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# Two-way communication between High-Energy Physics and Quantum Technologies

Enrique Rico Ortega
Thursday, 28/03/2024

Theory Colloquia

A Two-Way Communication Between High-Energy Physics and Quantum Technologies

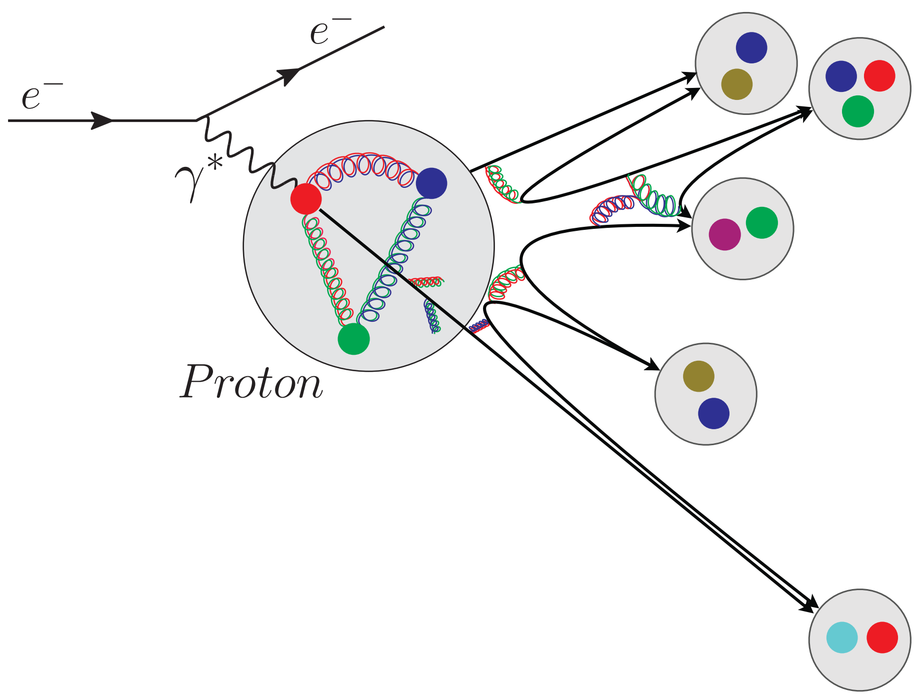
by Enrique Rico Ortega

Thursday Mar 28, 2024, 11:00 AM → 12:00 PM Europe/Zurich

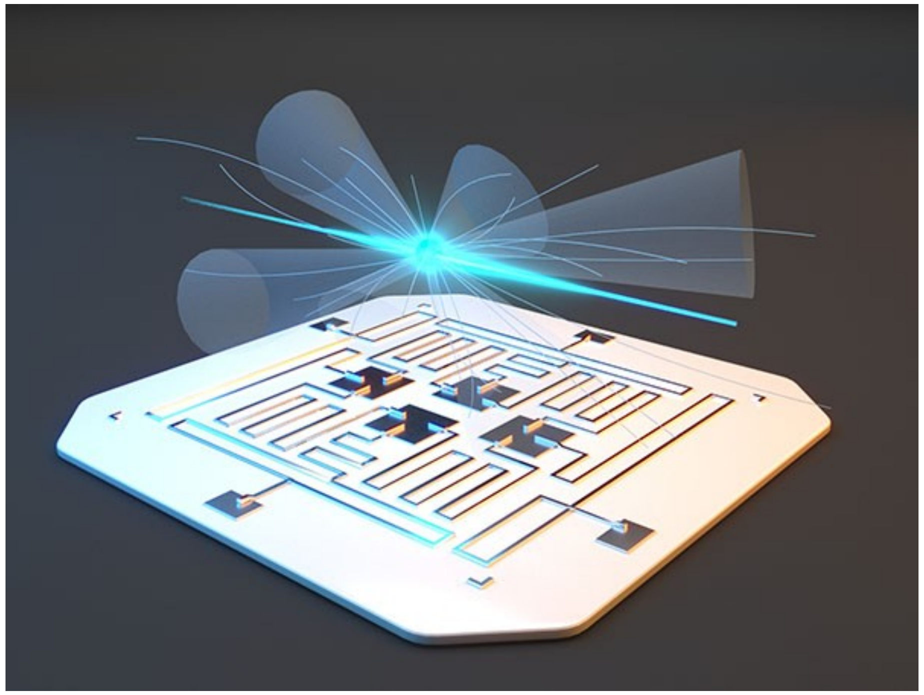
4/3-006 - TH Conference Room (CERN)

CERN

# A fruitful dialogue (two-way communication)




High-Energy and Nuclear Physics



Quantum Information Science and Technology

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# A fruitful dialogue (two-way communication)

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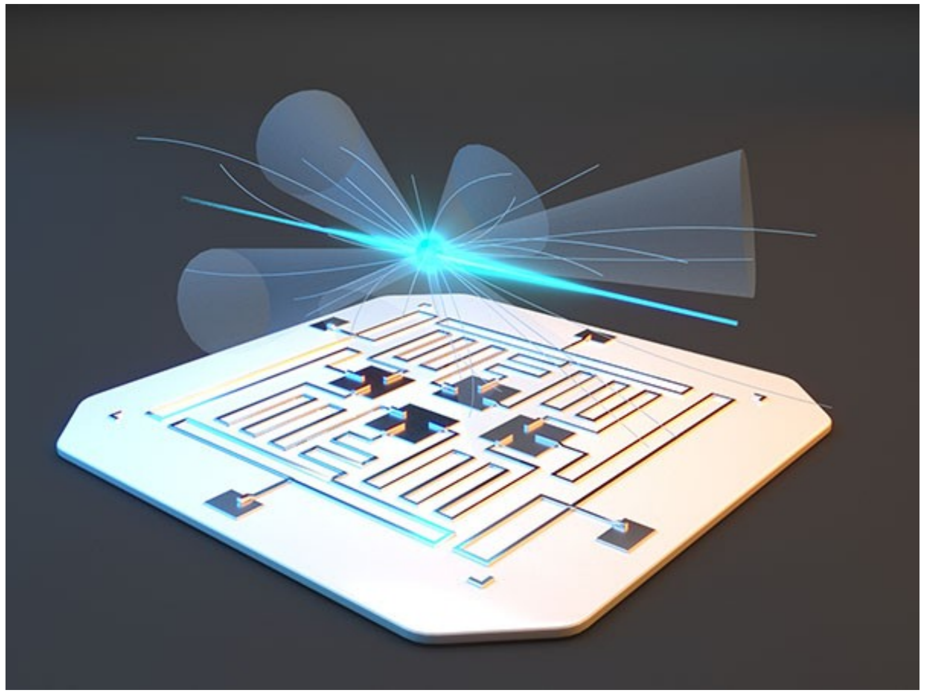
Simulating lattice gauge theories within quantum technologies



Collaborators: M. Dalmonte, S. Montangero, U.-J. Wiese, P. Zoller…

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]

# A fruitful dialogue (two-way communication)

**Quantum Simulation for High Energy Physics**
C.W. Bauer, Z. Davoudi, A.B. Balantekin, T. Bhattacharya, M. Carena, W.A. de Jong, P. Draper, A. El-Khadra, N. Gemelke, M. Hanada, D. Kharzeev, H. Lamm, Y.-Y. Li, J. Liu, M. Lukin, Y. Meurice, C. Monroe, B. Nachman, G. Pagano, J. Preskill, E. Rinaldi, A. Roggero, D.I. Santiago, M.J. Savage, I. Siddiqi, G. Siopsis, D. Van Zanten, N. Wiebe, Y. Yamauchi, K. Yeter-Aydeniz, S. Zorzetti
PRX Quantum 4, 027001, (2023)

**Lattice gauge theories simulations in the quantum information era**
M. Dalmonte, S. Montangero
Contemporary Physics 57, 388 (2016)

**Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices**
E. Zohar, J.I. Cirac, B. Reznik
Rep. Prog. Phys. 79, 014401 (2016)

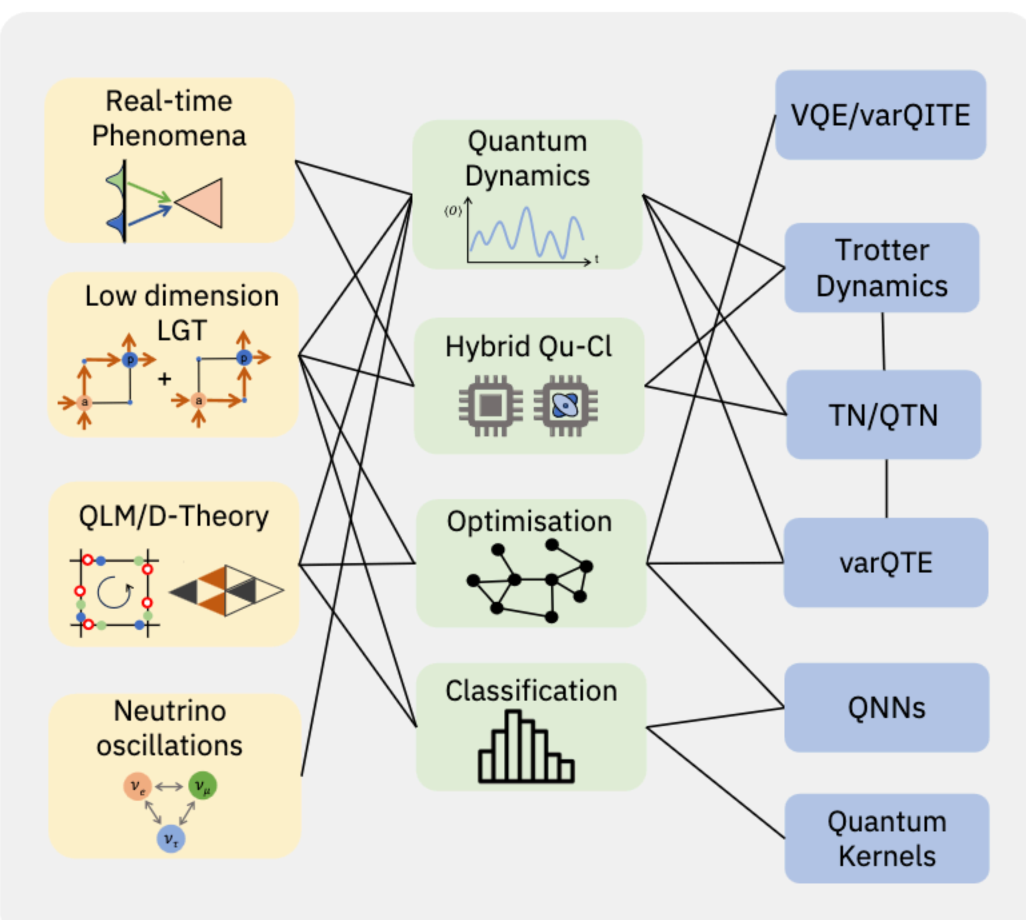
**Towards Quantum Simulating QCD**
U.-J. Wiese
Nucl.Phys. A931, 246-256 (2014)

