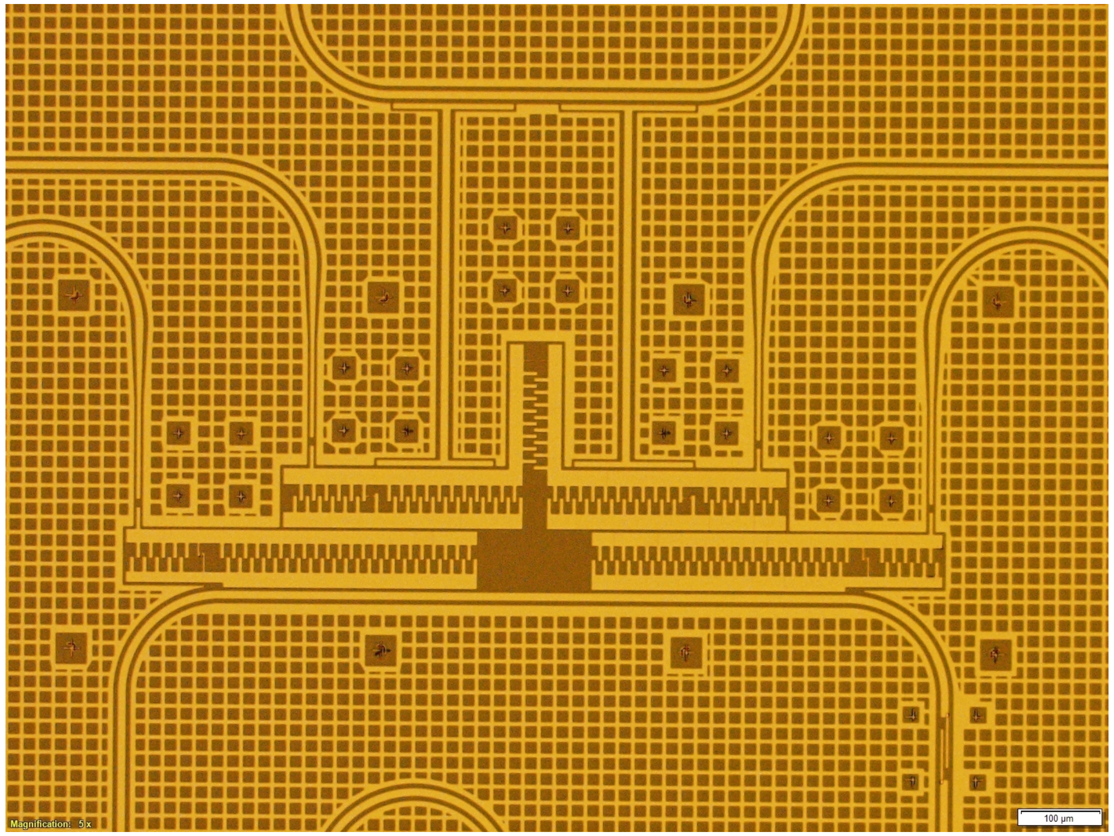

Superconducting circuits implementation

Simulating quantum electrodynamics in 2+1 dimensions with qubits and qumodes

Victor Ale,[1] Tommaso Rainaldi,[2] Enrique Rico,[3] Felix Ringer,[2] George Siopsis[1]

We nee

Tuneab

two-level atom (anharmonic)
cavity

Trigonometric continuous-variable gates and hybrid quantum simulations of the sine-Gordon model

Tommaso Rainaldi,[a] Victor Ale,[b] Matt Grau,[c] Dmitri Kharzeev,[a,d] Enrique Rico,[e] Felix Ringer,[a] Pubasha Shome[a] and George Siopsis[b]

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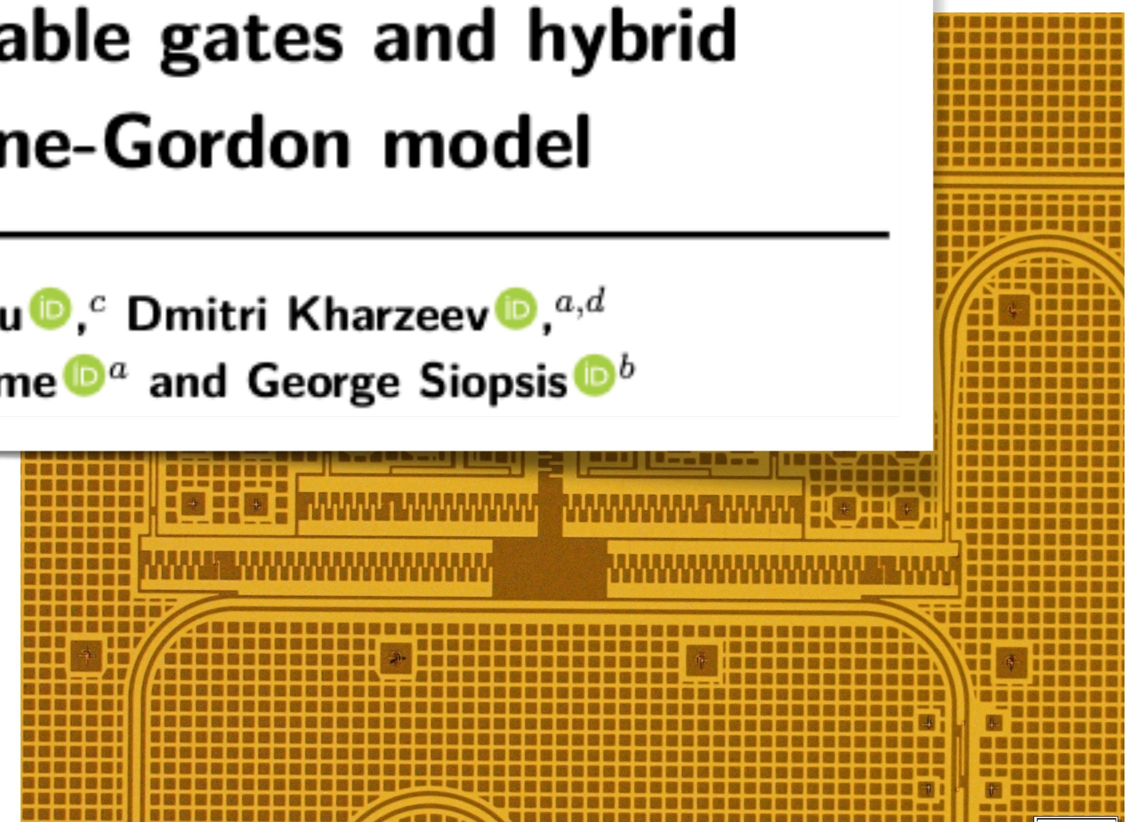

Superconducting circuits implementation

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See the next talk by Tommaso Rainaldi

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Trigonon... continuous-variable gates and hybrid quantum ...ulations of the sine-Gordon model

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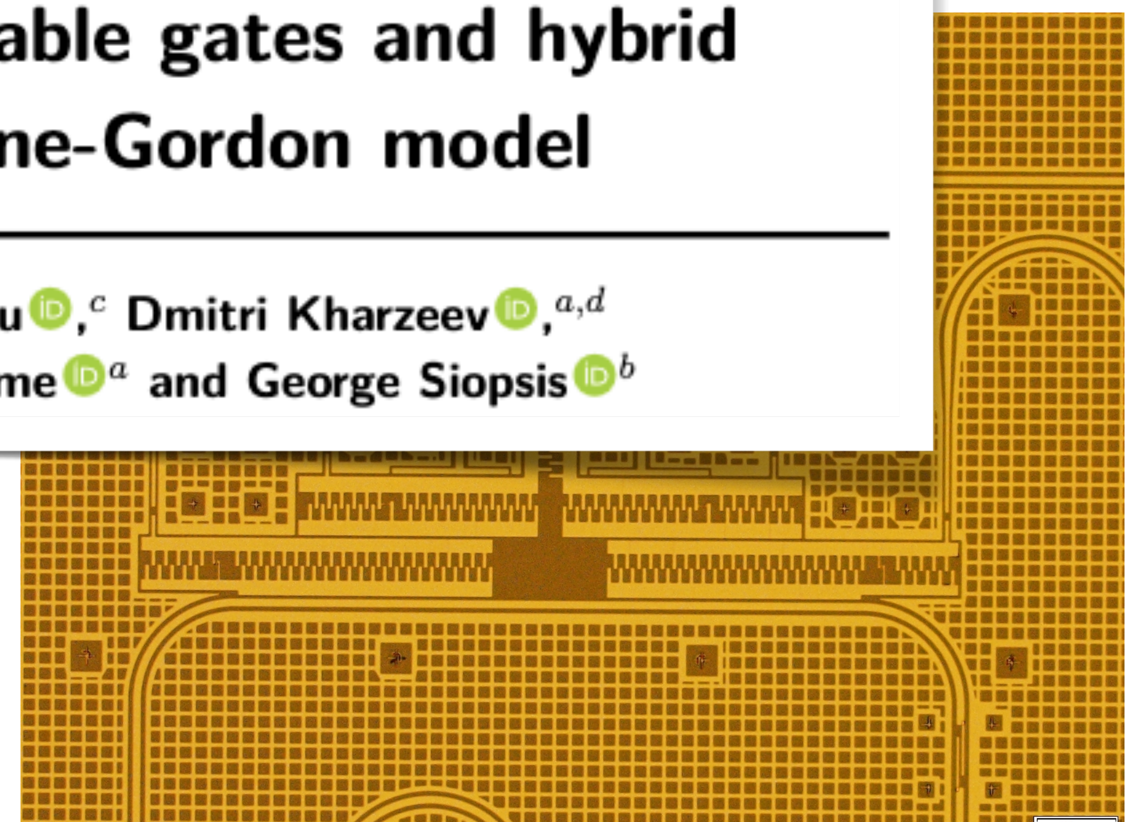
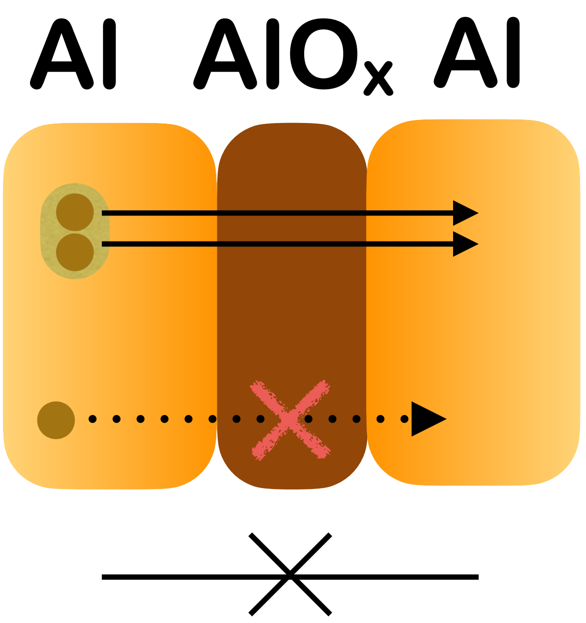


Superconducting circuits ingredients

Josephson tunnelling:

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



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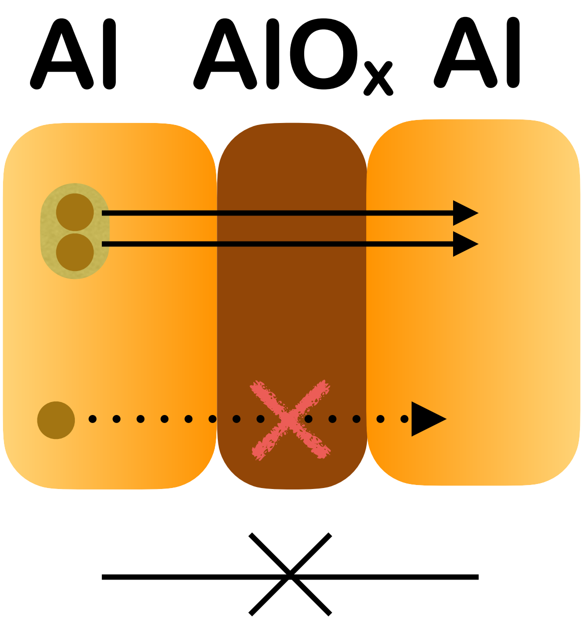

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Josephson Hamiltonian:

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

BasQ Basque Quantum · DIPC Donostia International Physics Center · ikerbasque Basque Foundation for Science · Universidad del País Vasco / Euskal Herriko Unibertsitatea · EHU QC EHU Quantum Center · CERN Accelerating Science NexTGen · IQ Quantum Technology Initiative · CERN

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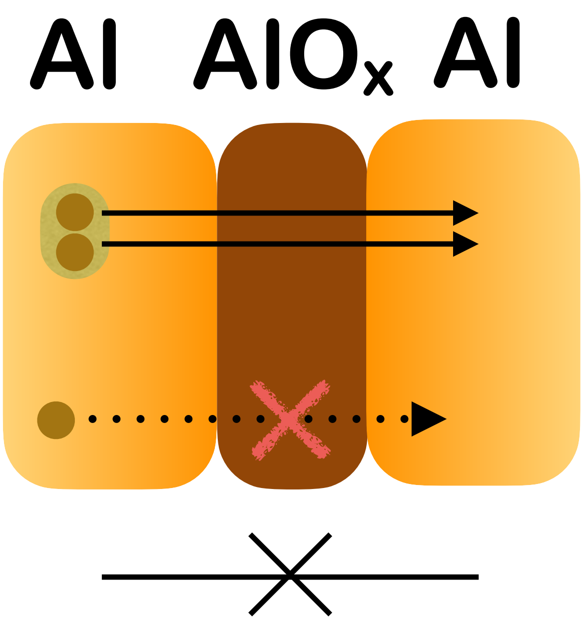

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$$= -E_J \cos\phi$$

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

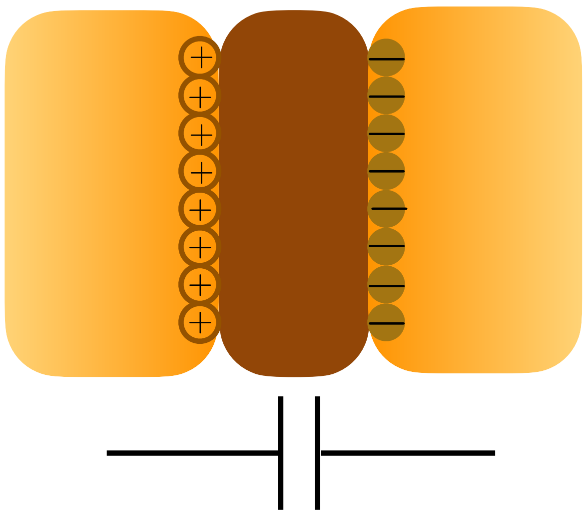
$$[\phi, n] = i$$

Superconducting circuits ingredients

Local degrees of freedom.-

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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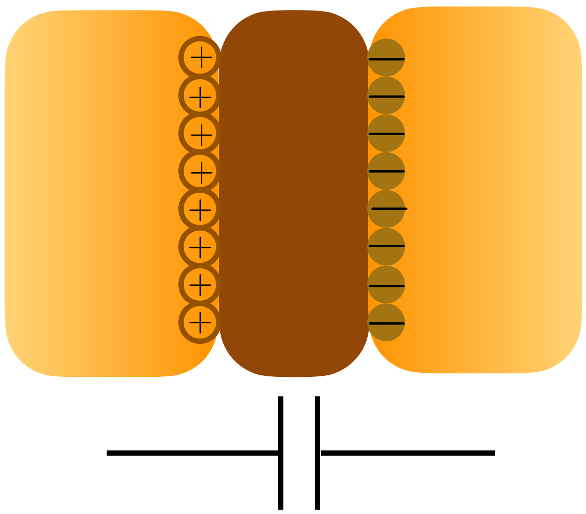
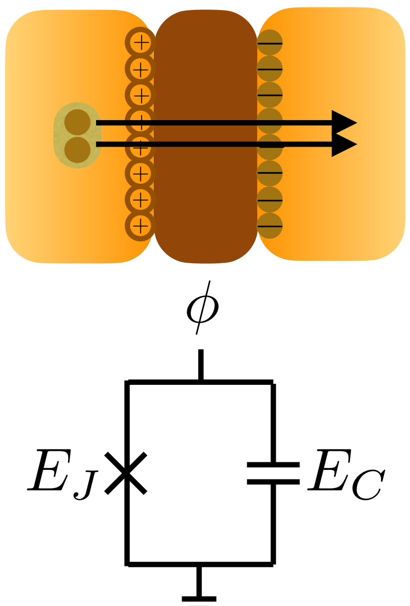
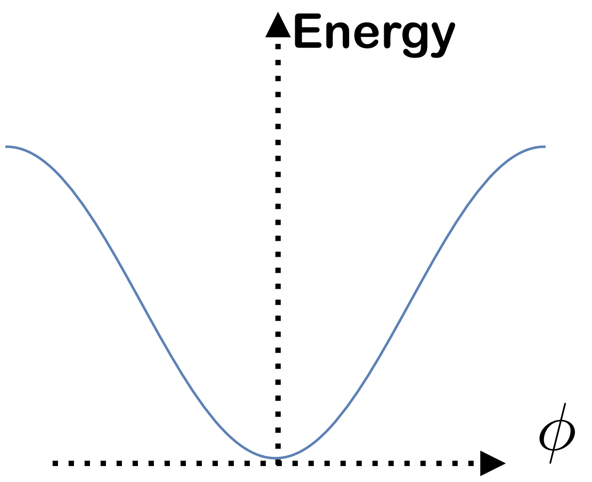


Non-linear oscillator - anharmonic cavity - Josephson junction:



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



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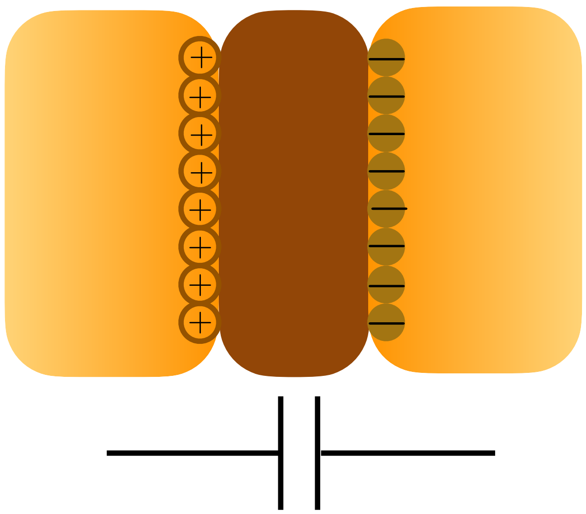