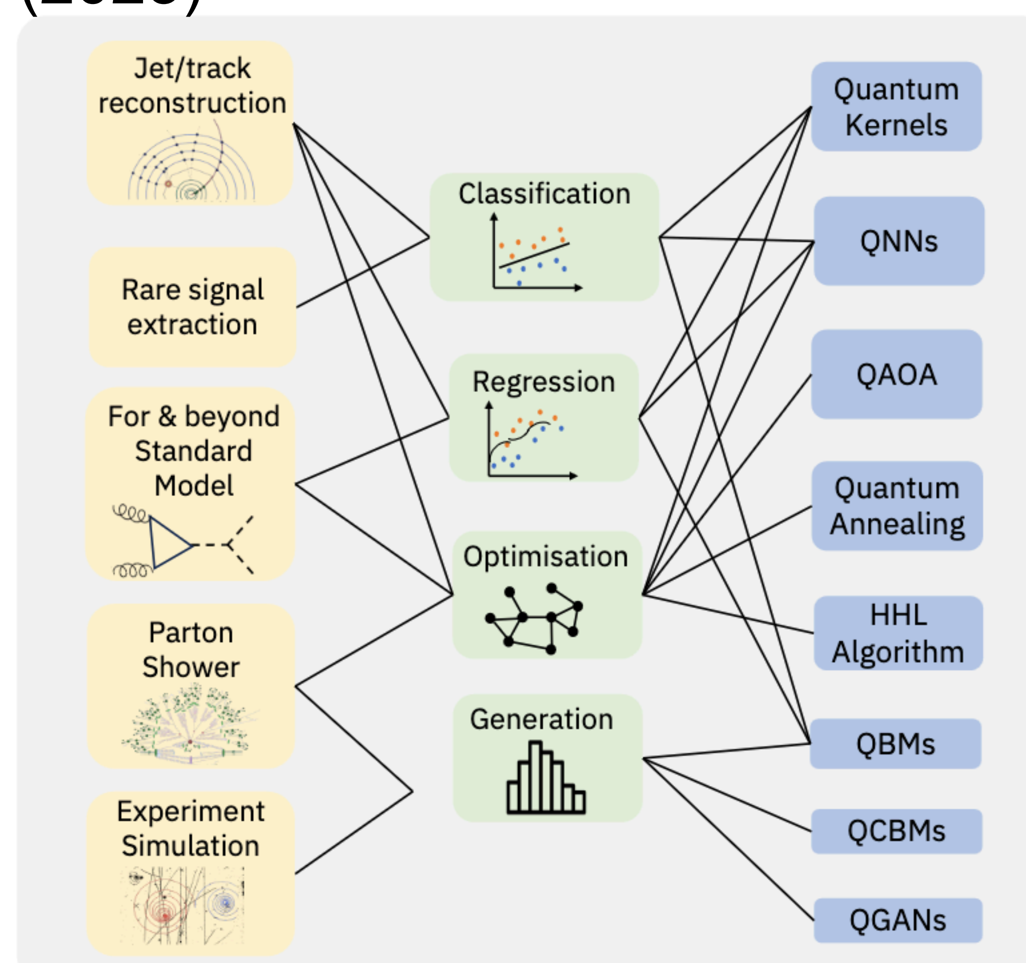
# A fruitful dialogue
# (two-way communication)

## Quantum Computing for High-Energy Physics
## State of the Art and Challenges
## Summary of the QC4HEP Working Group

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[5,3] Srinivasan Arunachalam,[6] Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[10,1] 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,[25,26,1] Miriam Lucio Martinez,[27,28] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[25,26] Lento Nagano,[29] Voica Radescu,[30] Enrique Rico Ortega,[31,32,33,34] Alessandro Roggero,[35,36] Julian Schuhmacher,[4] Joao Seixas,[37,38,39] Pietro Silvi,[25,26] Panagiotis Spentzouris,[40] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[29] Jordi Tura,[12,41] Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[42] Shinjae Yoo,[43] and Jinglei Zhang[44,45]

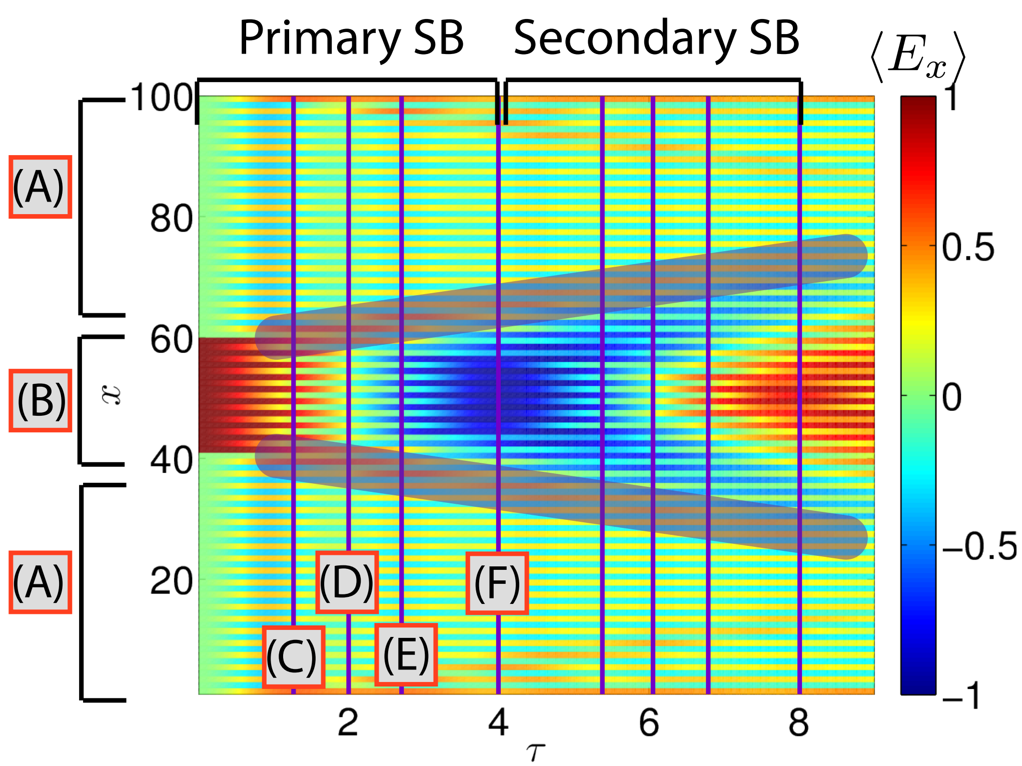
arXiv:2307.03236 (2023)



# Three (take-home) messages

## Tensor network algorithms: dynamical string breaking and hadronization



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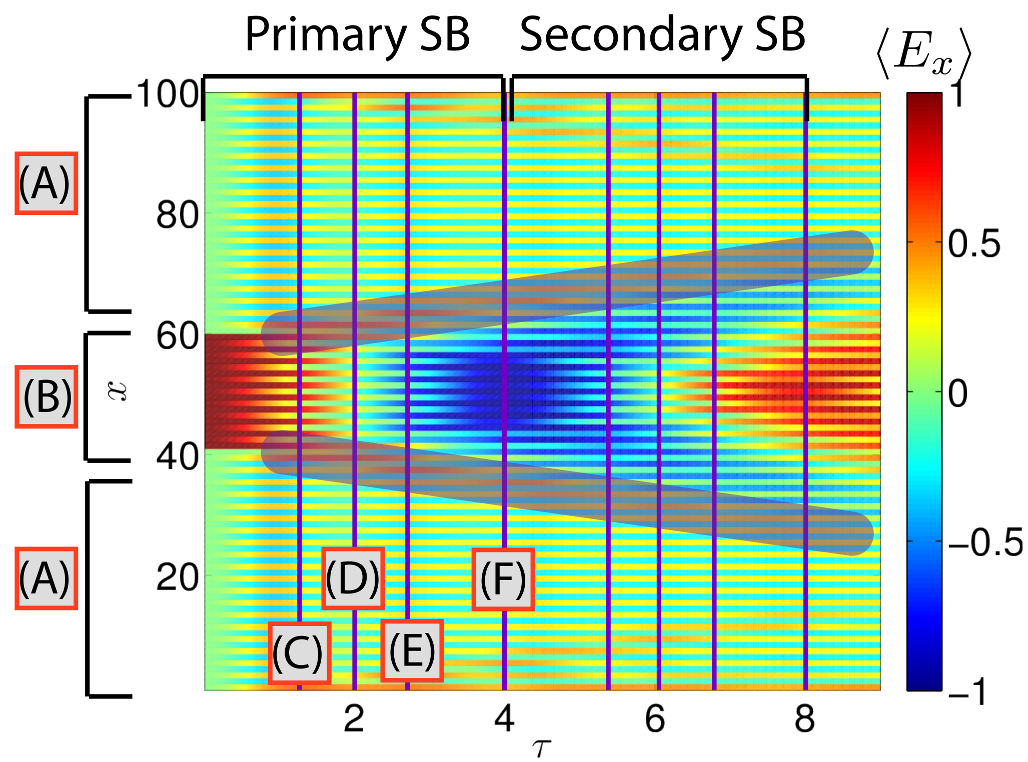


## Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

$$f_{f/P}(\xi) = \sum_S \int \frac{dy^-}{2\pi} e^{-i\xi p^+ y^-} \langle PS | \left[\bar{\psi}\mathcal{U}\right](y^-) \frac{\gamma^+}{2} \left[\mathcal{U}^\dagger \psi\right](0) | PS \rangle$$