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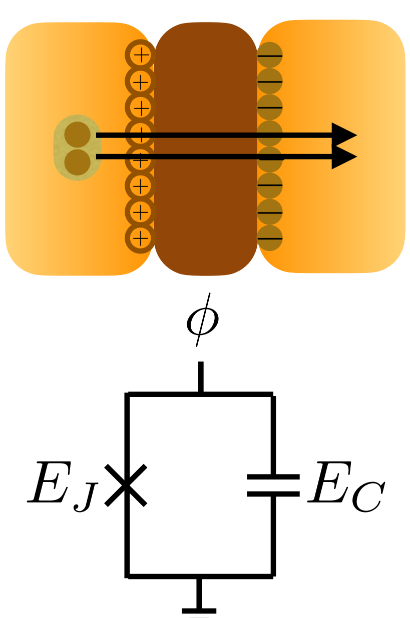

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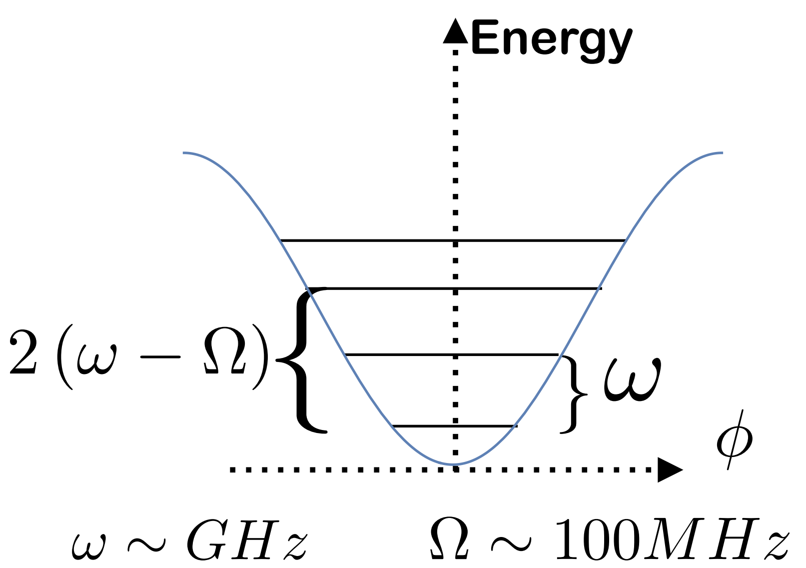
$$= \omega b^\dagger b - \Omega b^{\dagger 2} b^2$$



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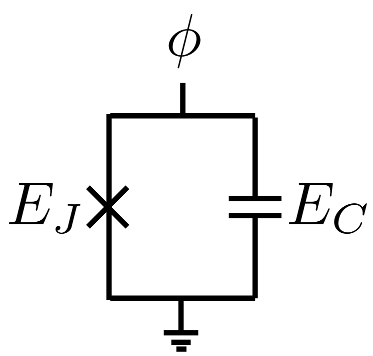

Important parameter: E_J/E_C

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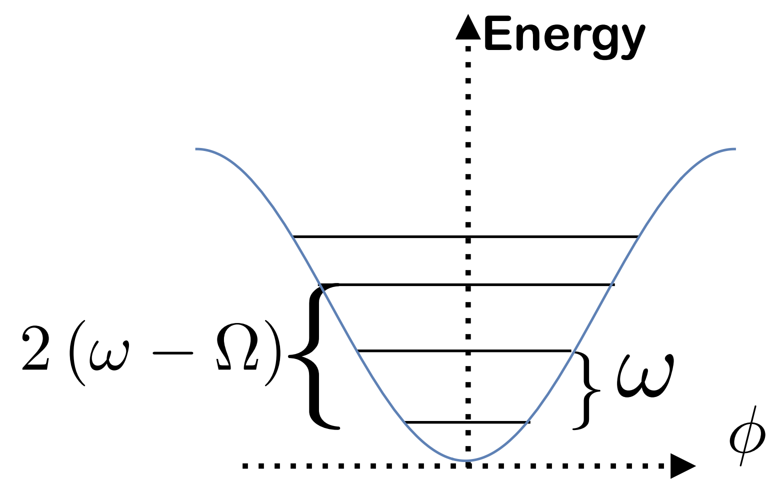

$E_C \rightarrow$ **Fixed by the geometry of the circuit**

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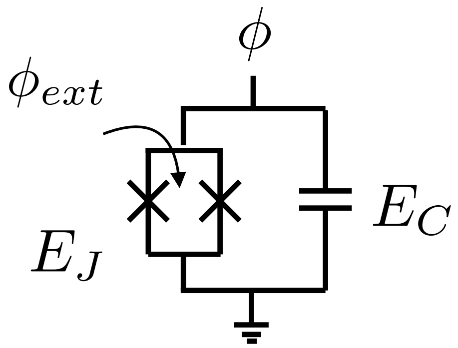

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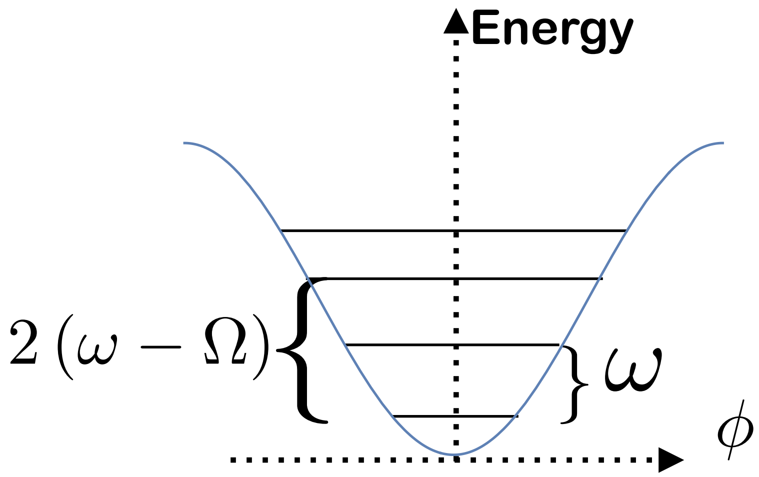


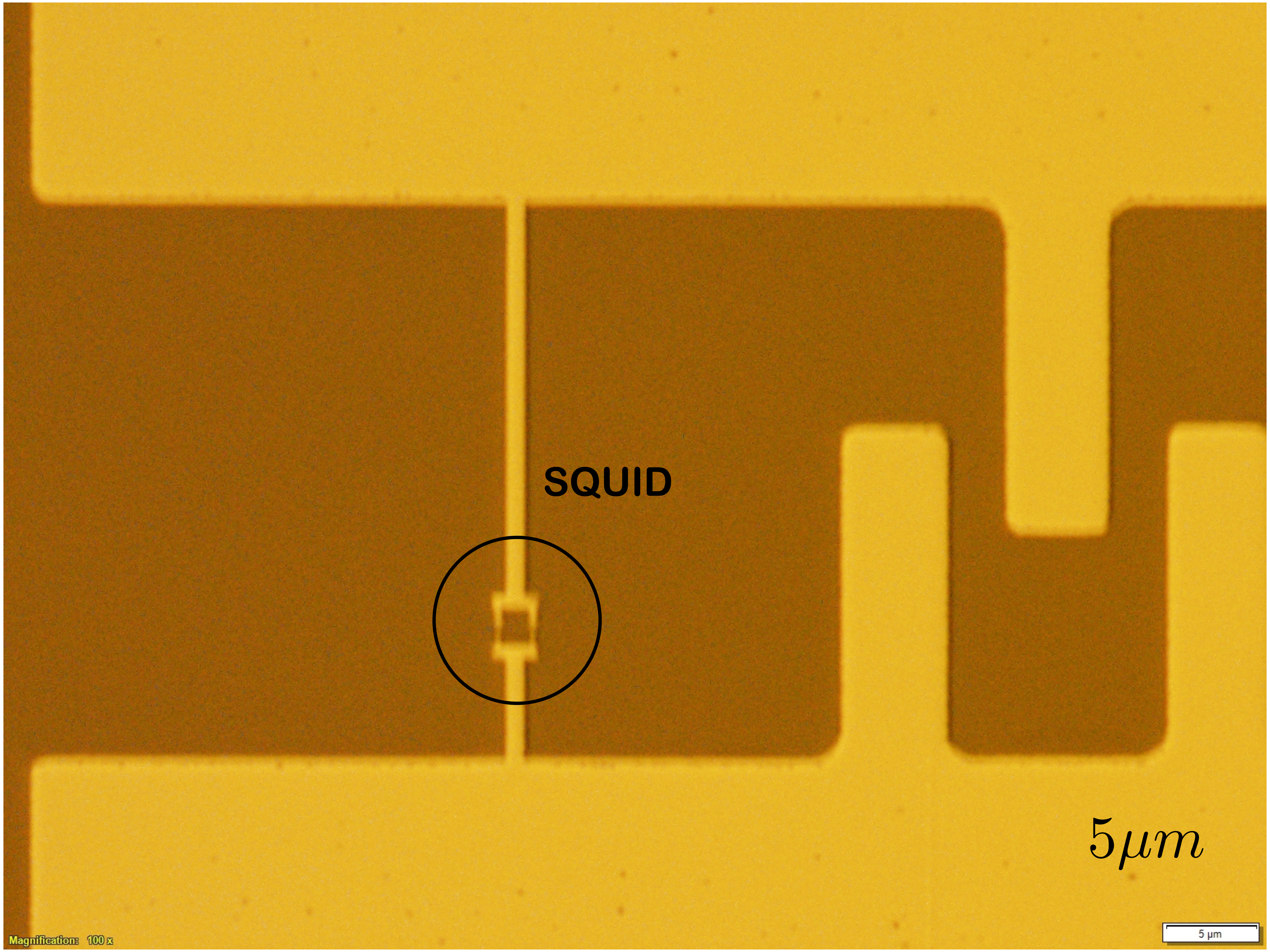
$E_C \rightarrow$ **Fixed by the geometry of the circuit**

$E_J \rightarrow$ **Introduction of a SQUID makes the junction tuneable with an external flux**

$$E_J(\phi_{ext}) = E_J^{\max}\cos(\phi_{ext})$$

$E_J/E_C \sim 20$ **Transmon regime, maximum anharmonicity**

Superconducting circuits ingredients



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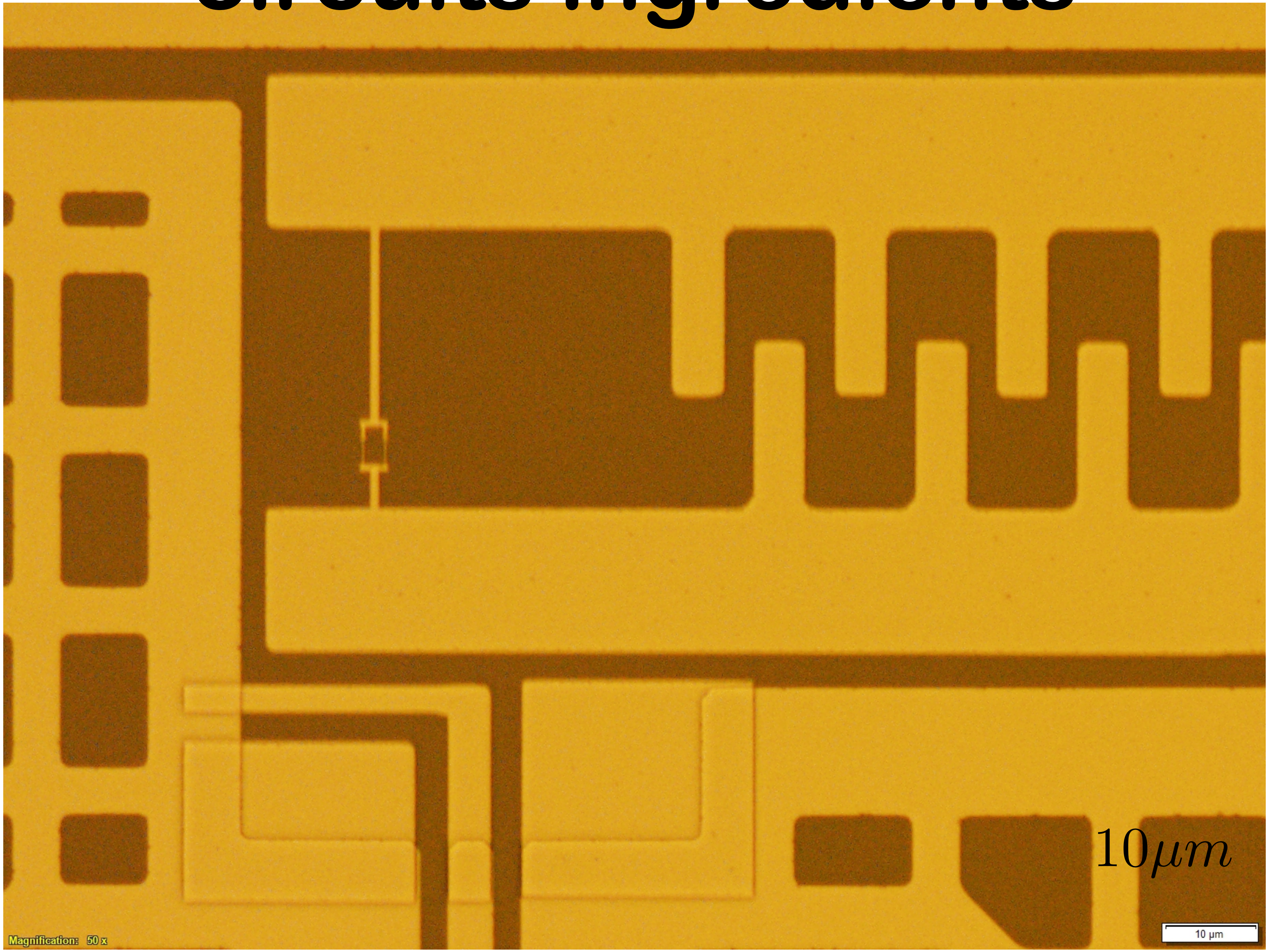

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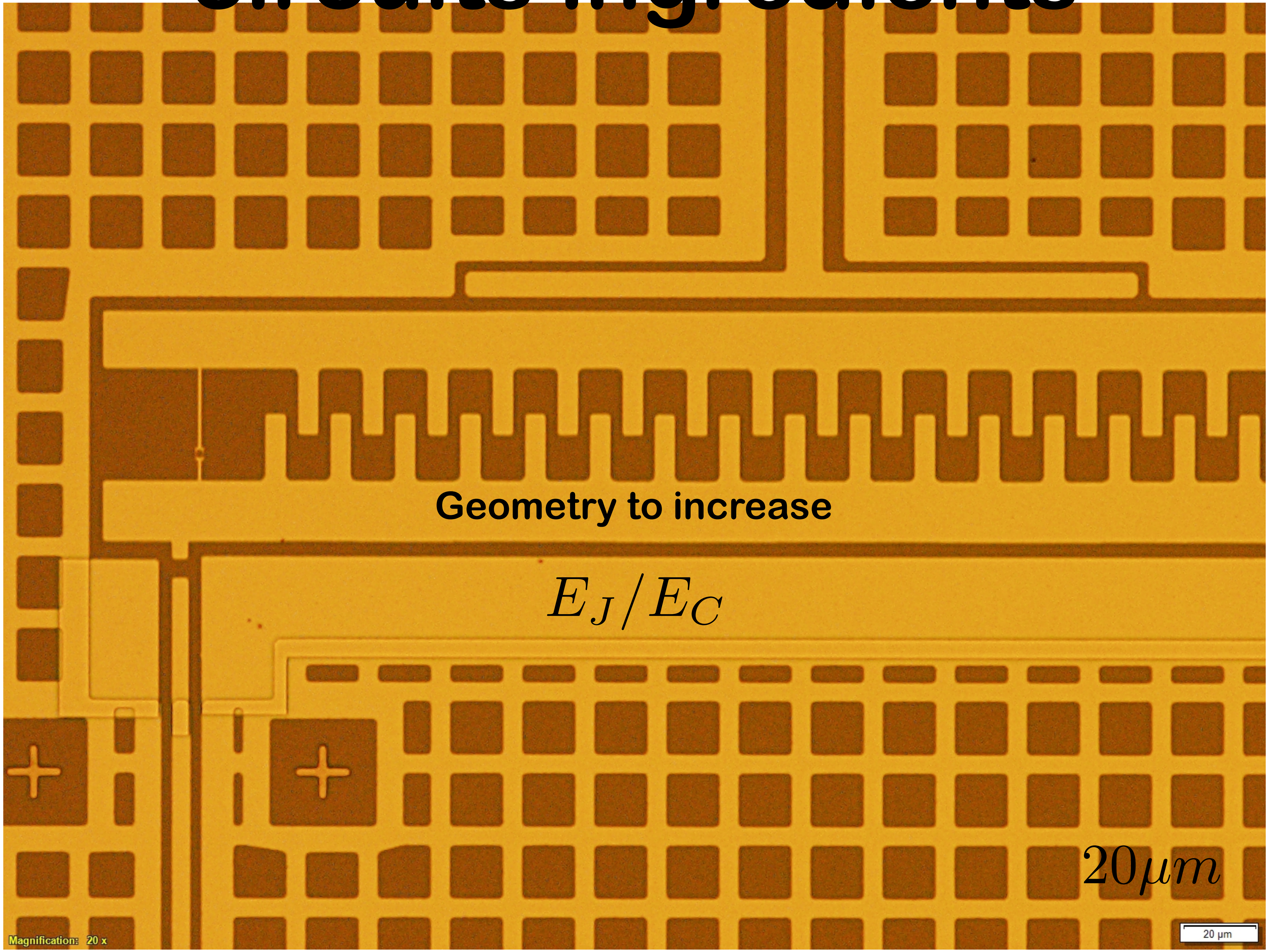
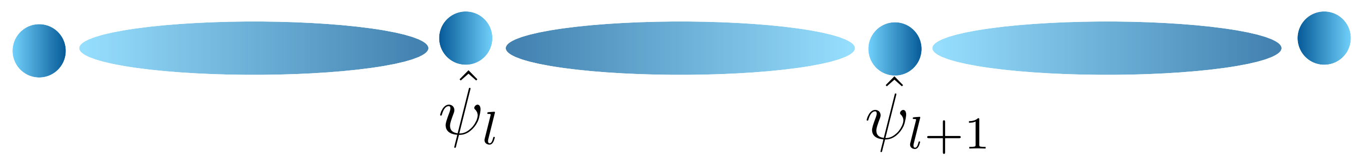


Integrating the different elements



$$H = \frac{g^2}{2}\sum_x \left[E_{x,x+1}\right]^2 - J\sum_x \left[\psi_x^\dagger U_{x,x+1}\psi_{x+1} + \text{h.c.}\right] + m\sum_x (-1)^x \psi_x^\dagger \psi_x$$

Electric term (on-site energy)

Matter-gauge coupling (correlated hopping)

Staggered mass (energy off-set)

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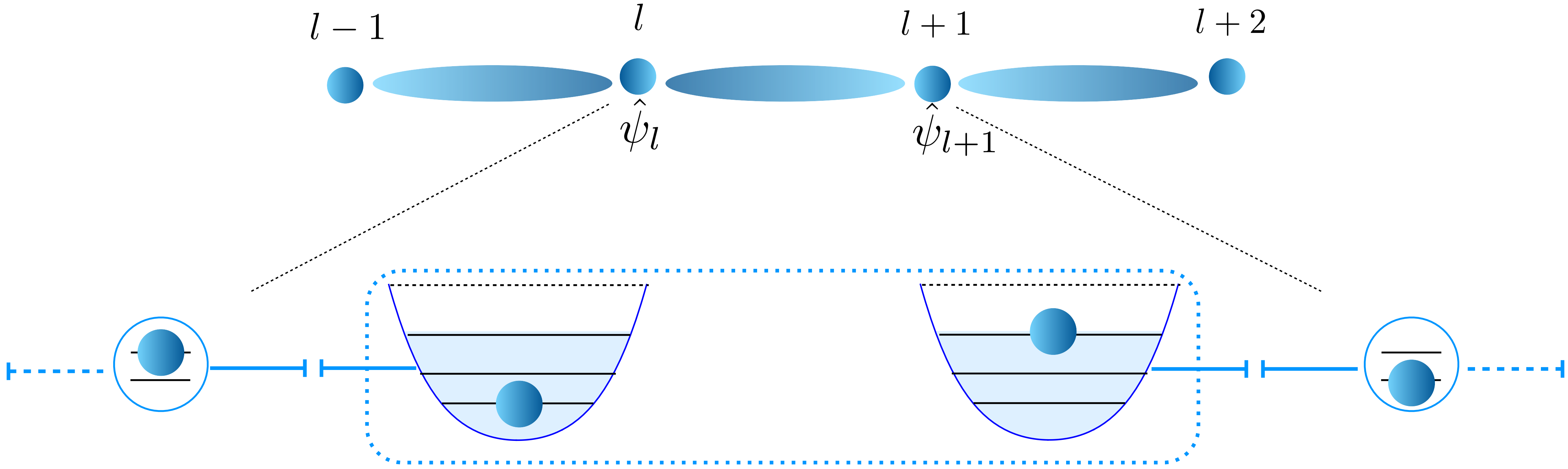

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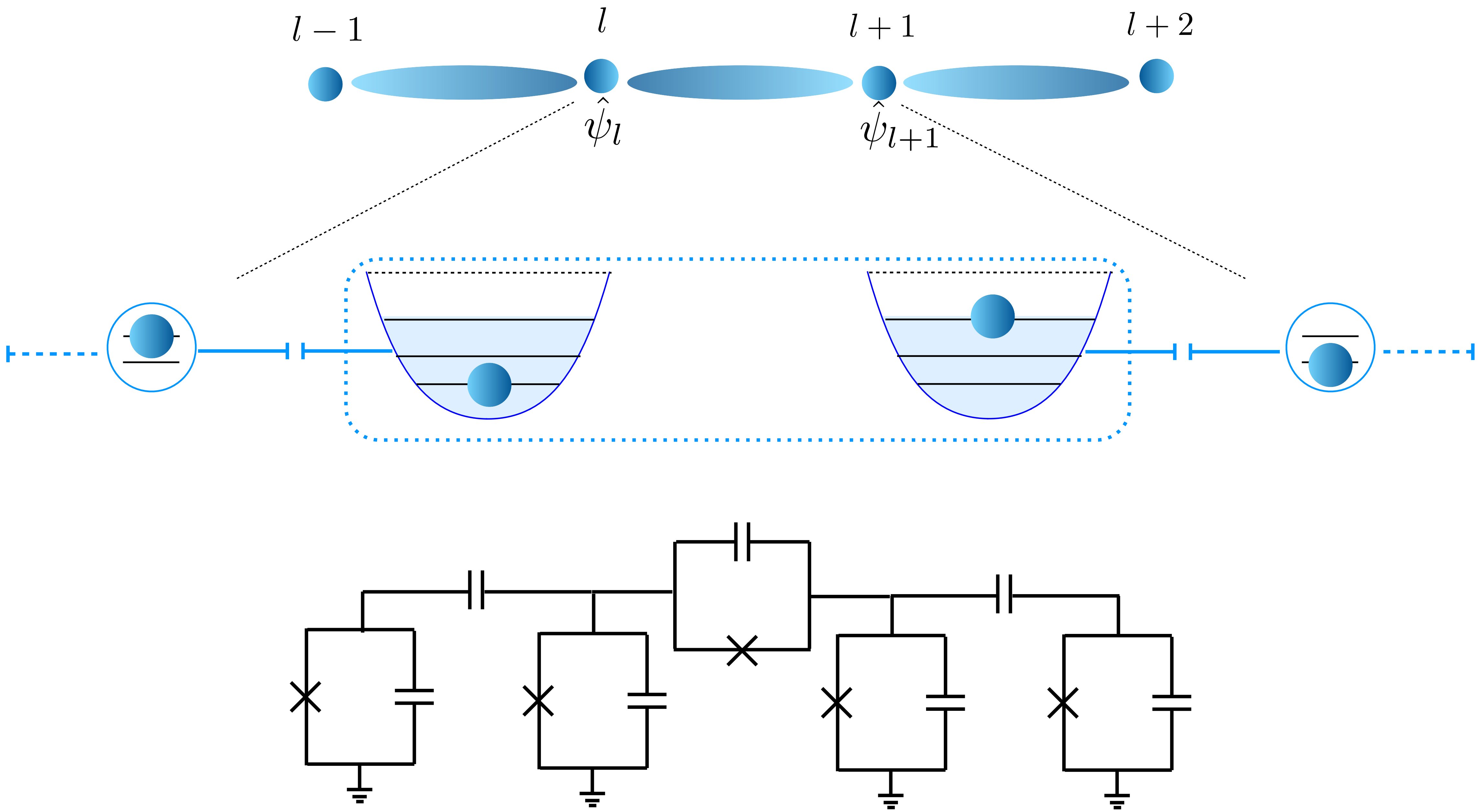

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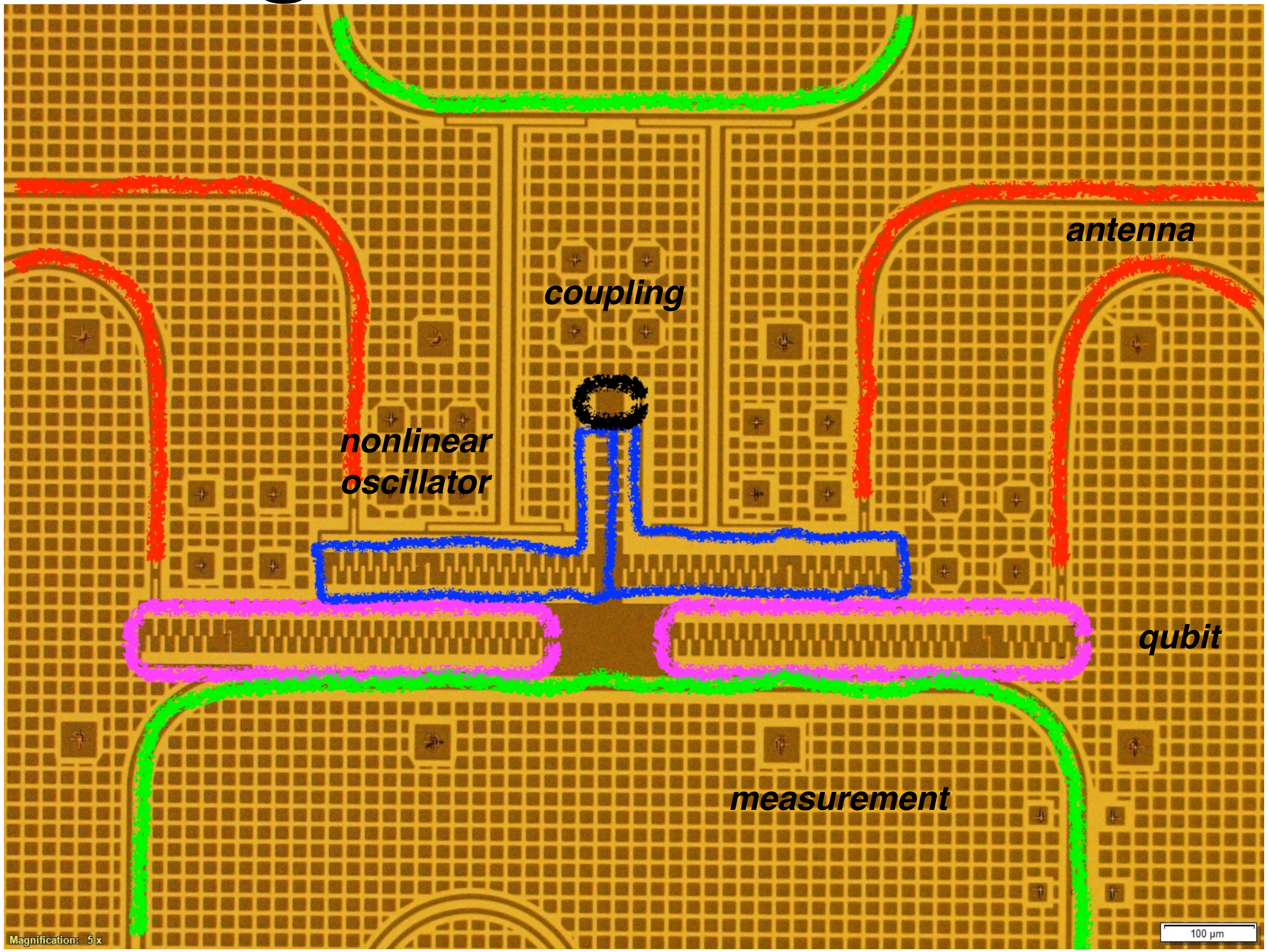

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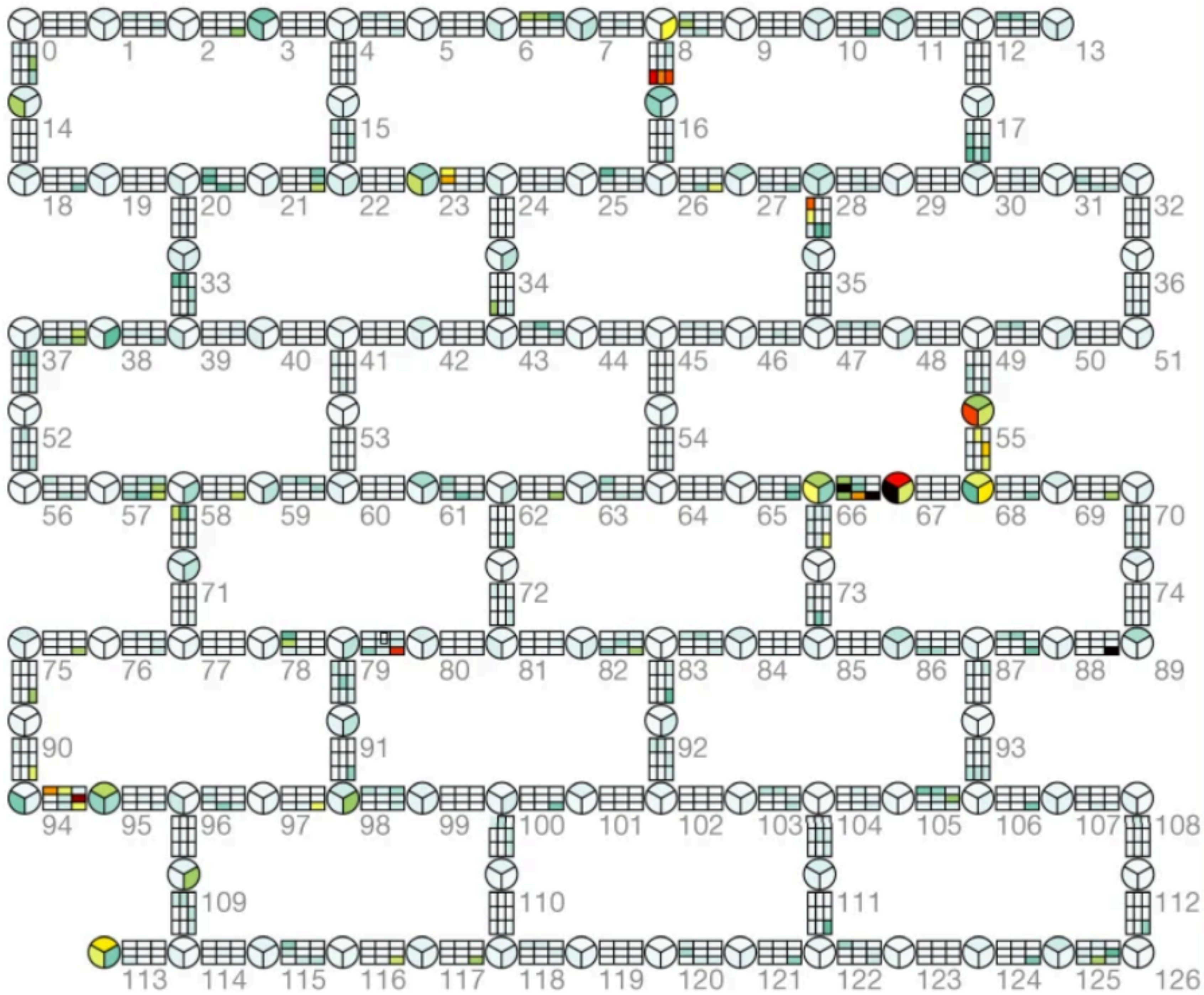
String on a chip



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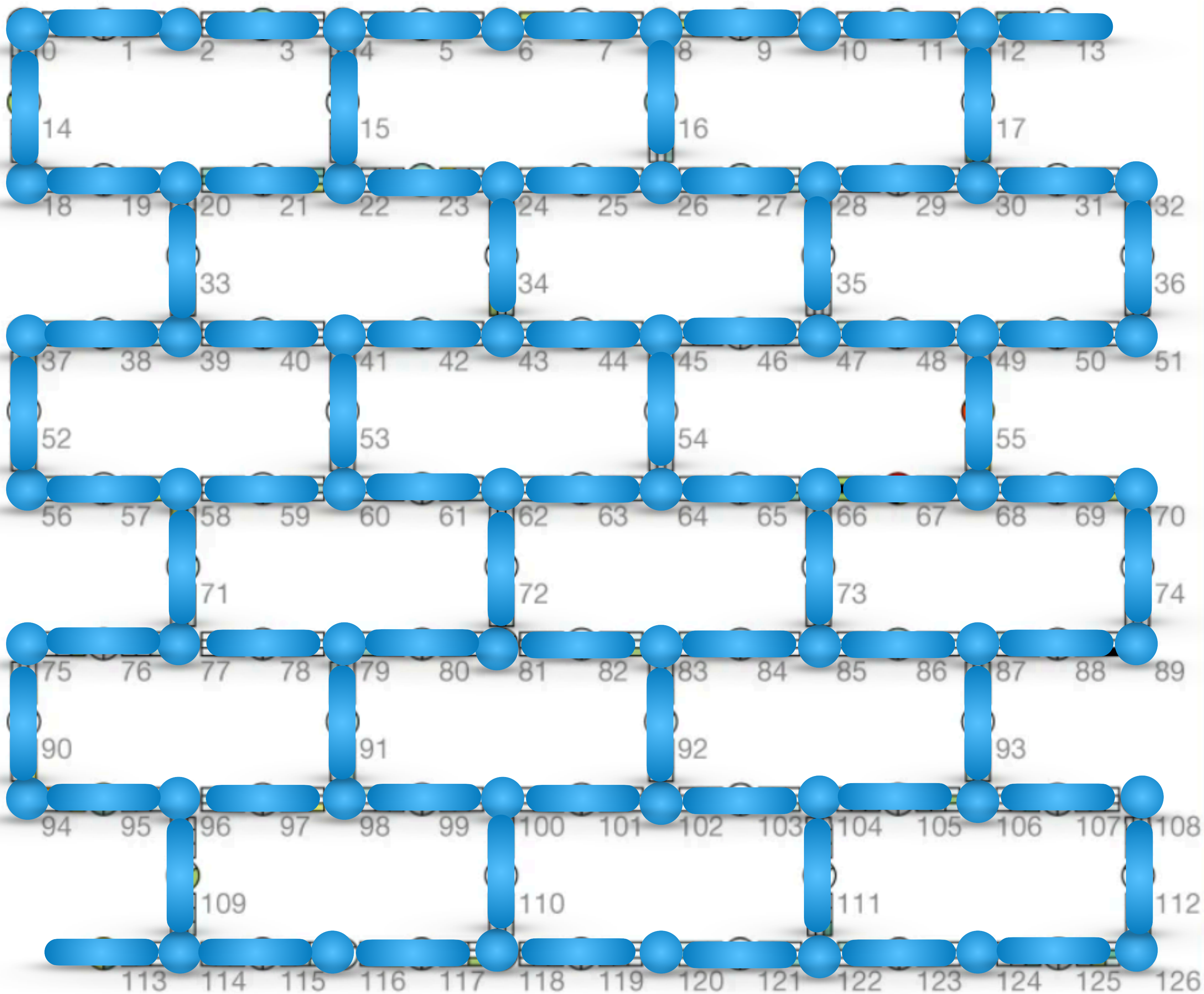