We show how to quantum simulate non-local Wilson loops in space and real-time

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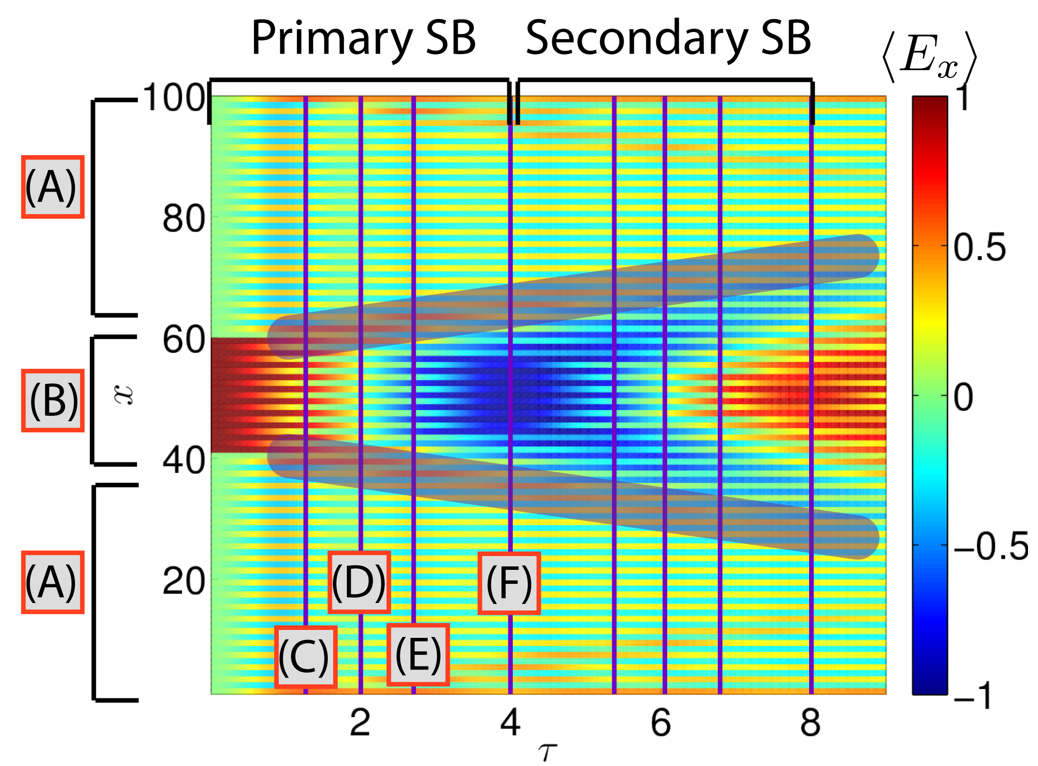
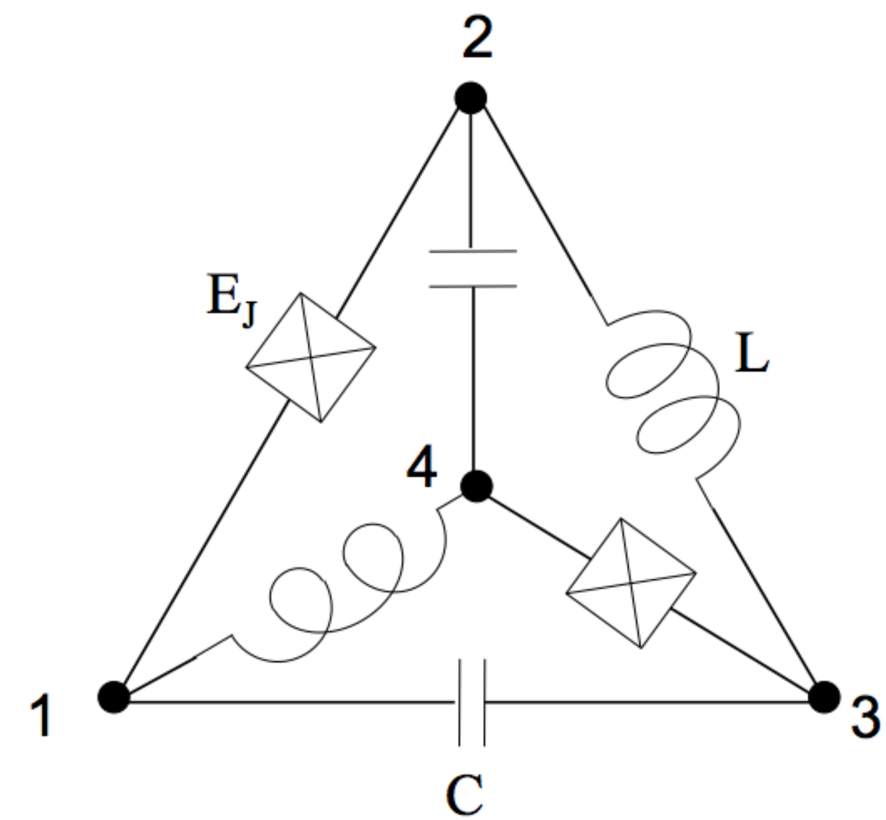



## The role of the anomaly on decoherence robust qubits

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# Three ingredients to describe Nature

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- Quantum matter as the basic building block

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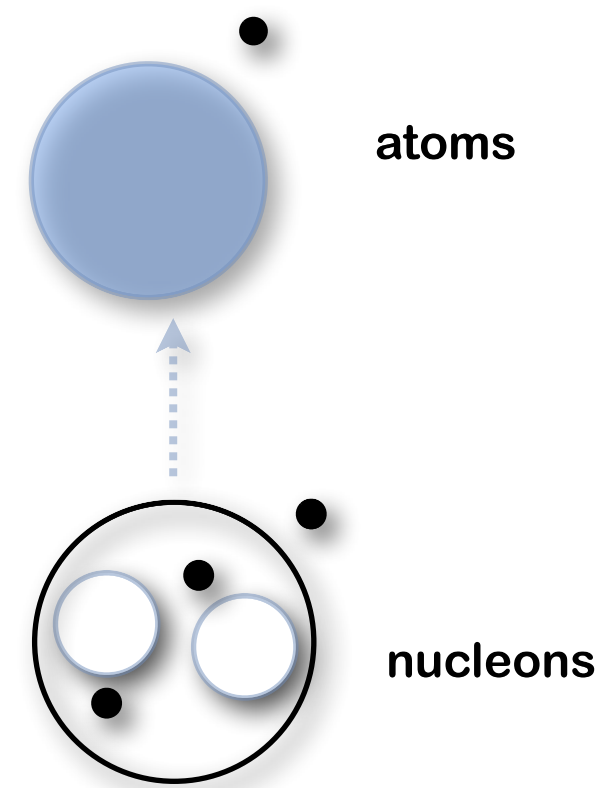
- Gauge symmetry as a fundamental principle and at the origin of every force

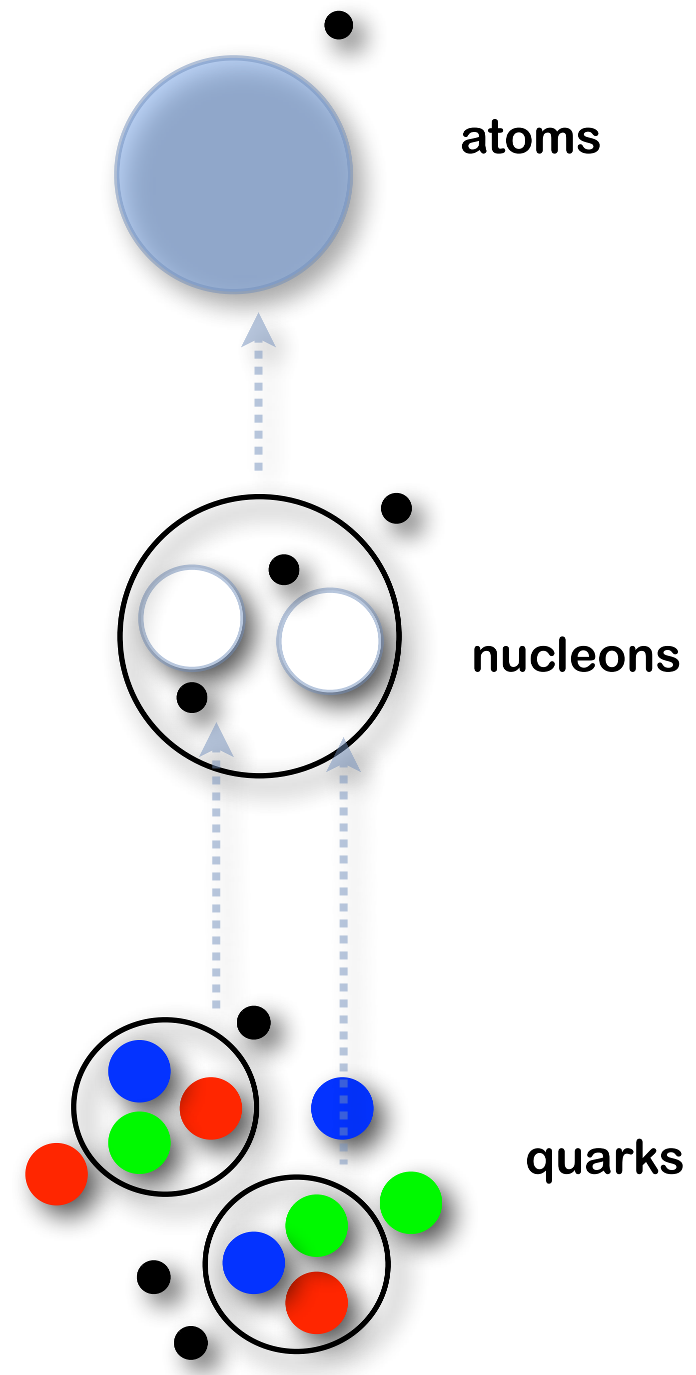


# Three ingredients to describe Nature

- Quantum matter as the basic building block

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

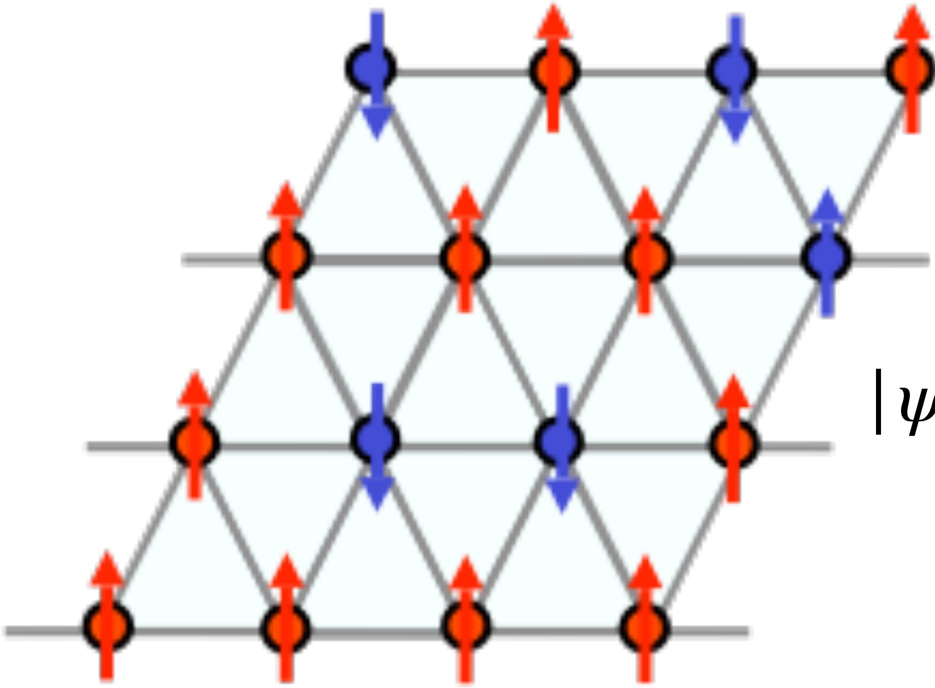
- Renormalisation group as a tool to study Nature at different scales



# Quantum matter as the basic building block



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



## Preparation of a general quantum state

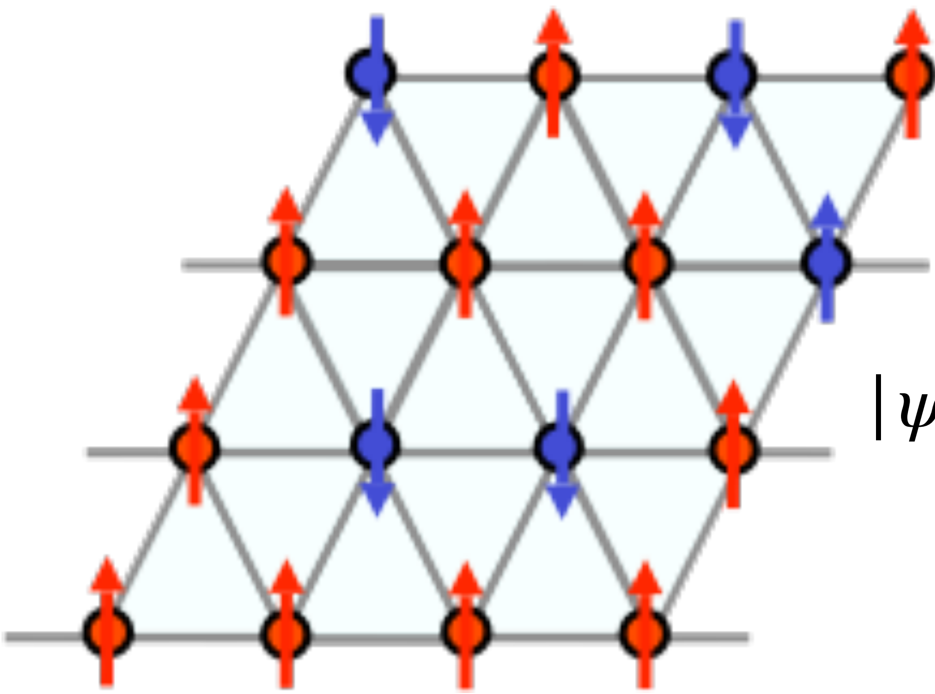
$$|\psi\rangle = c_1 | \uparrow \uparrow \cdots \uparrow \rangle + c_2 | \uparrow \uparrow \cdots \downarrow \rangle + \cdots + c_{2^N} | \downarrow \downarrow \cdots \downarrow \rangle$$

quantum correlations = entanglement

| | Classic | vs. | Quantum |
|---|---|---|---|
| **Memory** | $2^N$ | | $N$ |

# Quantum matter as the basic building block

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



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quantum correlations = entanglement

S. Lloyd, Science (1996)

## Evolution of a general quantum state

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

| | **Classic** | vs. | **Quantum** |
|---|---|---|---|
| **Memory** | $2^N$ | | $N$ |
| **Time** | $2^N$ | | Poly(N) |

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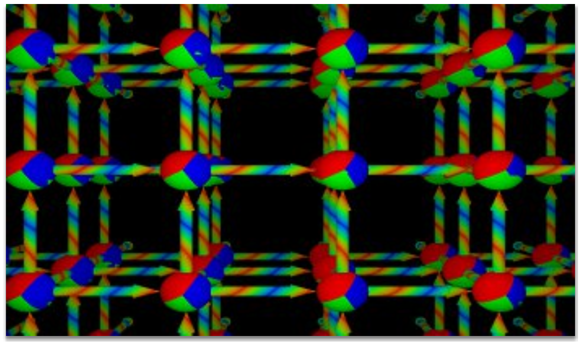
# Tensor network algorithms: an overview



**Variational (non-perturbative) method for Hamiltonian systems**
Extremely useful in 1D systems (MPS)
Proposals and extensions in higher dimensions (TNS)

Related works at:
ICFO, Barcelona (Lewenstein's group); MPQ, Munich (Cirac's group); Gent - Vienna (Verstraete's group)

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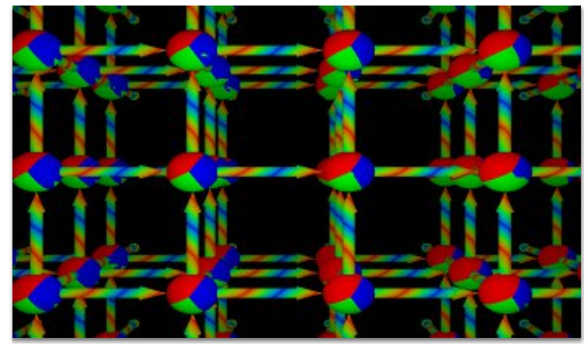

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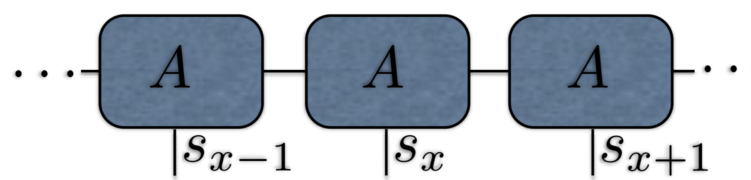


Ground states

Low-energy excitations

Thermal states

Time evolution

Proposal for fermionic systems

Related works at:

ICFO, Barcelona (Lewenstein's group); MPQ, Munich (Cirac's group); Gent - Vienna (Verstraete's group)

# Tensor network algorithms: an overview

## A class of tailored variational ansatz states on a lattice many-body quantum system

$$|\Psi_{\text{many-body}}\rangle = \sum_{s_1,\cdots,s_N} \Psi_{s_1,\cdots,s_N} |s_1,\cdots,s_N\rangle$$

$$\dim\left(\mathscr{H}\right) = \mathrm{d}^{\mathrm{N}}$$

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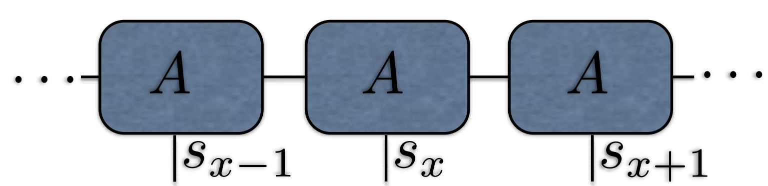
## $\Psi$ is obtained contracting smaller tensors over auxiliary indexes

$$|\Psi_{\text{MPS}}\rangle = \sum_{\{s_i\},\{\alpha_i\}} A^{(s_1)}_{\alpha_1} A^{(s_2)}_{\alpha_1,\alpha_2} \cdots A^{(s_N)}_{\alpha_{N-1}} |s_1, s_2, \cdots, s_N\rangle$$




$$\dim\left(\mathrm{MPS}\right) = \mathrm{N\,d\,D}^2$$

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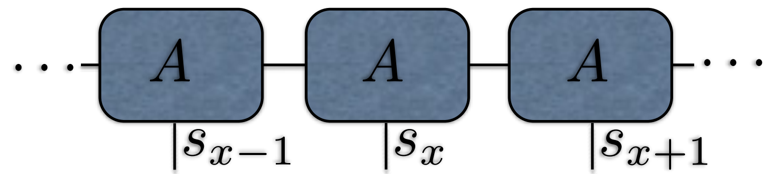


$$\dim\left(\mathrm{MPS}\right) = \mathrm{N\,d\,D^2}$$

quantum correlations = entanglement =

$$\log\left(D\right) \propto \frac{c+\bar{c}}{3}\log\left(N\right)$$

C. Holzhey, F. Larsen, F. Wilczek, Nucl. Phys. B (1994)
G. Vidal, J.I. Latorre, E. Rico, A. Kitaev, Phys. Rev. Lett. (2003)
B.-Q. Jin, V.E. Korepin, J. Stat. Phys. (2004)
P. Calabrese, J.J. Cardy, Stat. Mech. (2004)

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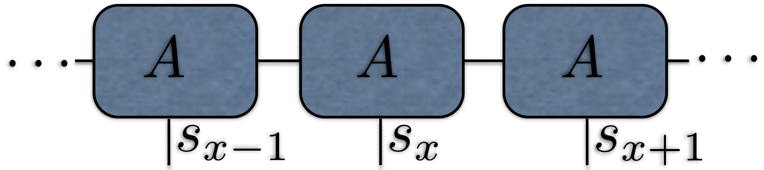
# Tensor network algorithms: an overview




## Matrix Product States: M.P.S.

Well-suited to described translational invariant systems

Encoded the entropic boundary law (VBS picture)

Optimal to minimize the energy (DMRG)

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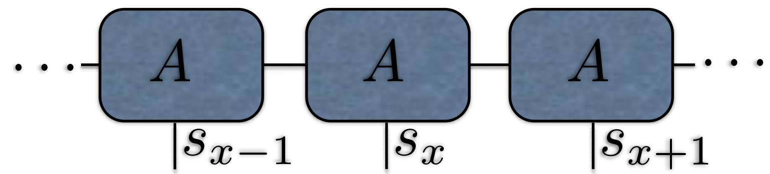


## Matrix Product States: M.P.S.

Well-suited to described translational invariant systems

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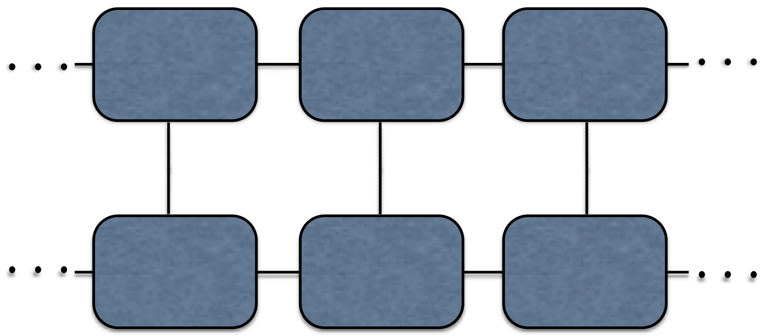
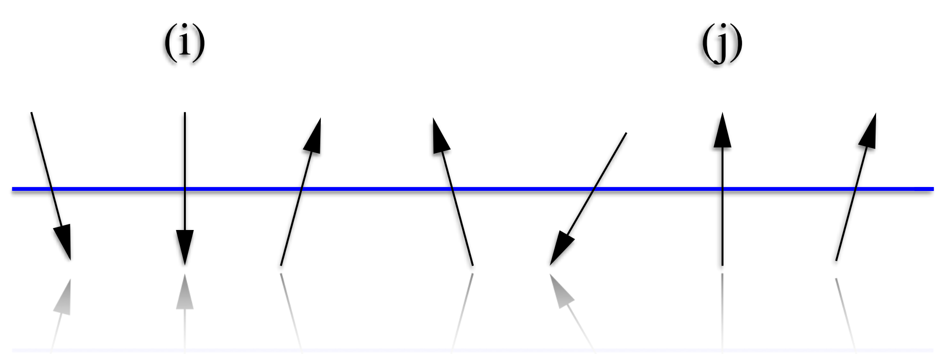
Optimal to minimize the energy (DMRG)

Simple way to obtain any expectation value (Transfer matrix)






$$E = \sum_s A^*[s] \otimes A[s]$$

$$\langle O_i O_j \rangle = \mathrm{Tr}\left\{ E^{N-j+i-2} \tilde{O}_i E^{j-i} \tilde{O}_j \right\}$$

$$\tilde{O} = \sum_{s,s'} A^*[s] \otimes A[s'] \langle s|O|s'\rangle$$

# Tensor network algorithms: an overview

## Exact description of the gauge invariant subspace with tensor network states

$$|\text{phys}\rangle = \sum_{s_1,\cdots,s_x,\cdots} a(s_1,\cdots,s_x,\cdots)\text{Tr}\left[A^{(s_1)}\cdots A^{(s_x)}\cdots\right]|s_1,\cdots,s_x,\cdot\rangle$$

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# Tensor network algorithms: an overview

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**CP symmetry breaking in the Schwinger model in a background electric field**

**Imaginary time evolution (Phase diagram)**

**Finite density phase diagram of a SU(2) gauge invariant Fermi-Hubbard model**

# Tensor network algorithms: an overview

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**Real time evolution (Quench experiment)**

**Entanglement characterisation of dynamical string breaking**

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- CP symmetry breaking in the Schwinger model in a background electric field
- Finite density phase diagram of a SU(2) gauge invariant Fermi-Hubbard model

**Real time evolution (Quench experiment)**

- Entanglement characterisation of dynamical string breaking

**Embedding and model building (Chiral symmetry breaking)**

- "Nuclear Physics" in a SO(3) gauge invariant model

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# Tensor network algorithms: dynamical string breaking and hadronization

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]