$\hat{\tau}^x_{\vec{r}}$ $\hat{\sigma}^x_{\vec{r},\vec{r}+\check{\mu}}$ $\hat{\tau}^x_{\vec{r}+\check{\mu}}$

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

minimal coupling

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

$\vec{r}$

mass-term

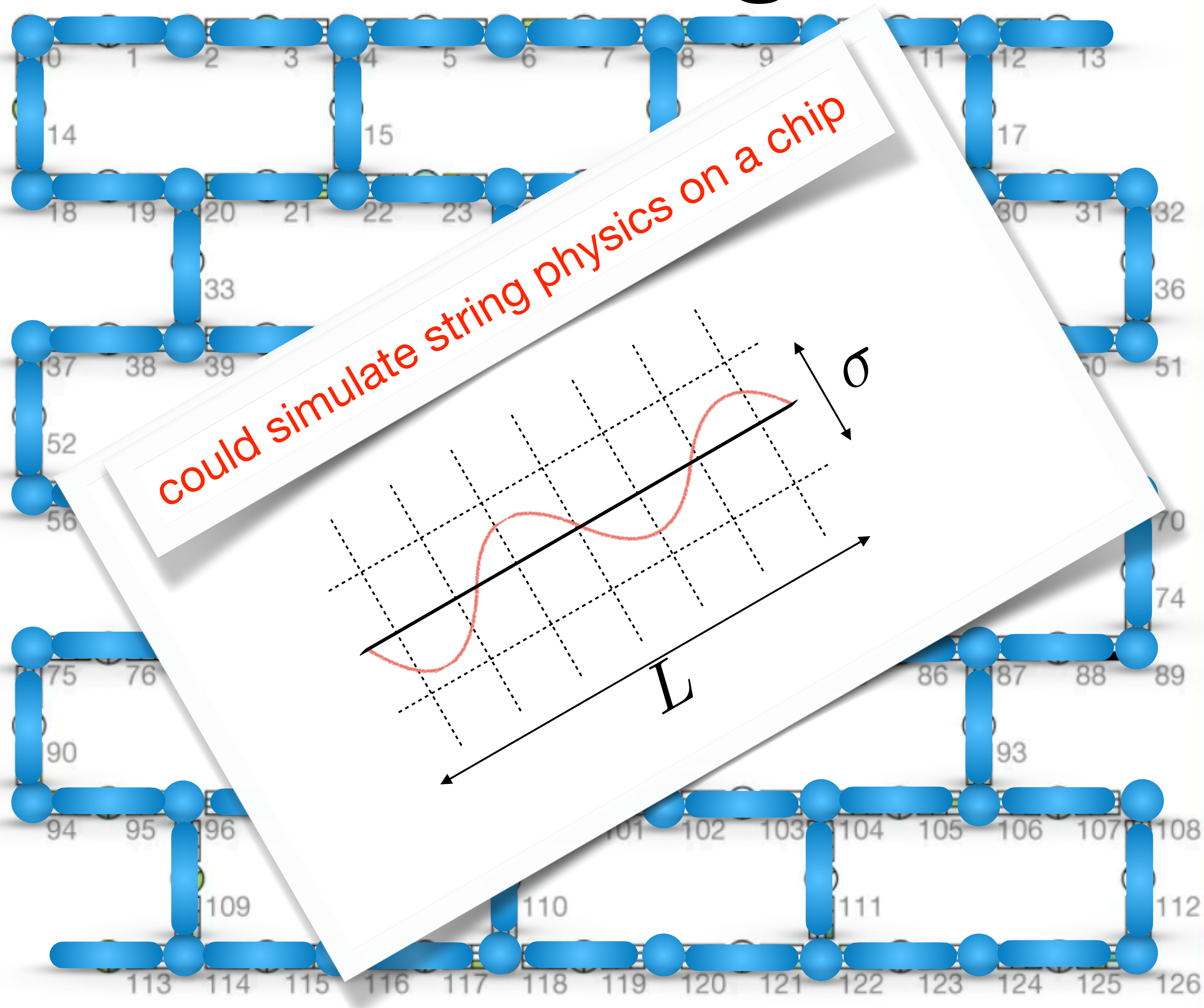
$-g\hat{\sigma}^z_{\vec{r},\vec{r}+\check{\mu}}$

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

electric energy

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

String on a chip



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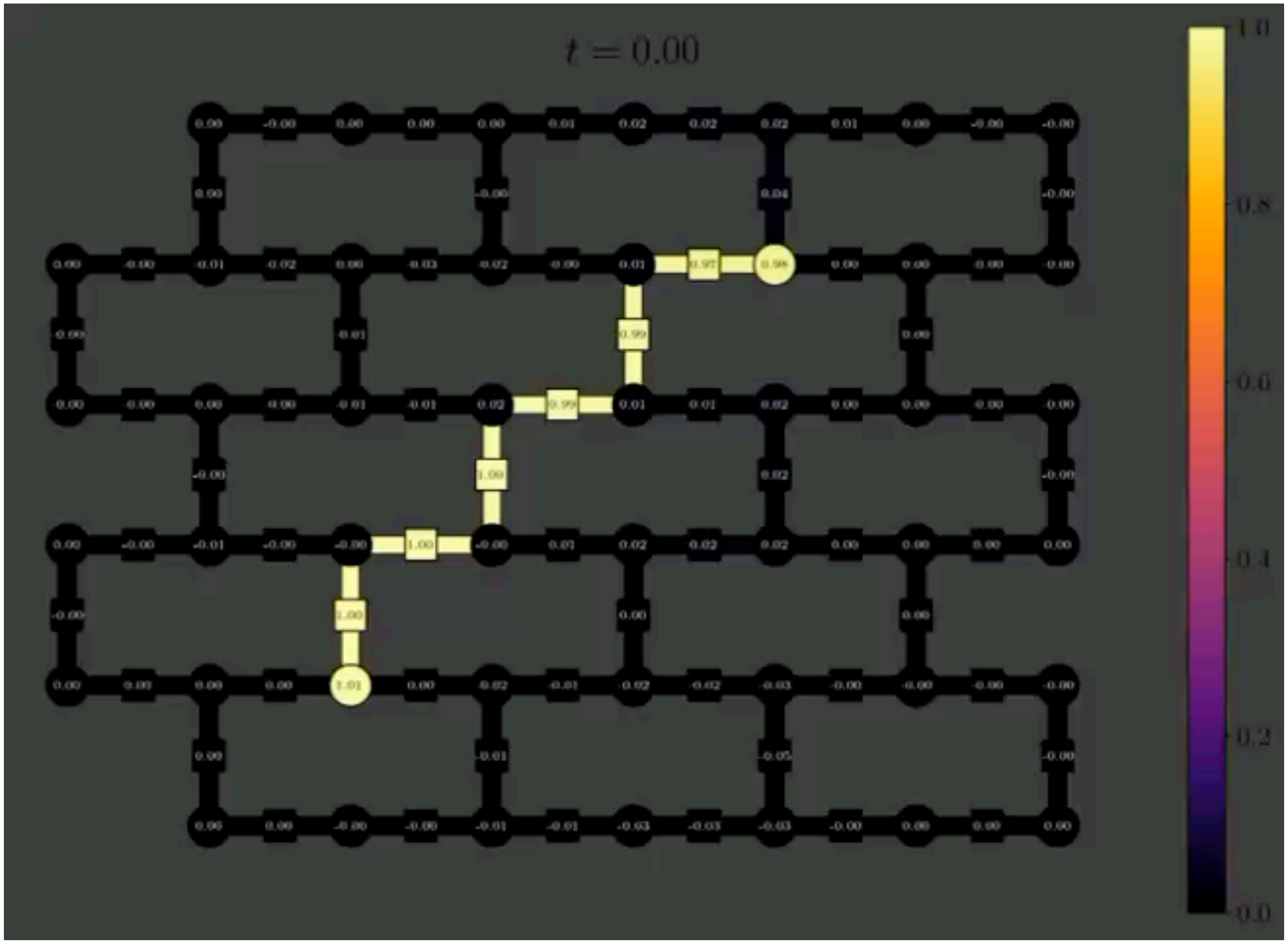
Quantum Real-Time Dynamics of the $\mathbb{Z}_2$ Higgs model

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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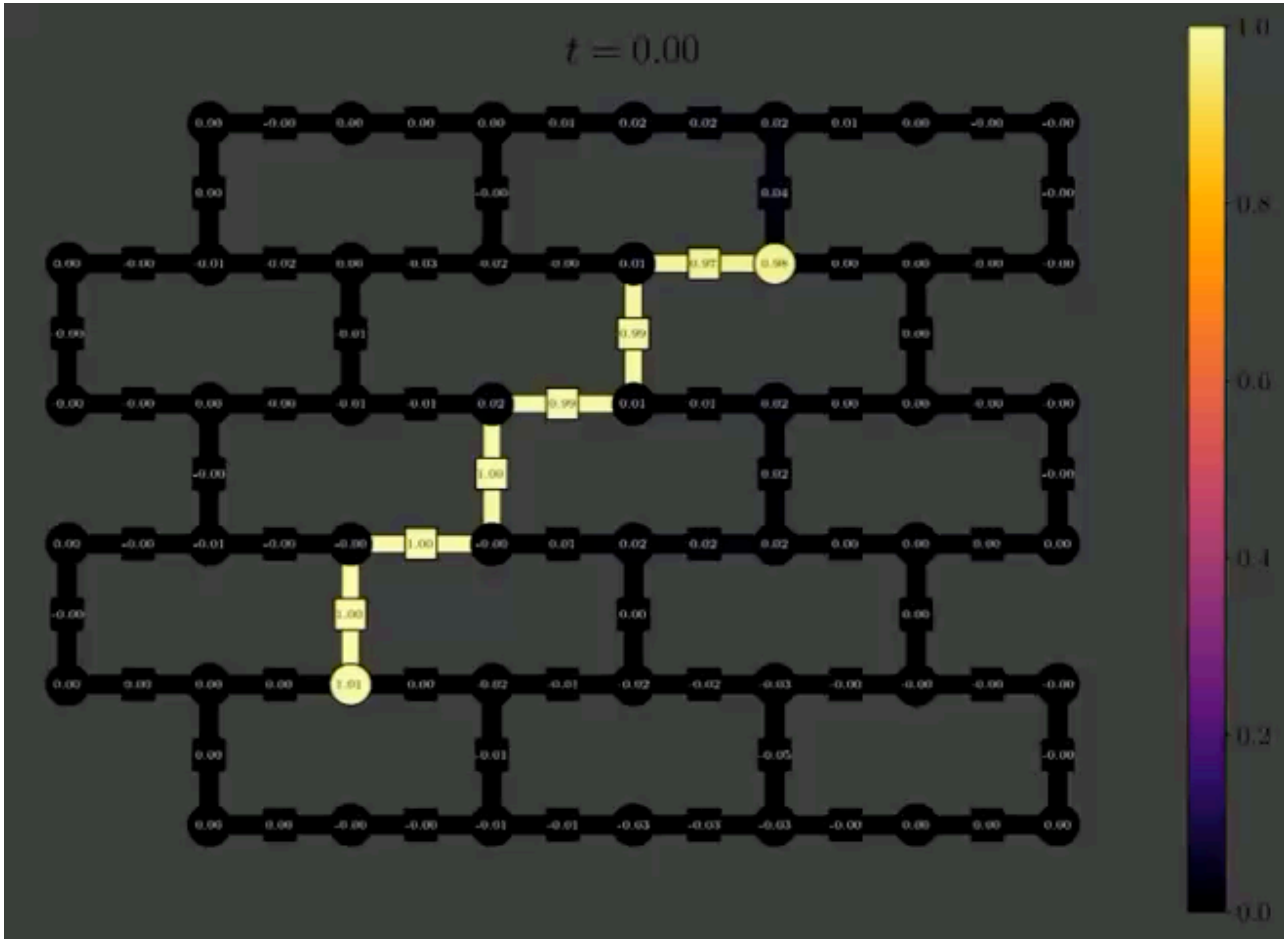

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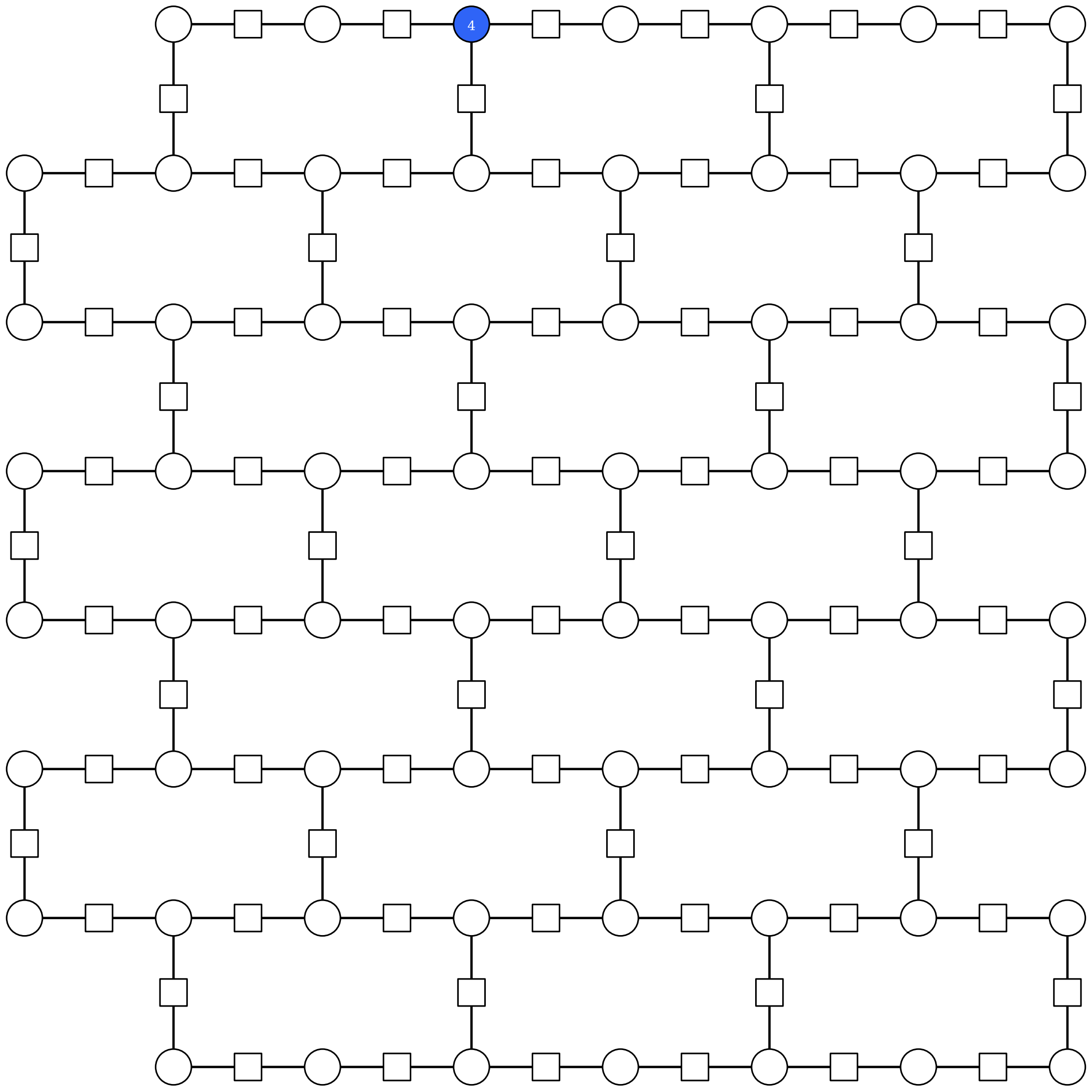
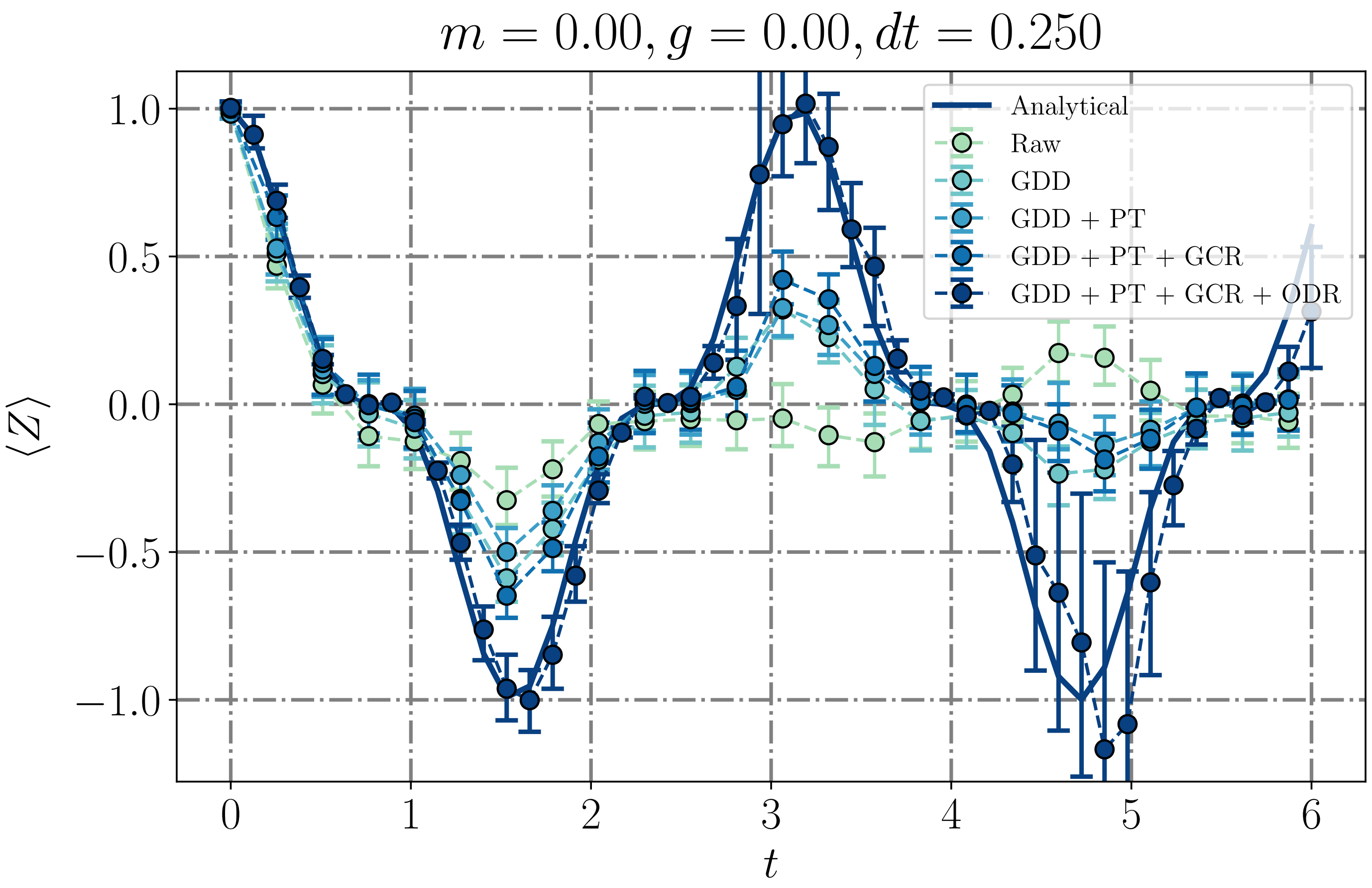
Quantum Real-Time Dynamics of the $\mathbb{Z}_2$ Higgs model

Customized error mitigation techniques:

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





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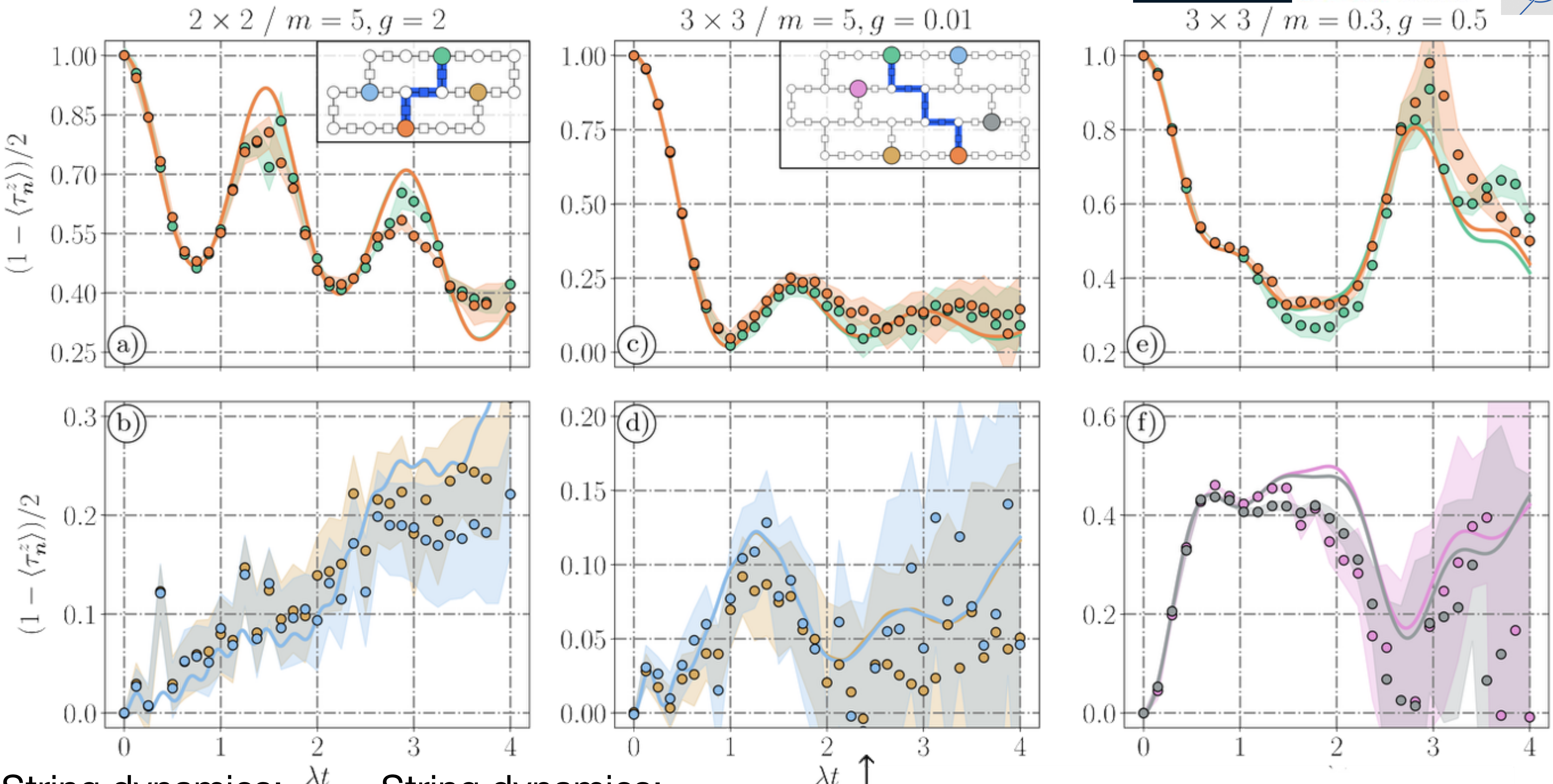
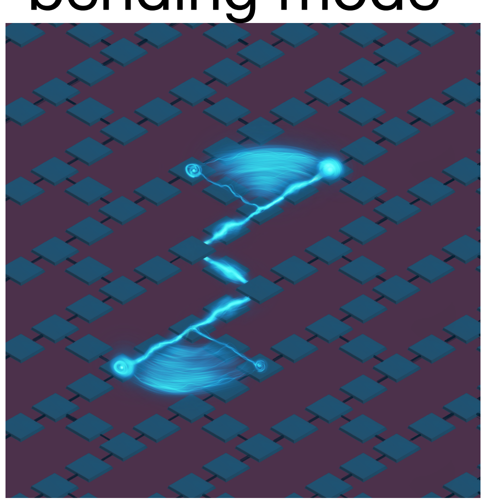
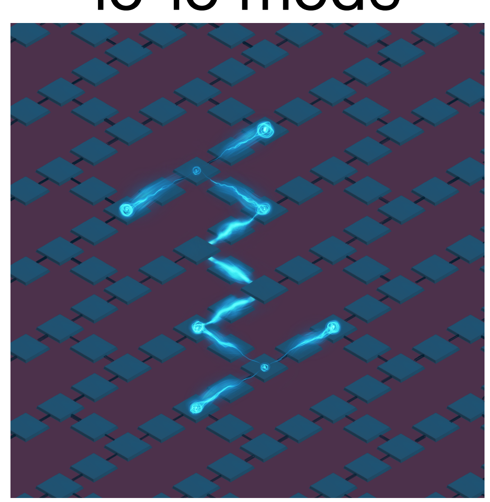
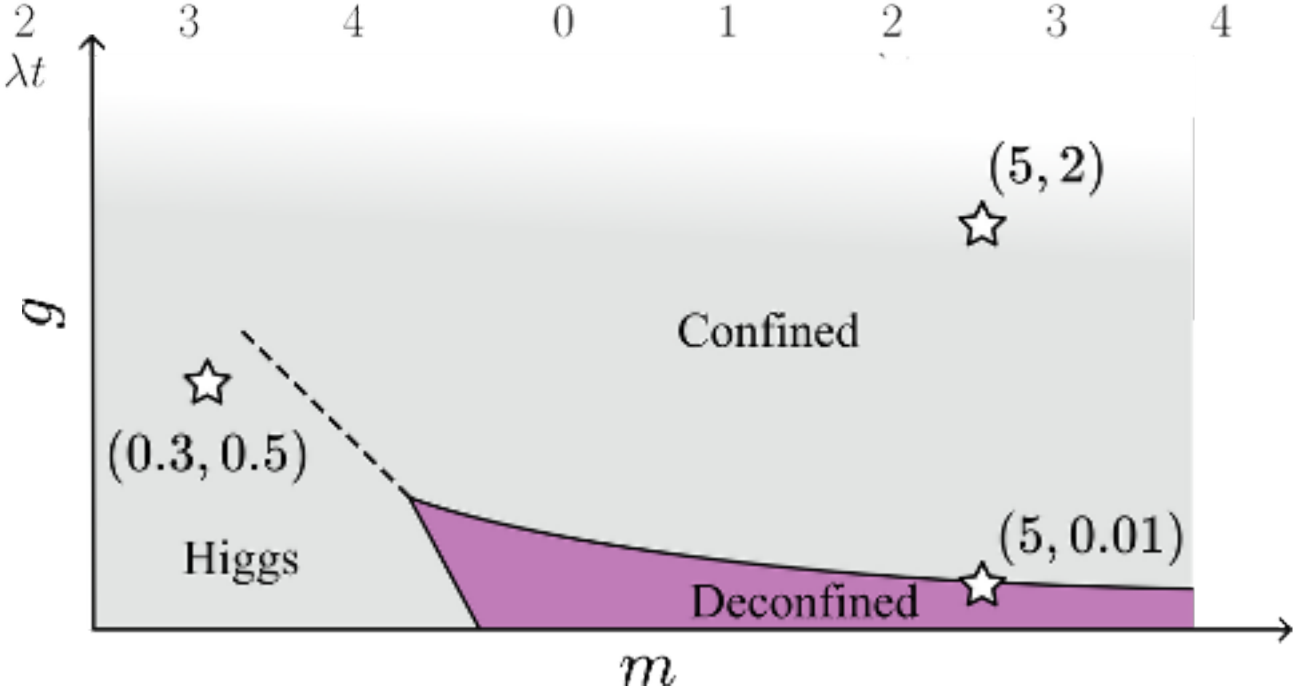


String dynamics: bending mode



String dynamics: io-io mode

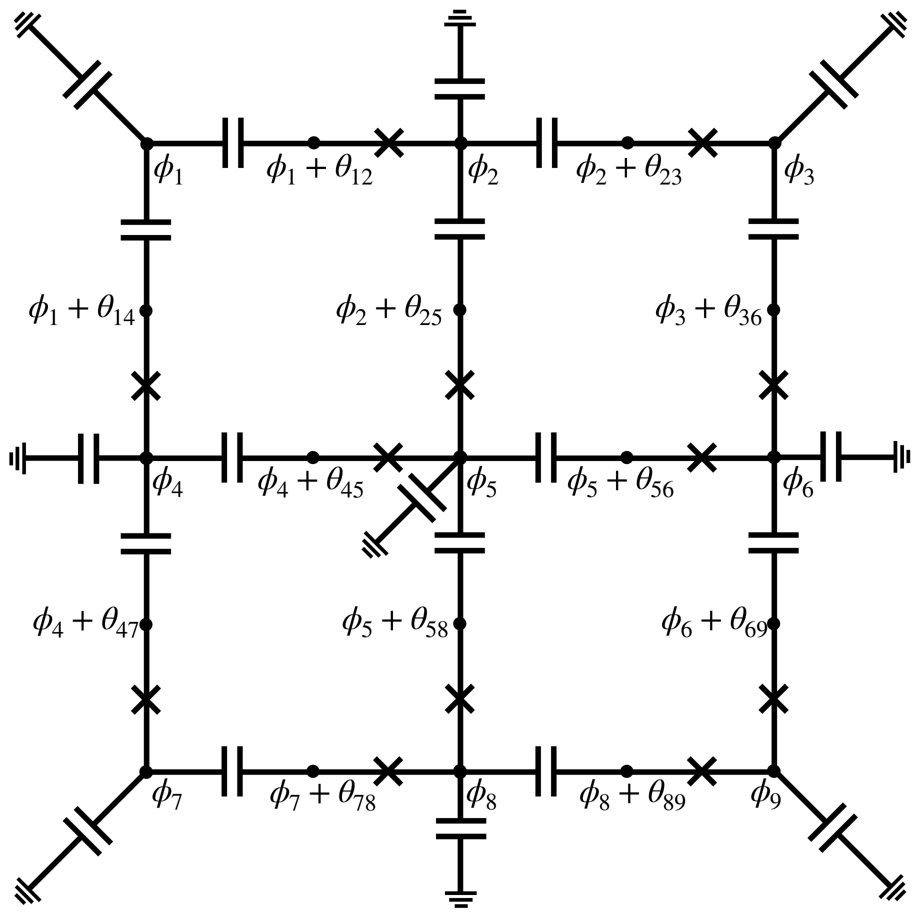




Native U(1) gauge theory

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

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



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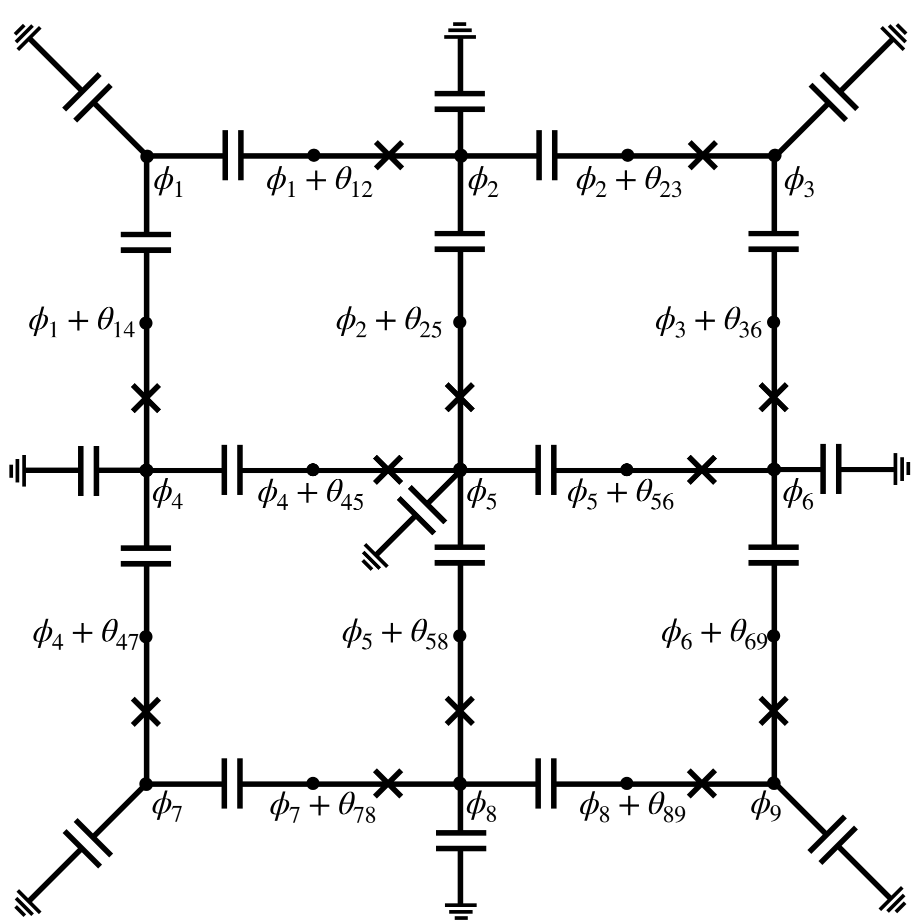