**Hamiltonian:** Staggered fermions in 1D coupled to a U(1) gauge field

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

**Electric term** **Matter-gauge coupling** **Staggered mass**

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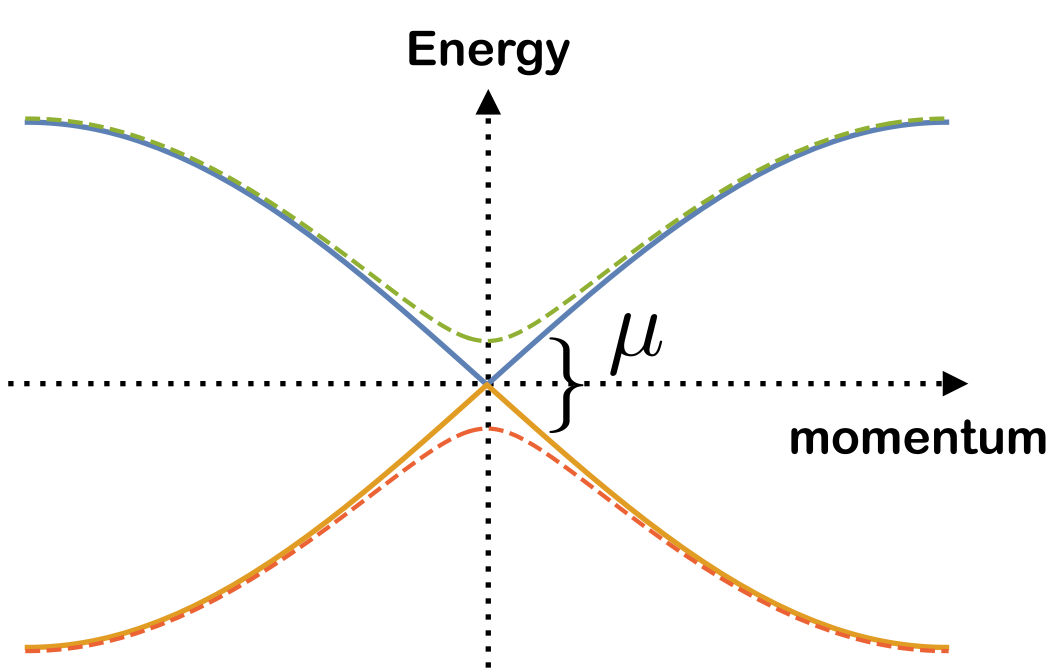



**Staggered fermions in 1D at half-filling:**

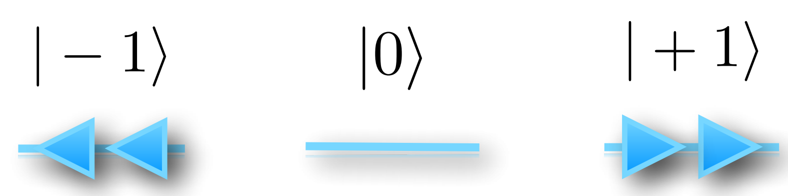
- massless case: linear dispersion relation and two chiral modes
- mass gap: particle-hole excitation proportional to the staggered mass

# Tensor network algorithms: dynamical string breaking and hadronization



## Confinement and string breaking: QED in (1+1)-d (Schwinger model)

### Spin-1 representation

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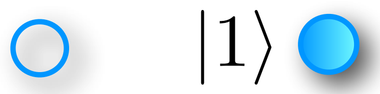
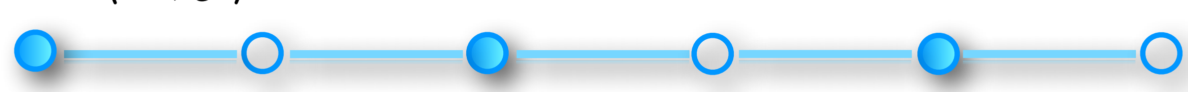
$|0\rangle$ $|1\rangle$



$|-1\rangle$ $|0\rangle$ $|+1\rangle$

### Vacuum (reference) state

$$H = \frac{g^2}{2} \sum_{\langle x,y \rangle} \left( S^{(3)}_{x,y} \right)^2 + m \sum_x (-1)^x \, \psi^\dagger_x \psi_x$$



$2x-1$ $2x$ $2x+1$

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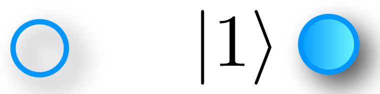

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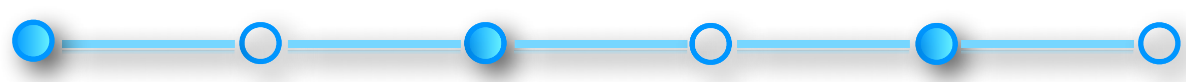
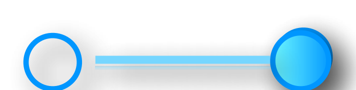


$2x-1$ $2x$ $2x+1$

### Creating a quark - antiquark pair:

$$\psi^\dagger_{2x} S^+_{2x,2x+1} \psi_{2x+1}$$



# Tensor network algorithms: dynamical string breaking and hadronization

## Confinement and string breaking: QED in (1+1)-d (Schwinger model)

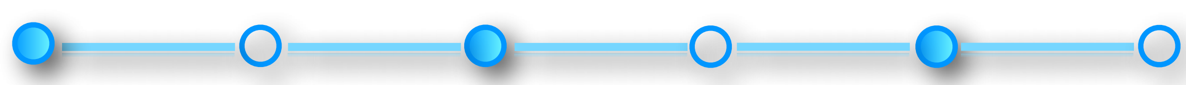
### Spin-1 representation

$|0\rangle$ ○  $|1\rangle$ ●

$|-1\rangle$  $|0\rangle$  $|+1\rangle$

### Vacuum (reference) state

$$H = \frac{g^2}{2}\sum_{\langle x,y\rangle}\left(S^{(3)}_{x,y}\right)^2 + m\sum_x (-1)^x\,\psi^\dagger_x\psi_x$$



$2x-1$  $2x$  $2x+1$

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# Tensor network algorithms: dynamical string breaking and hadronization

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# Tensor network algorithms: dynamical string breaking and hadronization

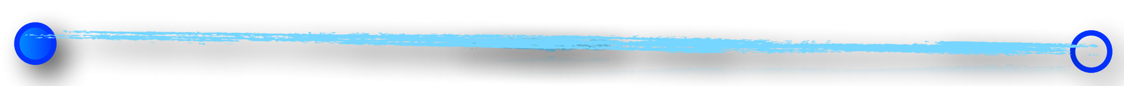


## Confinement and string breaking: QED in (1+1)-d (Schwinger model)

# Tensor network algorithms: dynamical string breaking and hadronization

## Confinement and string breaking: QED in (1+1)-d (Schwinger model)

### Confinement



$$E_{\text{string}} - E_0 = \frac{g^2}{2}(L-1)$$

# Tensor network algorithms: dynamical string breaking and hadronization

## Confinement and string breaking: QED in (1+1)-d (Schwinger model)

# Tensor network algorithms: dynamical string breaking and hadronization



## Confinement and string breaking: QED in (1+1)-d (Schwinger model)

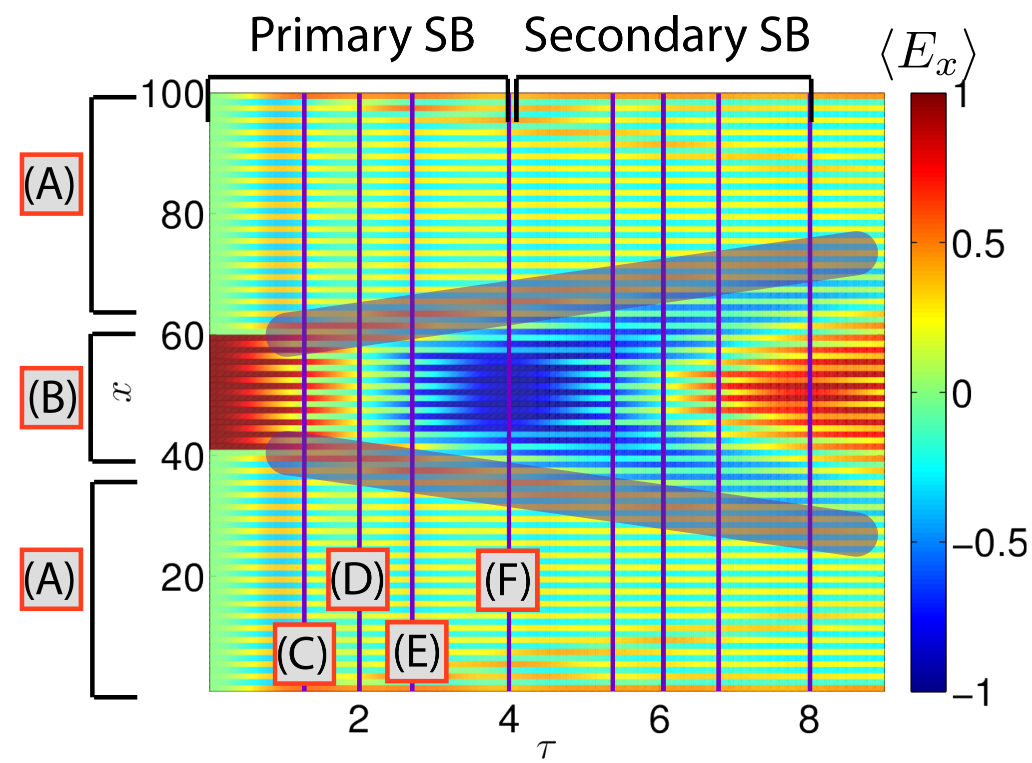
**String breaking and hadronization**


$$E_{\text{meson}} - E_0 = g^2 + 2m$$

$$L_c = 3 + \frac{4m}{g^2}$$

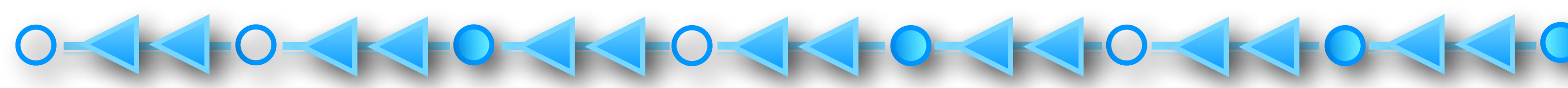
# Tensor network algorithms: dynamical string breaking and hadronization

## Confinement and string breaking: QED in (1+1)-d (Schwinger model)




### (A) Vacuum

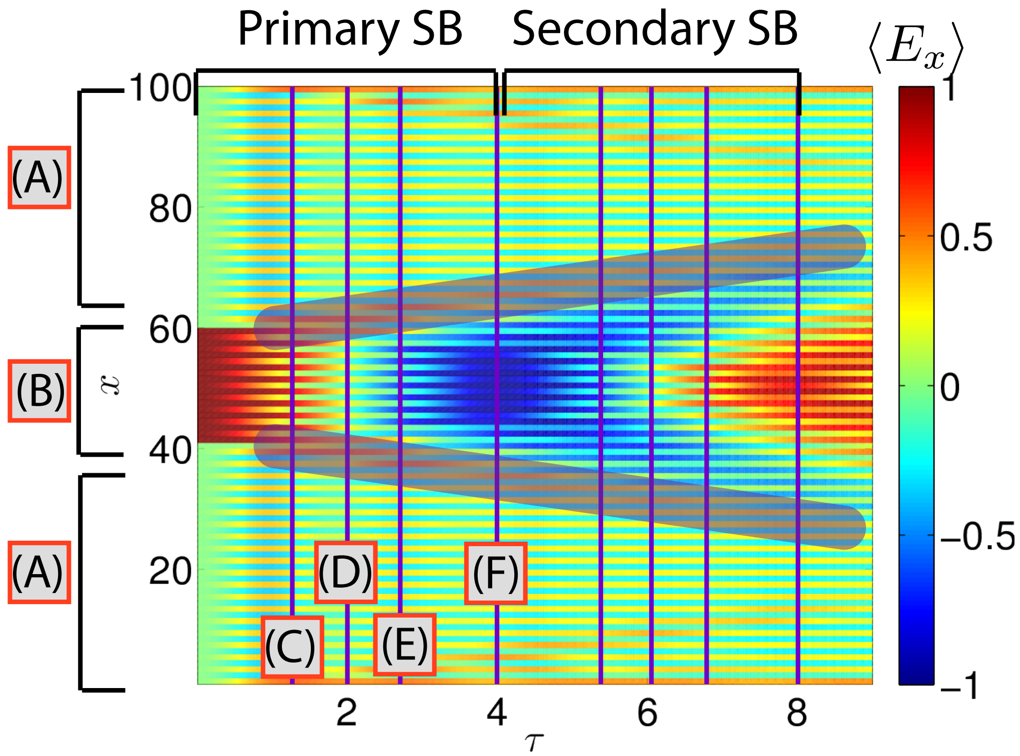
### (B) String

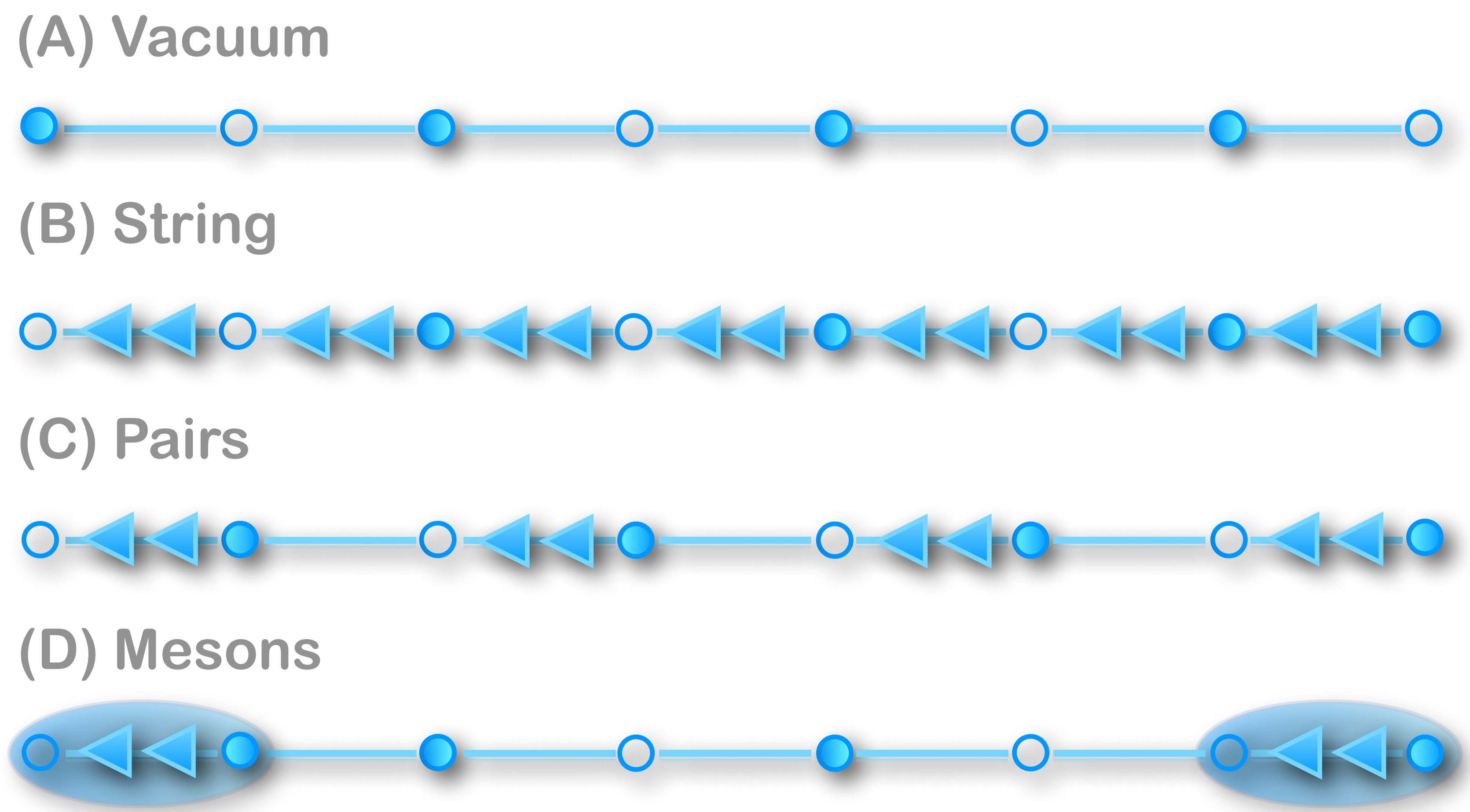


# Tensor network algorithms: dynamical string breaking and hadronization



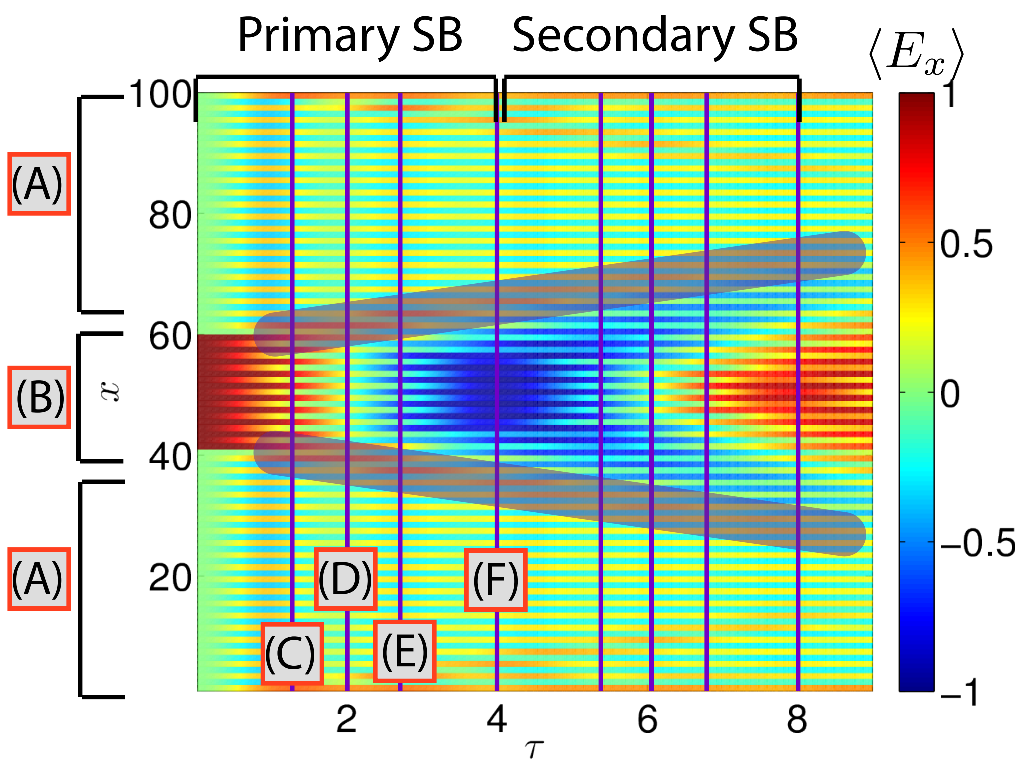
## Confinement and string breaking: QED in (1+1)-d (Schwinger model)



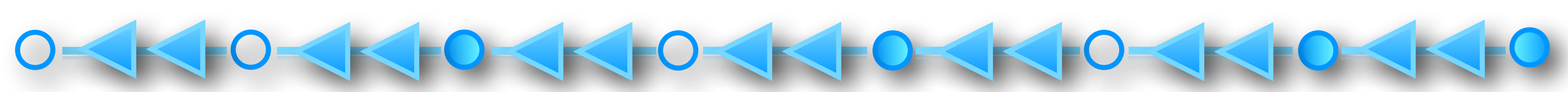
# Tensor network algorithms: dynamical string breaking and hadronization