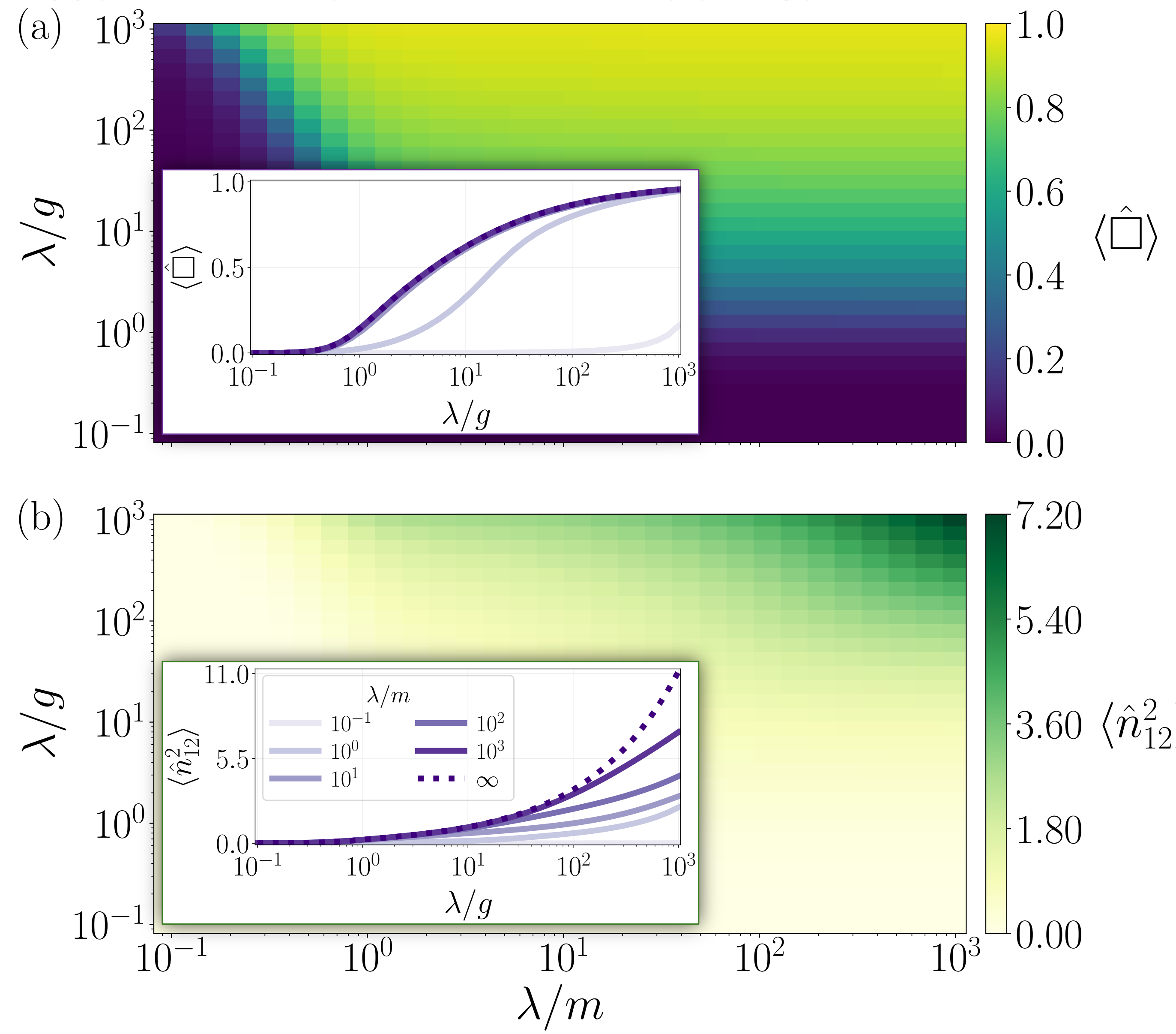

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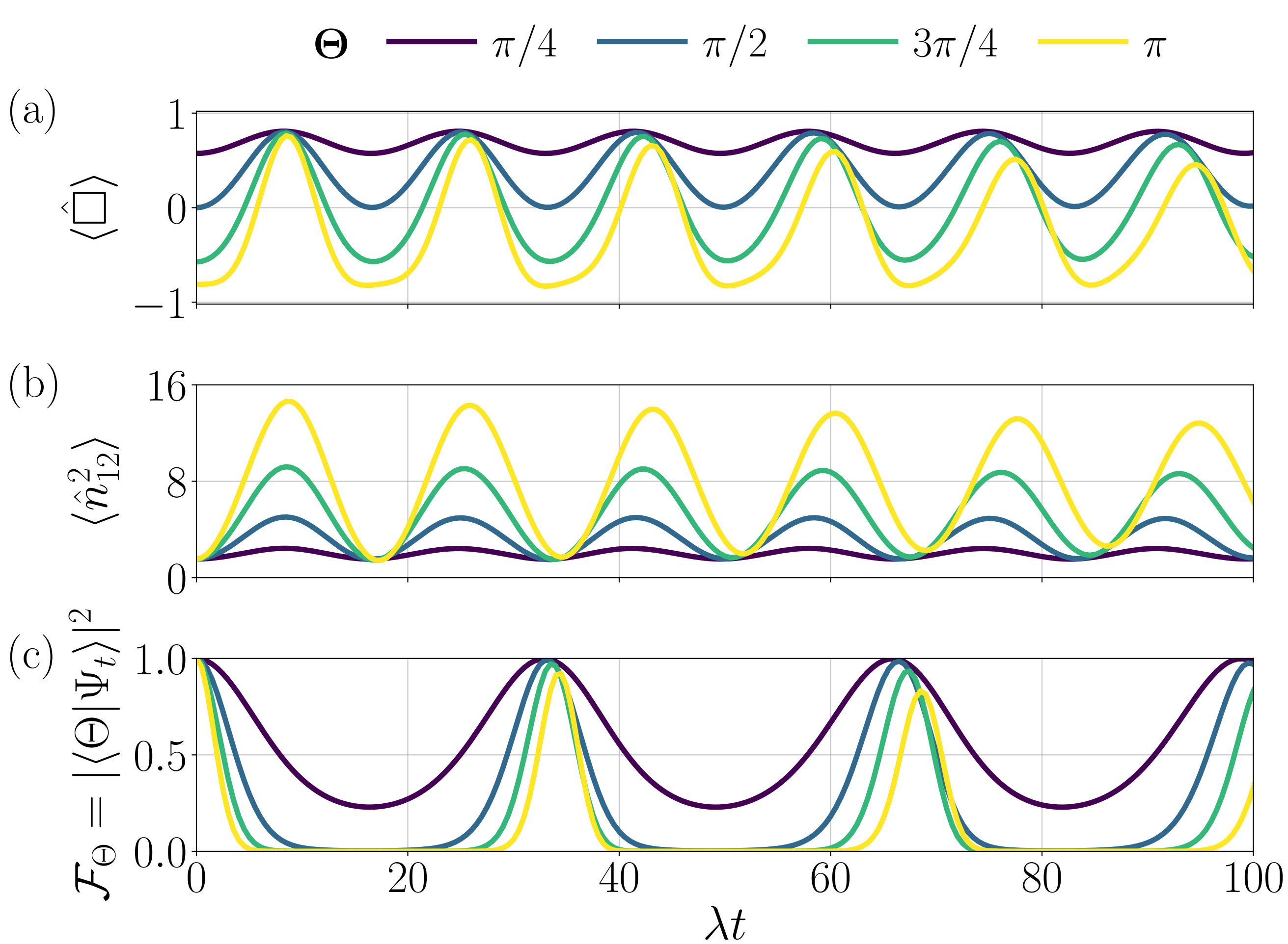
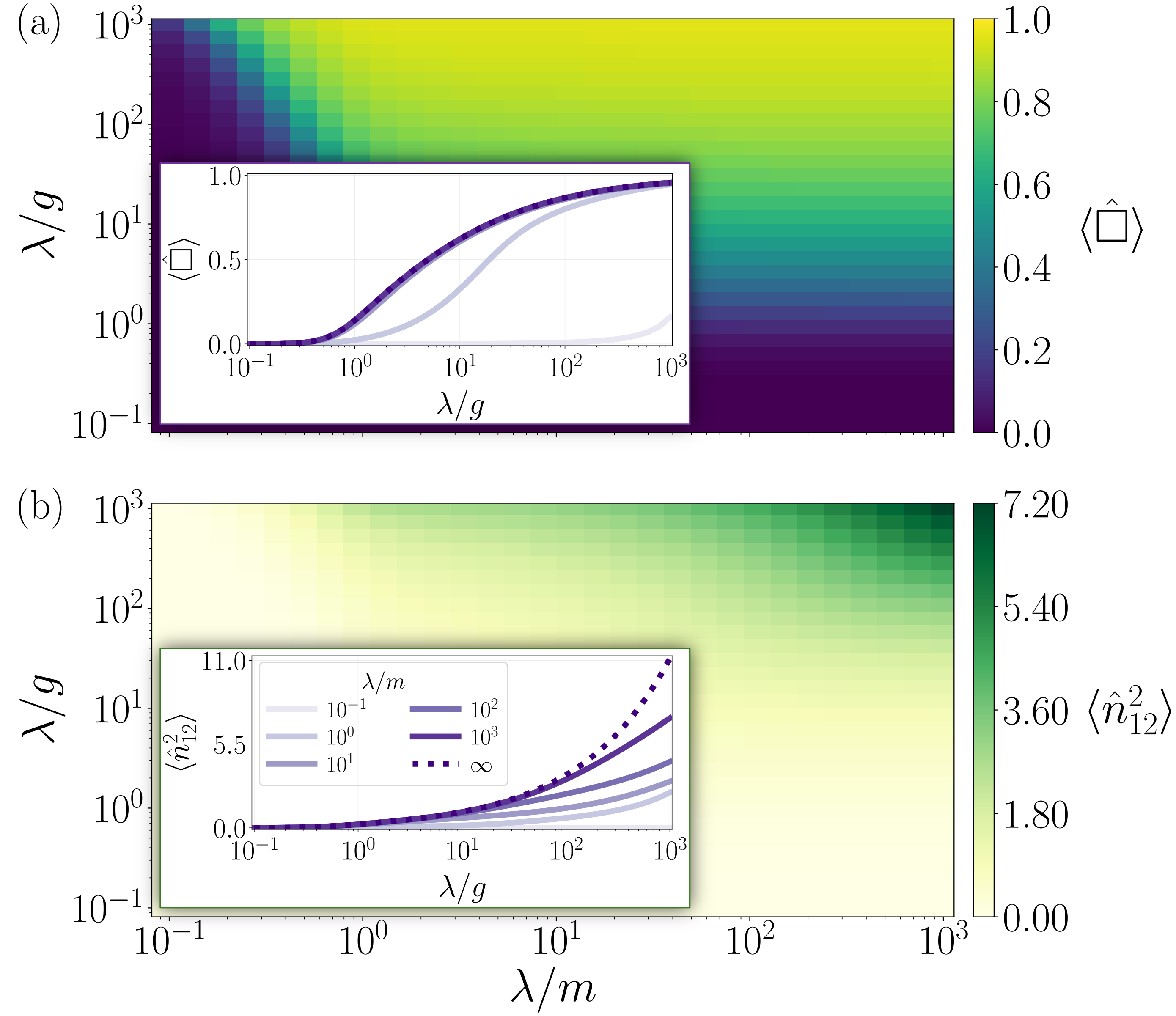
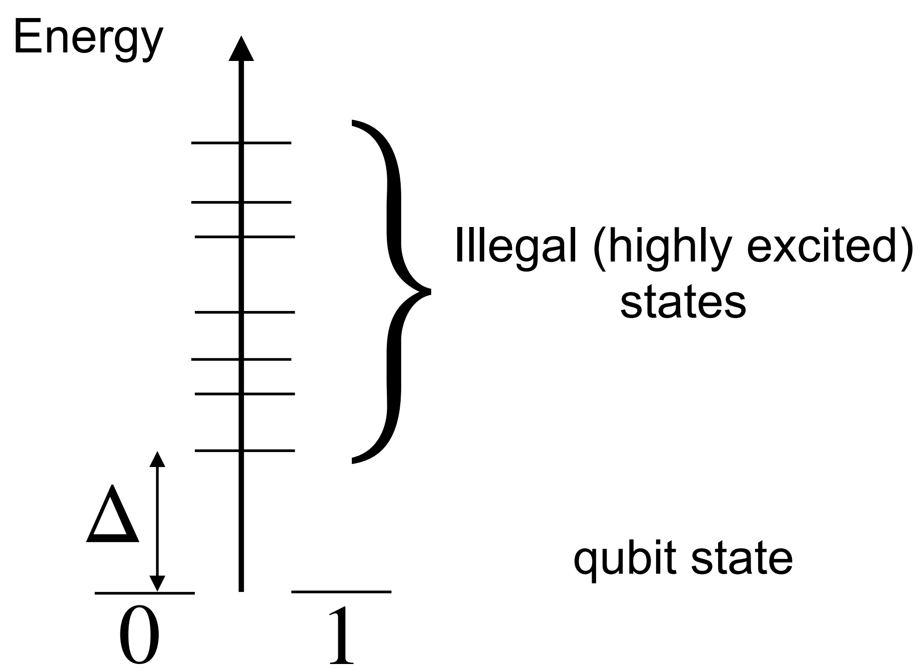




The role of the anomaly on decoherence robust qubits



Sources of decoherence: decay, dephasing, spin-flip

$$\hat{H} \propto \epsilon \mathbb{1}$$

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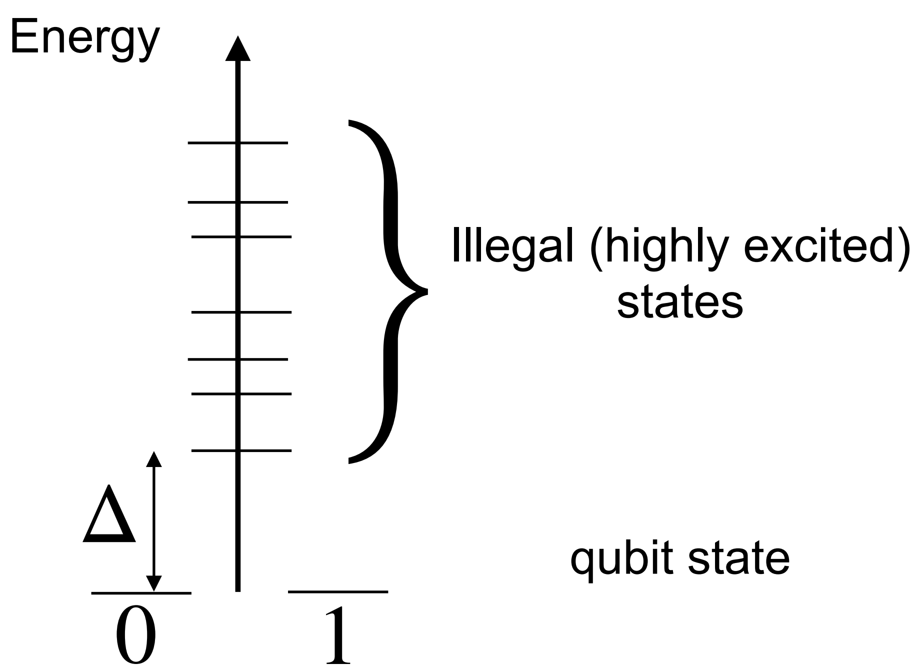

Sources of decoherence: decay, dephasing, spin-flip

$$\hat{H} \propto \epsilon \mathbb{I}$$

Qubit alive thanks to the anomaly

In quantum physics an anomaly or quantum anomaly appears when the symmetry of a classical theory is not equally represented by the quantum theory.

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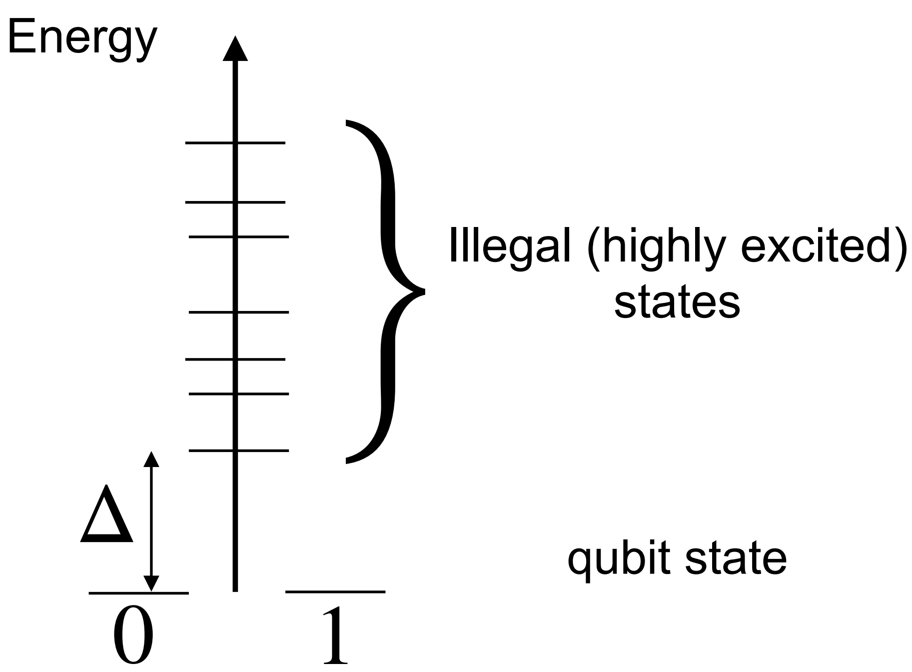

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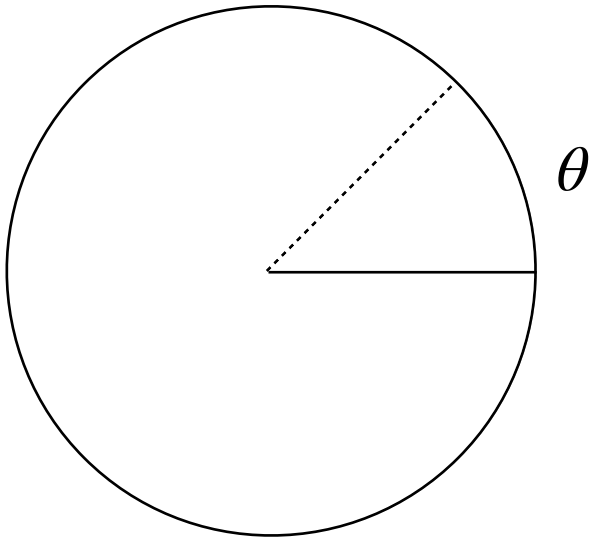
The degeneracies in the protected regime of the $0-\pi$ qubit
are a remnant of the anomalous symmetry.
Degeneracies independent of energy parameters

The role of the anomaly on decoherence robust qubits

Classical group symmetry of the ring



$$O(2) = SO(2) \times \mathbb{Z}_2$$

Rotation by any angle → $SO(2)$

Reflexion by an axis → $\mathbb{Z}_2$

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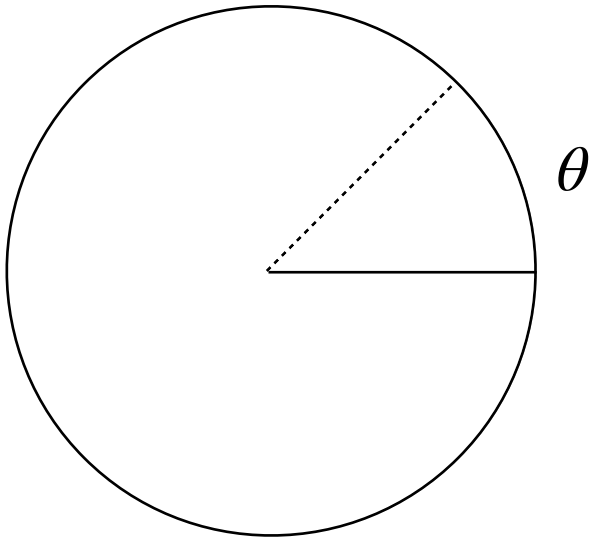