## Confinement and string breaking: QED in (1+1)-d (Schwinger model)

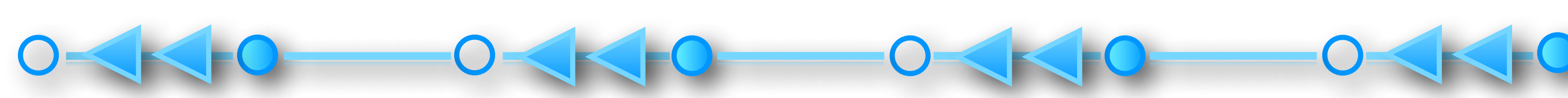



### (A) Vacuum

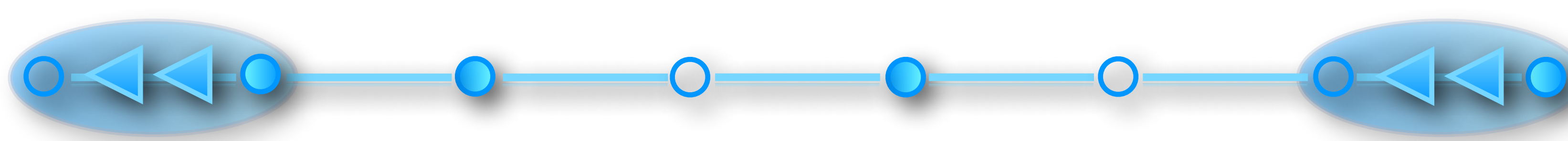
### (B) String



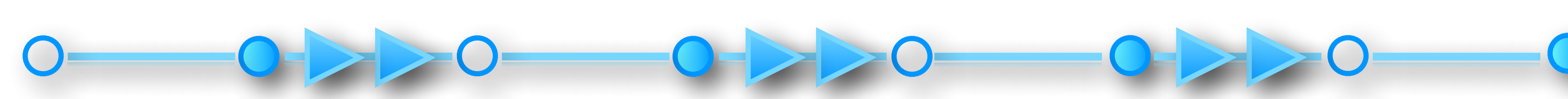
### (C) Pairs



### (D) Mesons



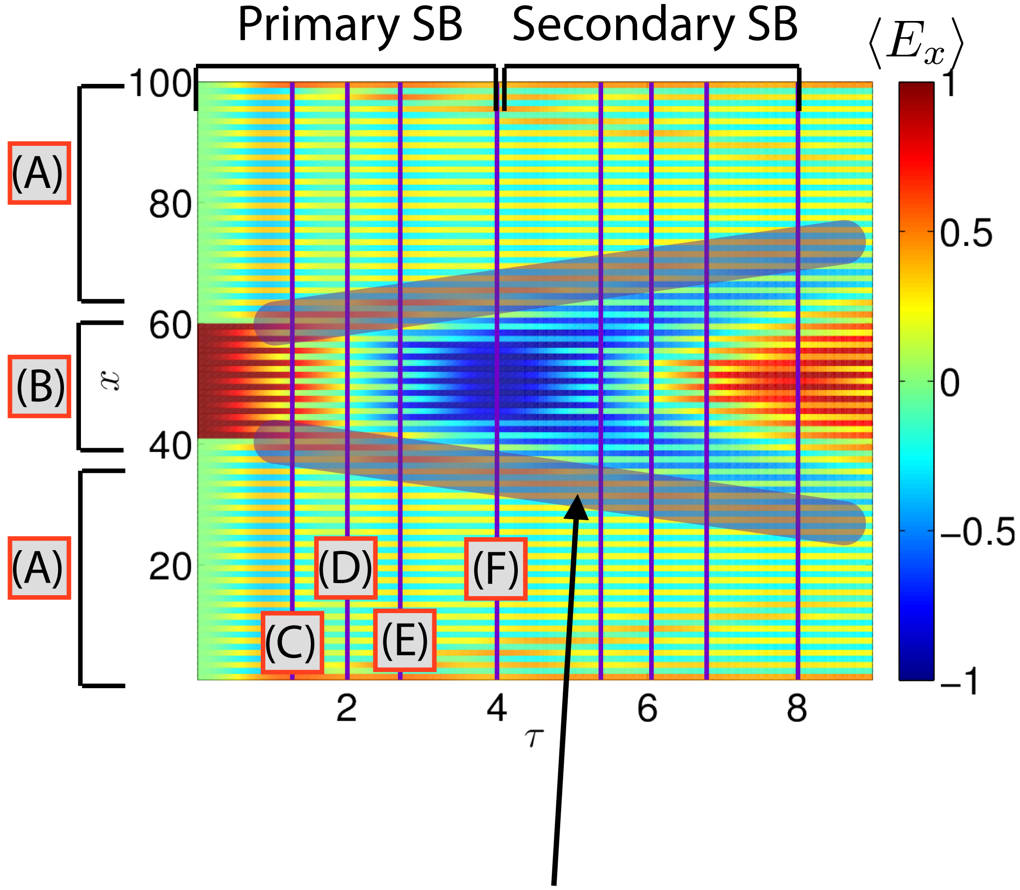
### (E) AntiPairs



### (F) AntiString

# Tensor network algorithms: dynamical string breaking and hadronization

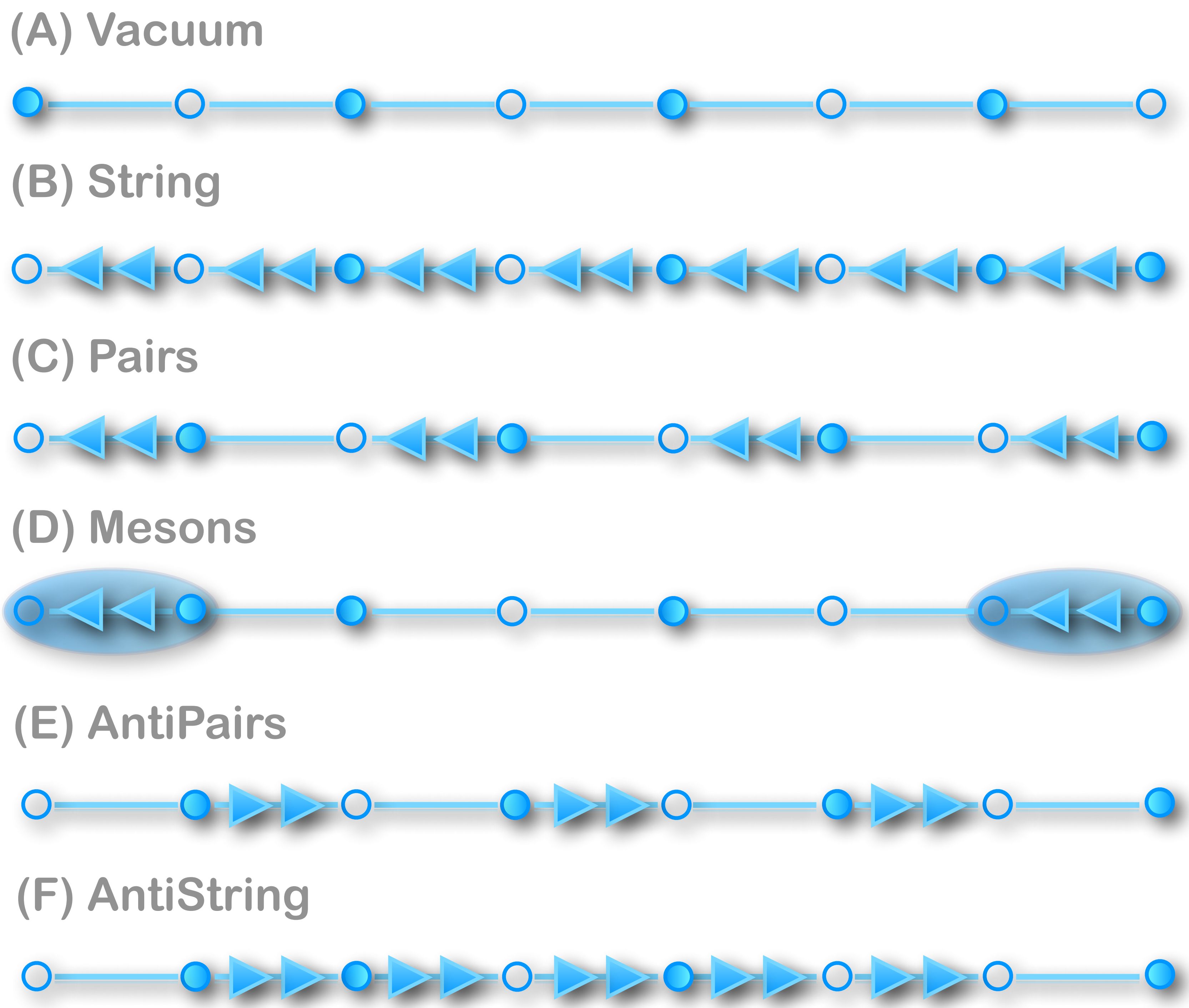
## Confinement and string breaking: QED in (1+1)-d (Schwinger model)




**String wave-front characterised by:**

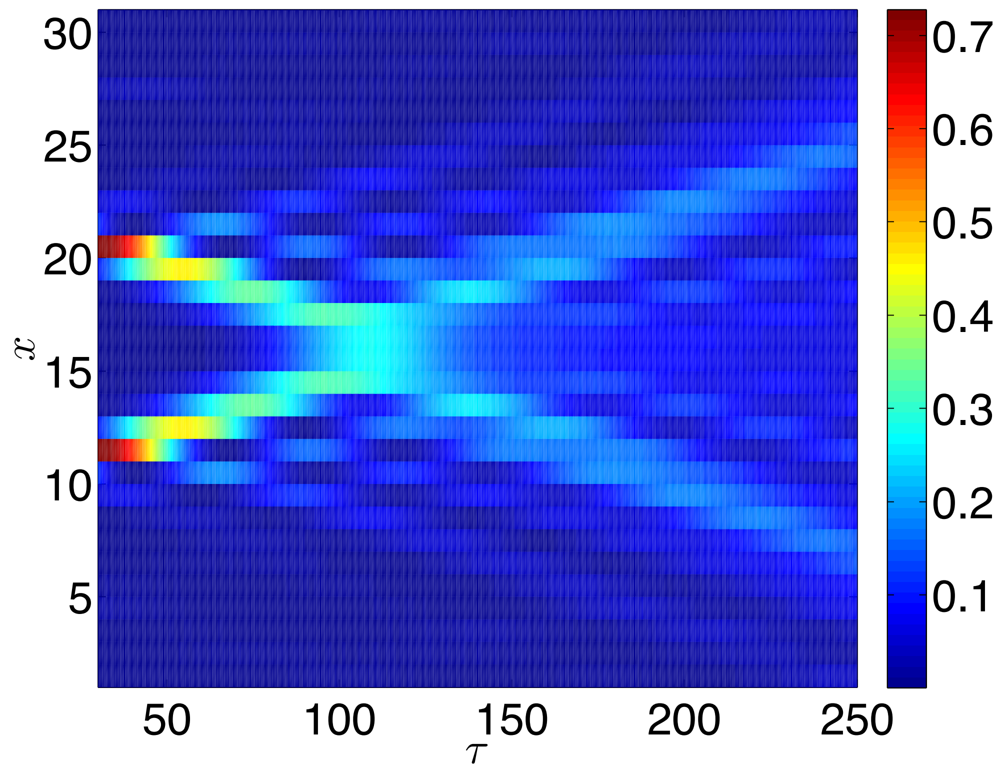
**-Electric field spreading**
**-Entanglement propagation**

**O(100) sites simulation**

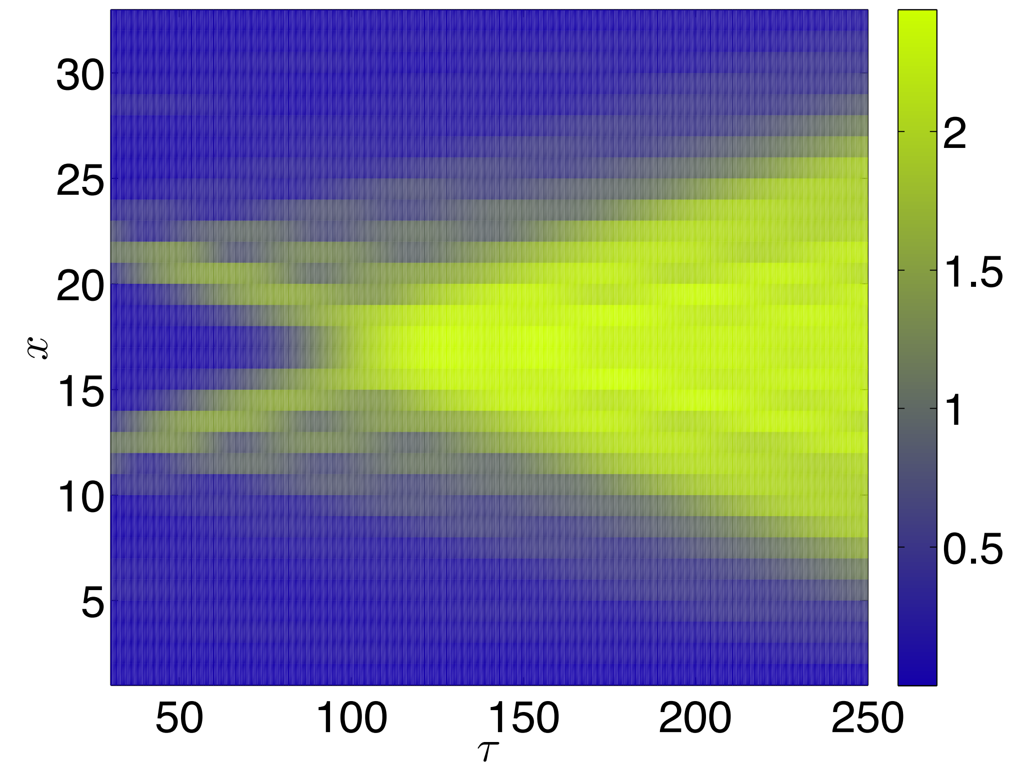


# Meson scattering

We prepare two mesons in a dynamical state giving them momentum towards the center




**Electric field of two mesons during the scattering evolution**




**Entanglement entropy during the scattering**

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# Tensor network algorithms and machine learning