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Quantum particle on a ring

$$\hat{H} = E_c \left(\hat{n} - n_g\right)^2$$

Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $\quad SO(2) \sim U(1)$

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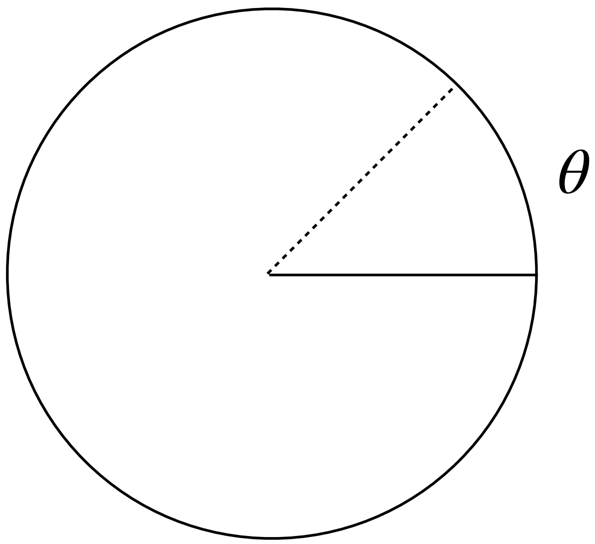

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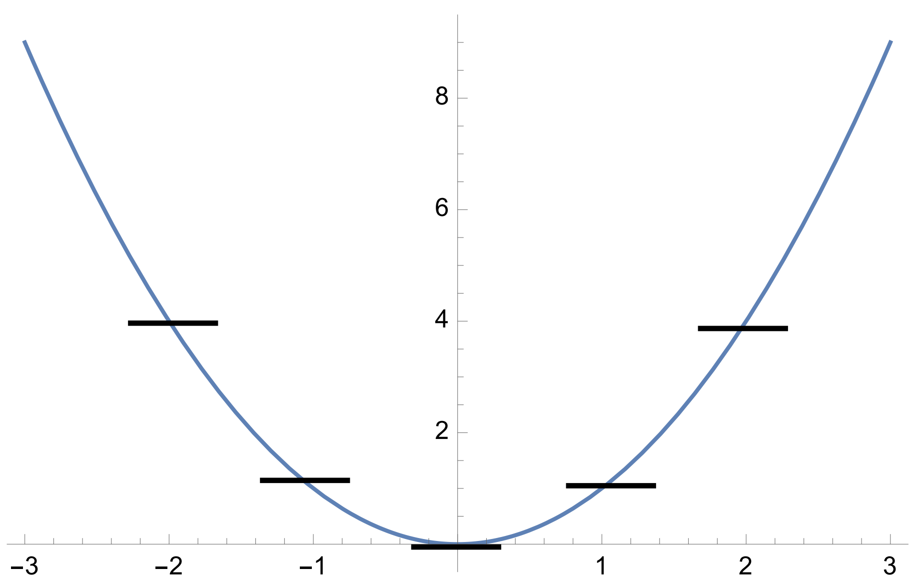
About the reflexion symmetry…

$$n_g = 0$$



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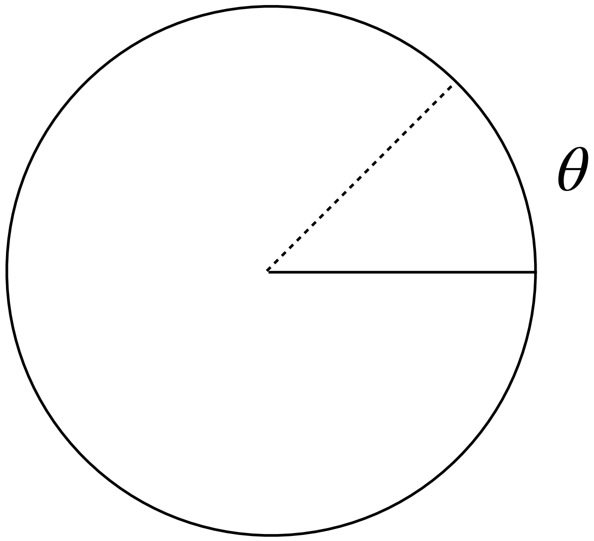

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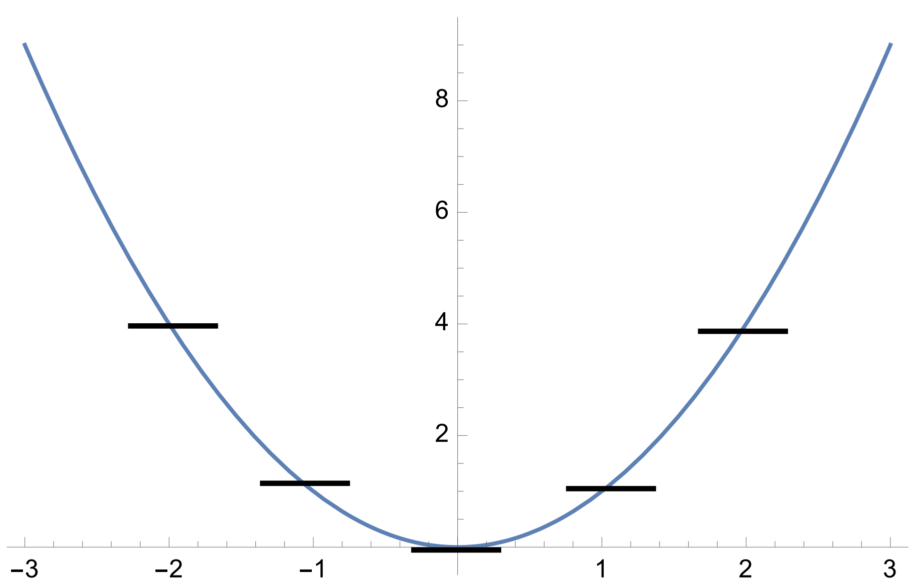

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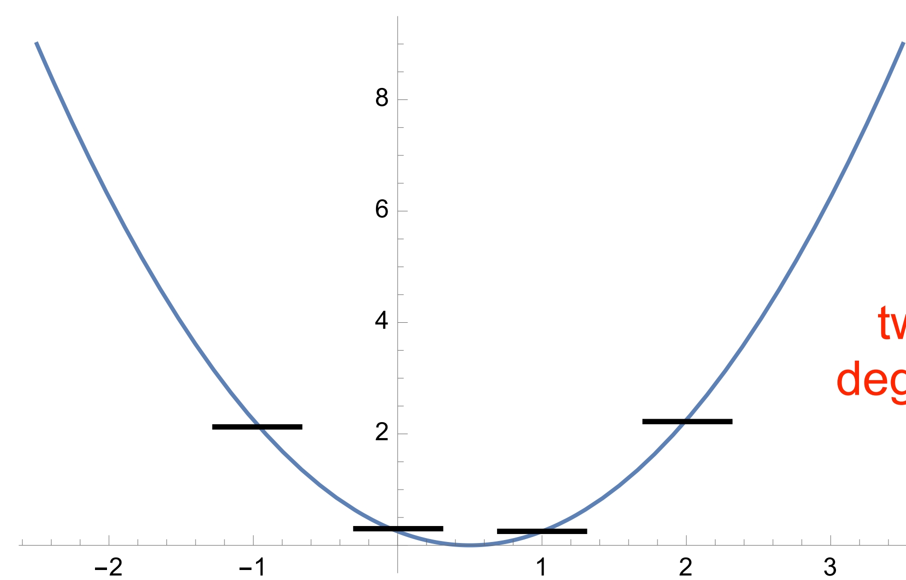
$n_g = 1/2$



two-fold degeneracy

anomalous realisation = projective representation
=double cover of $O(2)$

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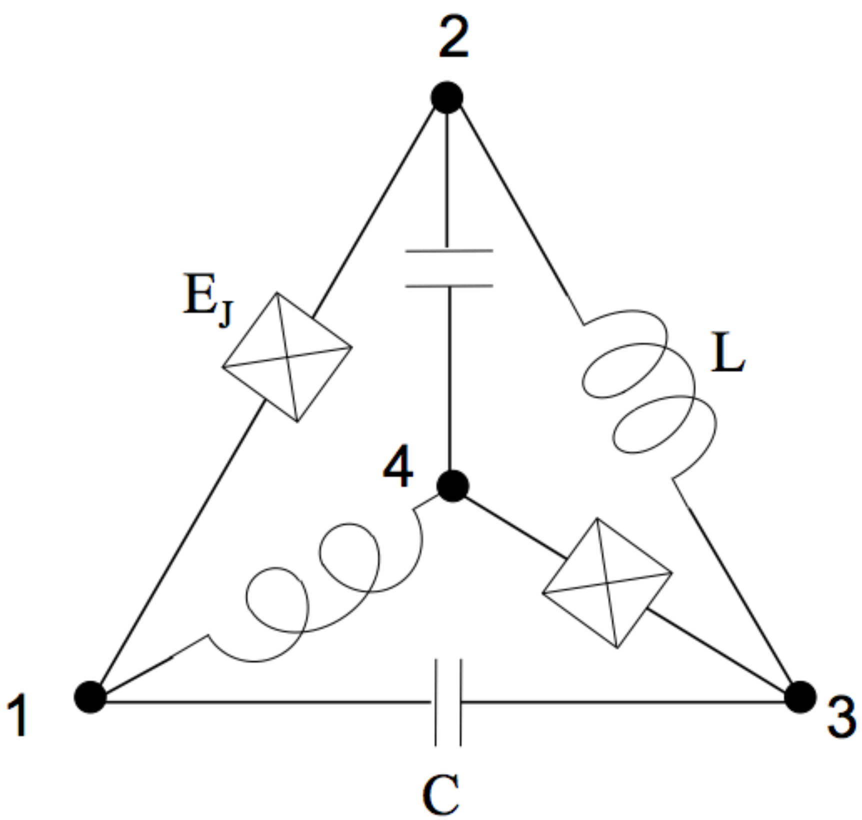
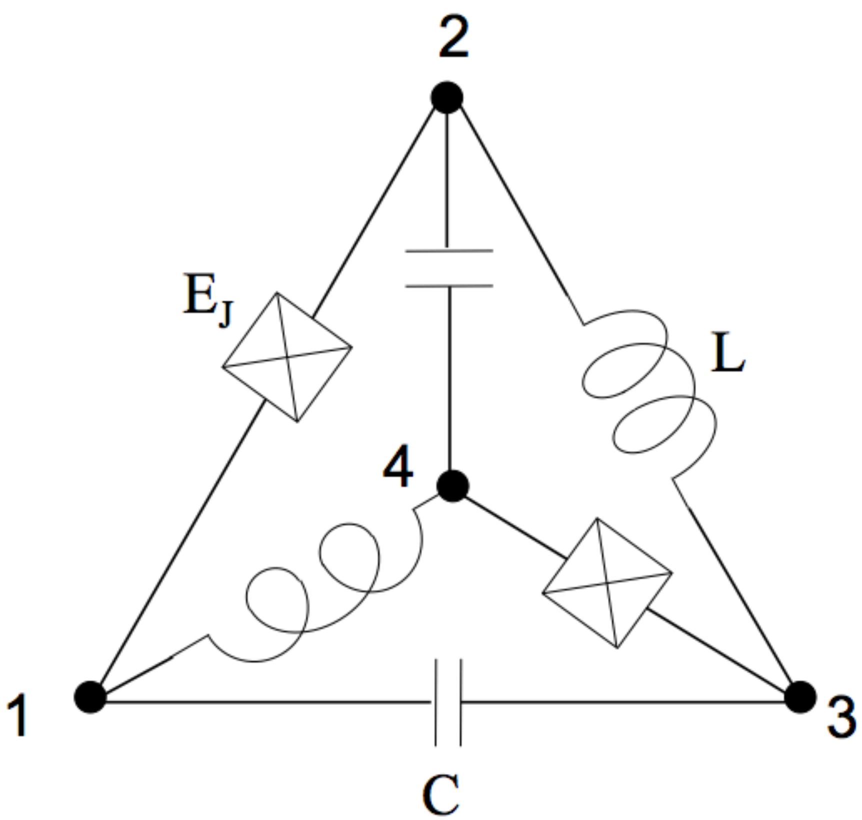


$0 - \pi$ Hamiltonian

$$H_{0-\pi} = 4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2 + 4E_{C_s}\left(\hat{n}_\theta - n_g\right)^2 - 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{ext}}{2}\right)$$

The role of the anomaly on decoherence robust qubits



$0 - \pi$ Hamiltonian

harmonic oscillator — diagonal — interaction

$$H_{0-\pi} = \underbrace{4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2}_{\text{harmonic oscillator}} + 4E_{C_s}\underbrace{\left(\hat{n}_\theta - n_g\right)}_{\text{diagonal}}^2 - 2E_J \cos\hat{\theta}\underbrace{\cos}_{\text{interaction}}\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)$$

$$\left[\hat{\theta}, \hat{n}_\theta\right] = i \qquad \theta \in (-\pi, +\pi] \qquad \text{spect}\left(\hat{\mathrm{n}}\right) \in \mathbb{Z}$$

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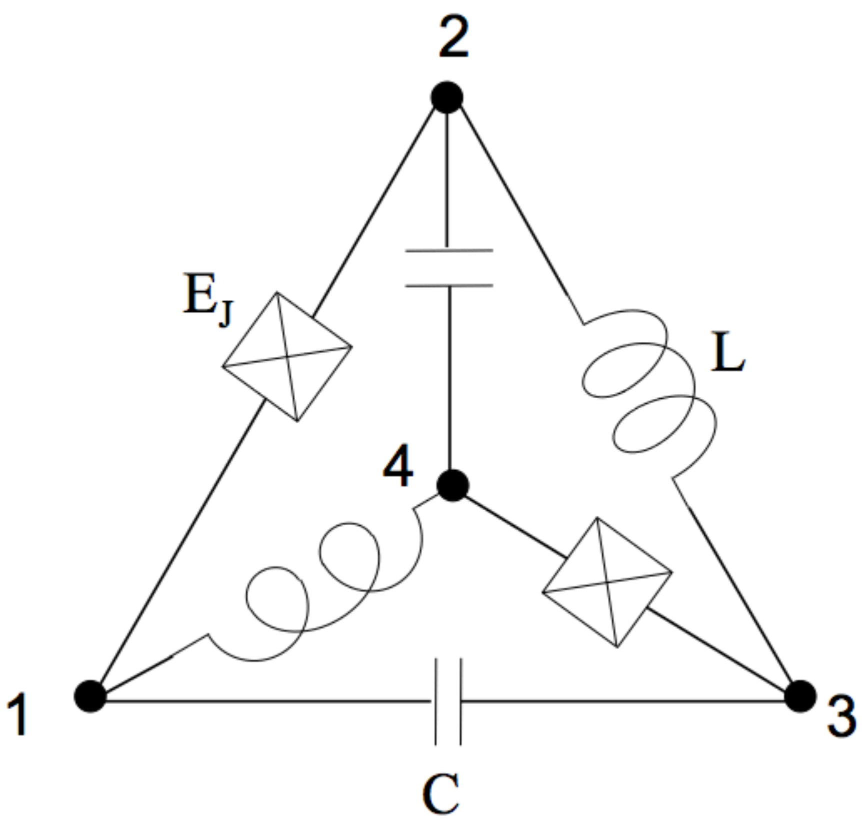

high symmetry point

$$n_g = 1/2,\ \varphi_{\text{ext}} = \pi$$

$$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P \qquad \begin{aligned} n_\theta &\to 1 - n_\theta \\ \theta &\to -\theta \end{aligned}$$

$$\hat{U}_\pi = e^{i\hat{n}_\theta \pi}\hat{P}_\phi \qquad \begin{aligned} \theta &\to \theta + \pi \\ \phi &\to -\phi \end{aligned}$$

$$\hat{V}_P\hat{U}_\pi = -\hat{U}_\pi\hat{V}_P$$

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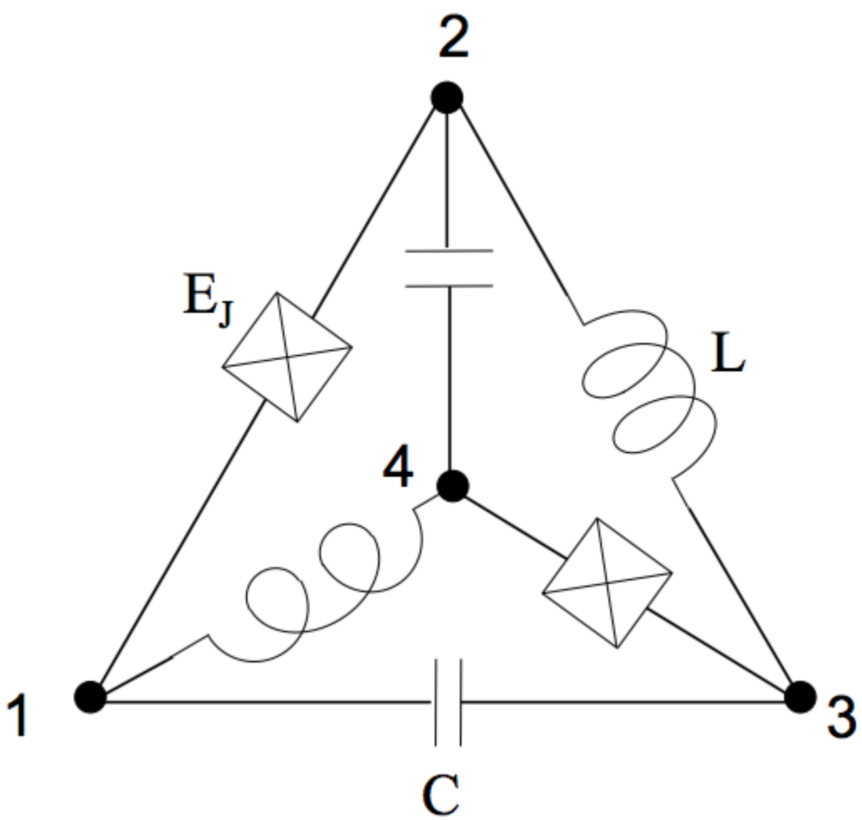

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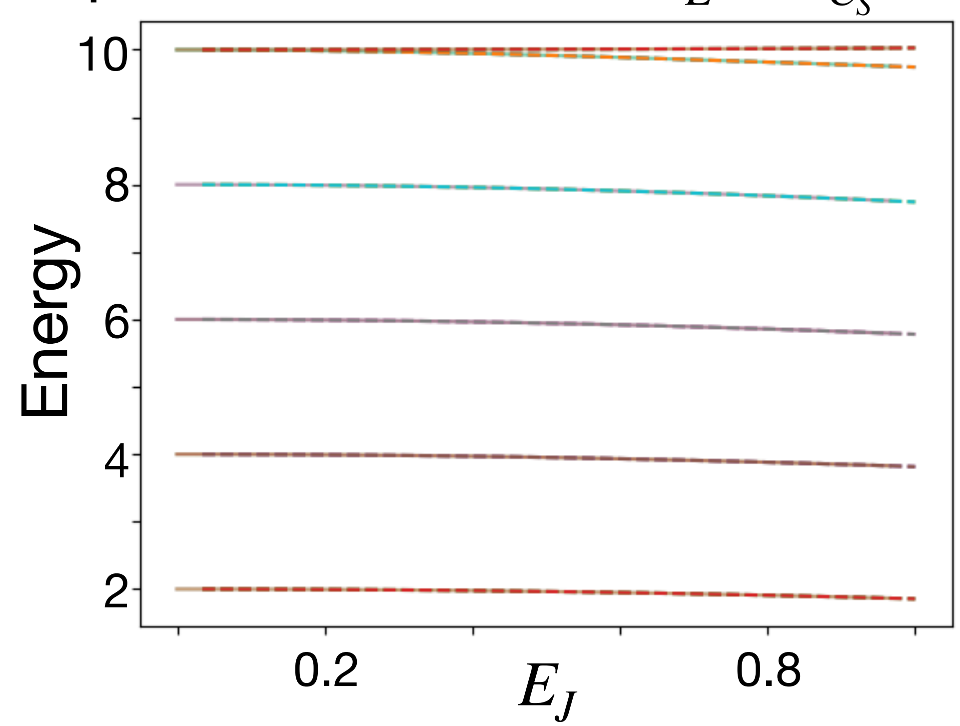
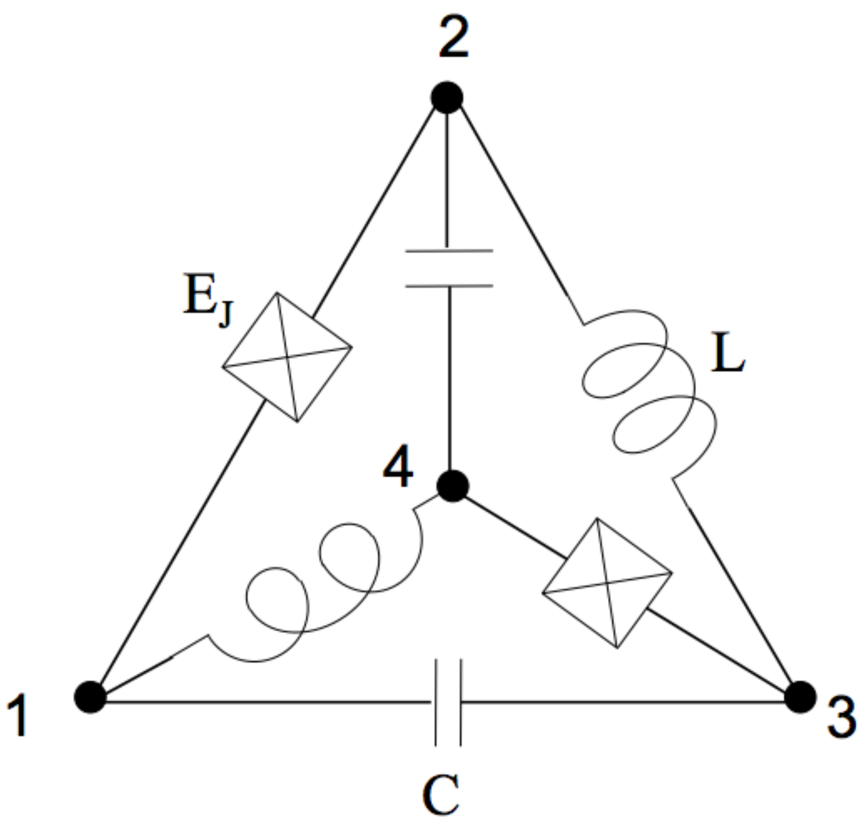
Spectrum in units of $E_L = E_{C_S} = E_{C_J}$



the whole spectrum is two-fold degenerate independent of any energy scales

The role of the anomaly on decoherence robust qubits



$0\text{-}\pi$ Hamiltonian

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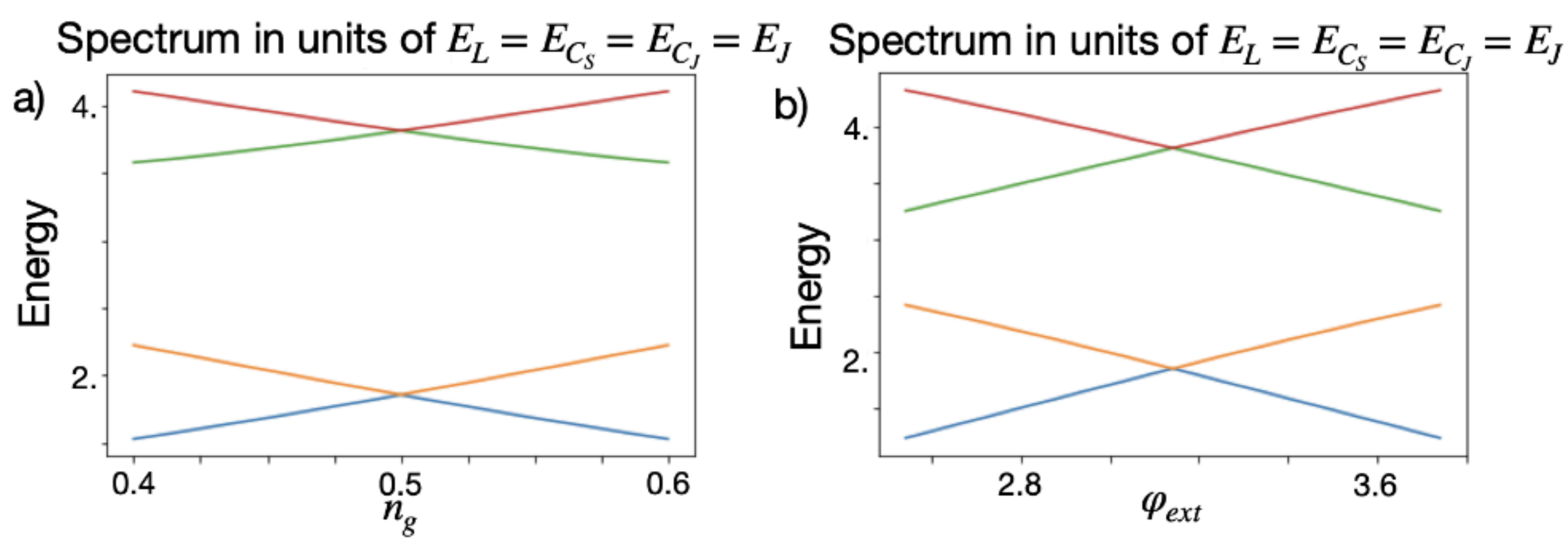

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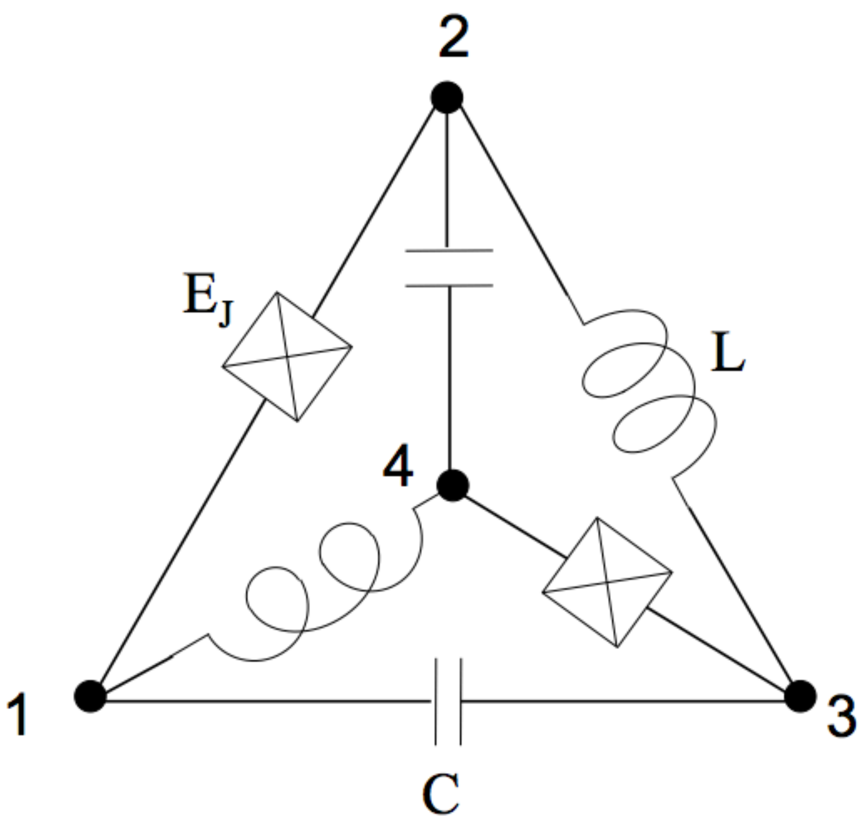

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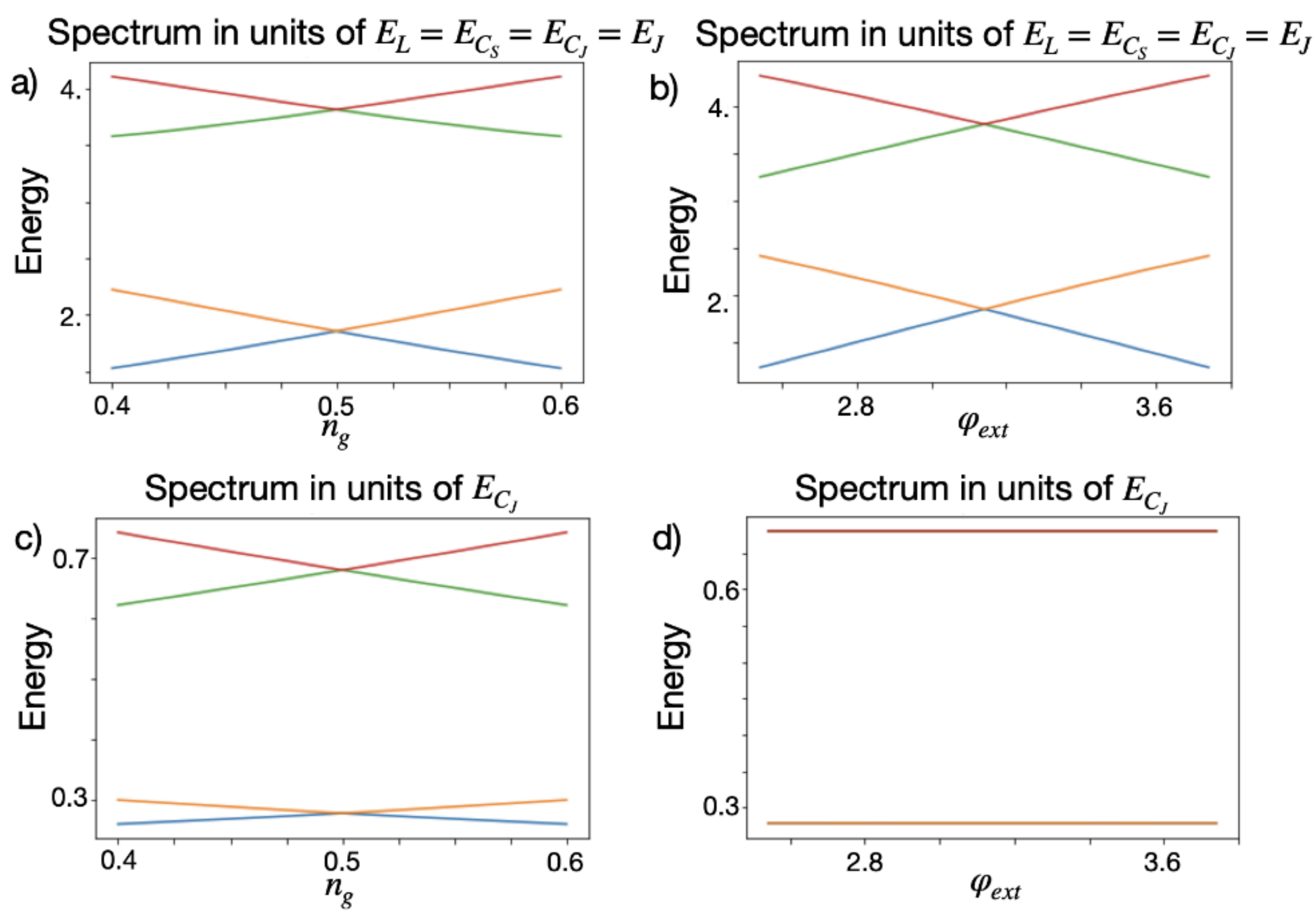
$$E_{C_J}^2 \gg E_{C_J}E_L \gg E_J^2 \gg E_{C_J}E_{C_s}$$



Hardware-native dynamical gauge simulation and protected qubits

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

Jesús Cobos, Joana Fraxanet, César Benito, Francesco di Marcantonio, Pedro Rivero, Kornél Kapás, Miklós Antal Werner, Örs Legeza, Alejandro Bermudez, Enrique Rico

arXiv:2507.08088

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

J. M. Alcaine-Cuervo, S. Pradhan, E. Rico, Z. Shi, C. M. Wilson

arXiv:2601.23150

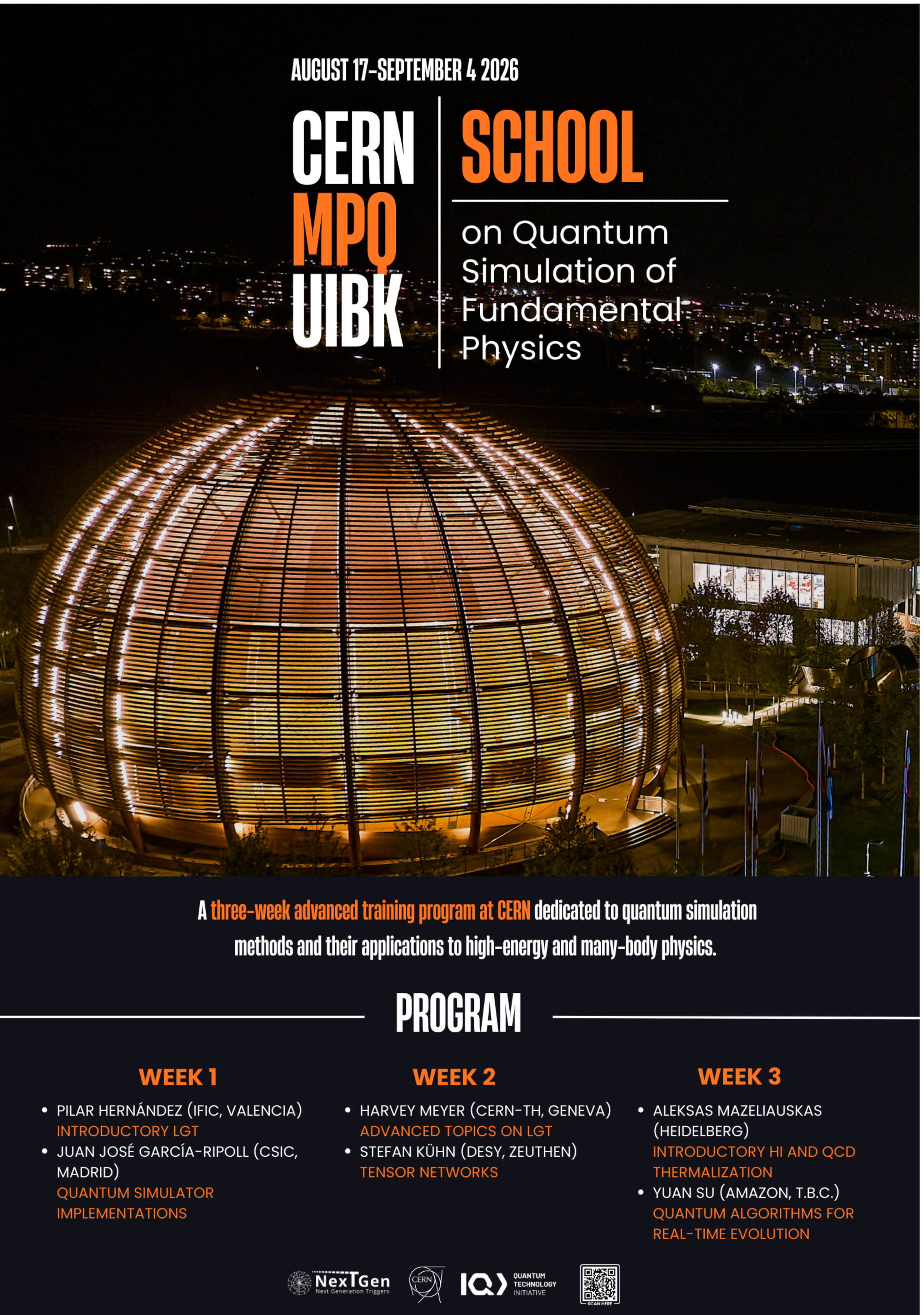
Role of anomalous symmetry in 0–π qubits

I.L. Egusquiza, A. Iñiguez, E. Rico, A. Villarino

arXiv:2109.11824

CERN-MPQ-UIBK School on Quantum Simulation of Fundamental Physics

August 17, 2026 to September 4, 2026
CERN
Europe/Zurich timezone



First week.-
- Pilar Hernández (IFIC, Valencia) — Introductory LGT
- Juan José García-Ripoll (CSIC, Madrid) — Quantum simulator implementations

Second week.-
- Harvey Meyer (CERN-TH, Geneva) — Advanced topics on LGT
- Stefan Kühn (DESY, Zeuthen) — Tensor networks

Third week.-
- Aleksas Mazeliauskas (Heidelberg) — Introductory HI and QCD thermalization
- Yuan Su (Amazon, t.b.c.) — Quantum algorithms for real-time evolution