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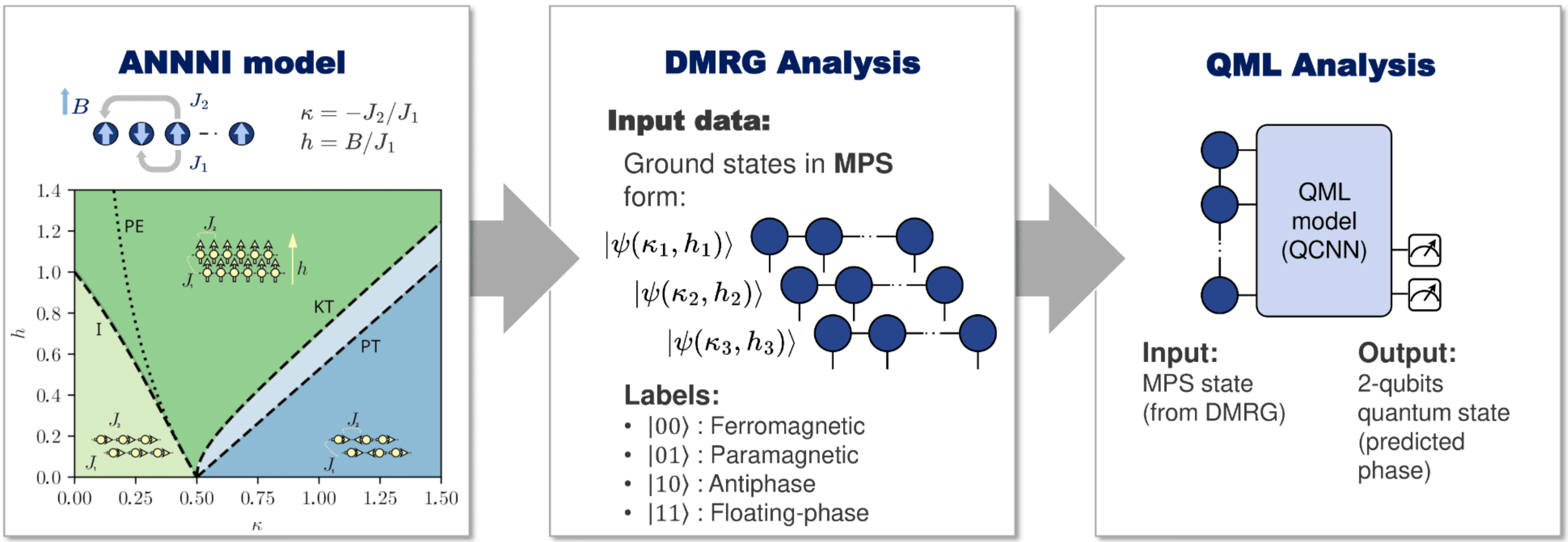
## Exploring the Phase Diagram of the quantum one-dimensional ANNNI model

M. Cea,[1,2,*] M. Grossi,[3,†] S. Monaco,[4,5,‡] E. Rico,[6,7,8,9,§] L. Tagliacozzo,[10,¶] and S. Vallecorsa[3,**]

arXiv:2402.11022 (2024)

**O(400) sites simulation**



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# Tensor network algorithms and machine learning

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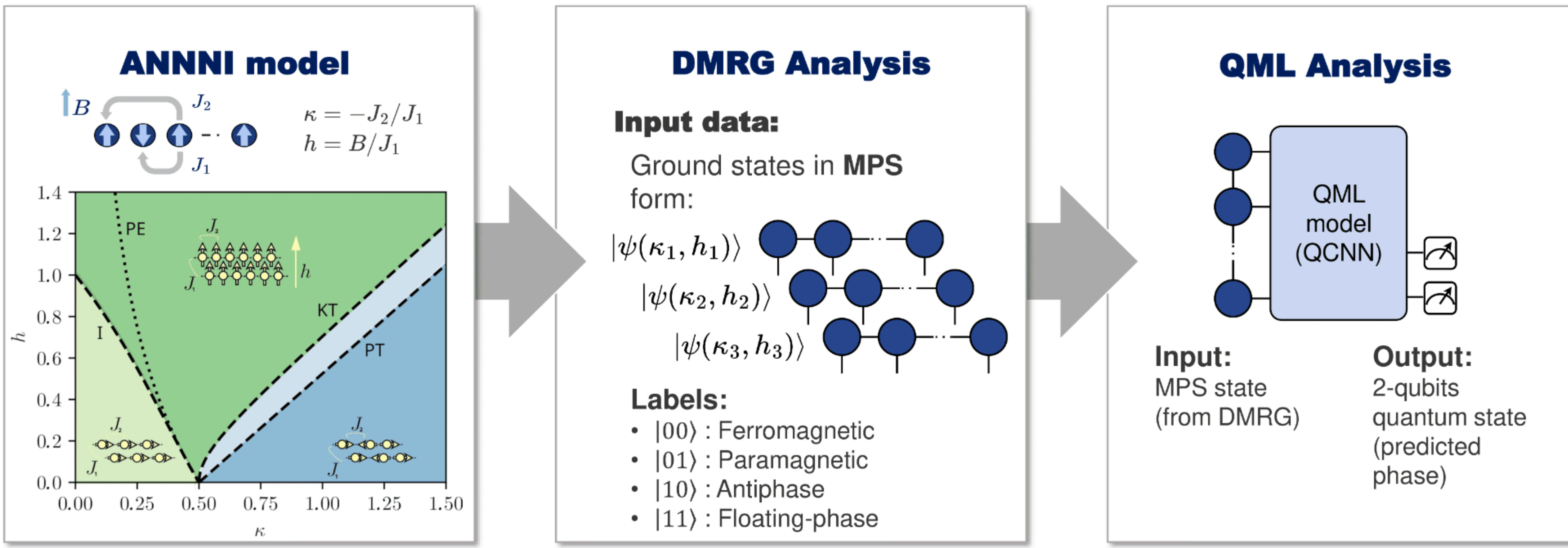


# Quantum Many-Body phase diagram characterization using Fidelity-based Kernels

**Francesco Di Marcantonio[2,3]**
Nicola Mariella[1], Enrique Rico[2], Sofia Vallecorsa[3],
Sergiy Zhuk[1]

in preparation

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# CERN's new Next Generation Triggers Project (NGT), supported by a grant from the E&W Schmidt Fund for Strategic Innovation.

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## *Core objectives for Quantum Simulation:*

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*Developing Tensor Network Algorithms for Quantum Many-body Problems:* advancing tensor network algorithms for real-time dynamics and phase studies in high-energy process simulations, thereby facilitating in-depth fermionic system analyses and real-time simulations.

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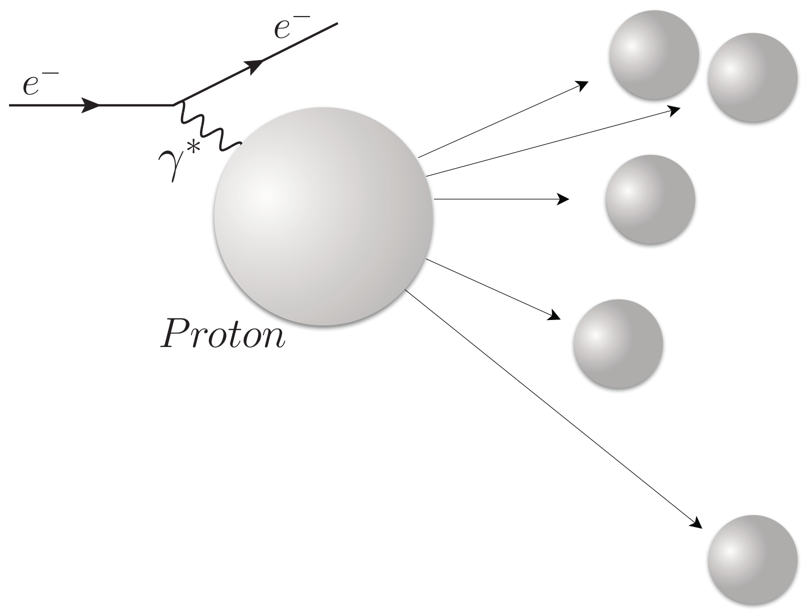
*Prototyping TPUs and GPUs Implementation of Tensor Network Simulations:* investigating how hardware accelerators like graphical processing units (GPUs) can scale tensor network algorithms to unprecedented bond dimensions, speed, and accuracy, thereby revolutionising quantum simulations.

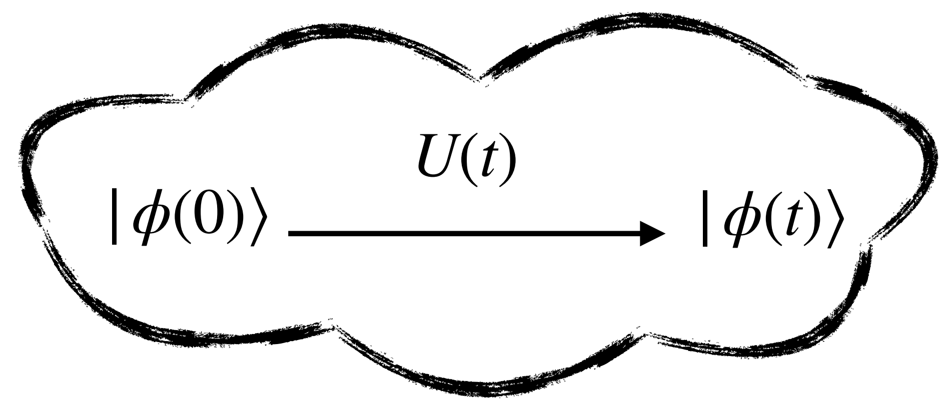
# Quantum matter as the basic building block



## Problem to compute




## Quantum system

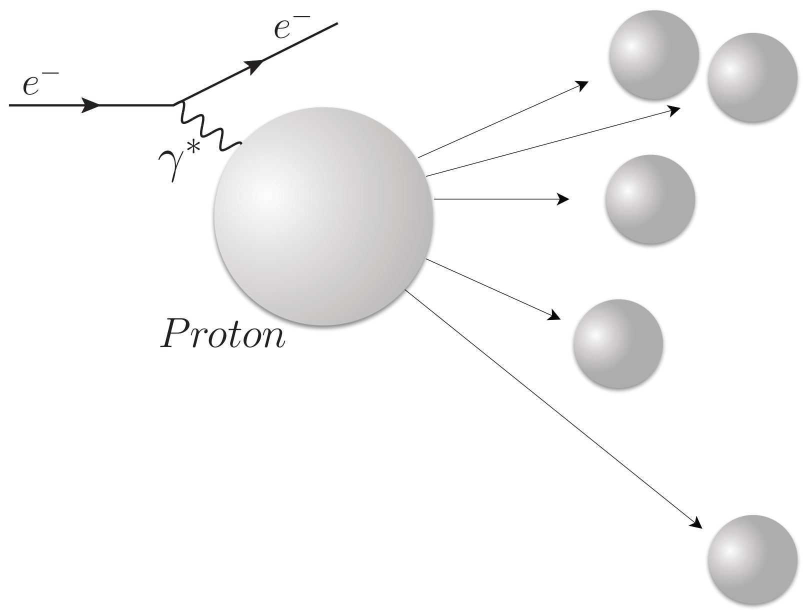



Goal: Simulate the physics of a quantum system of interest by another quantum device that is easier to control and to measure

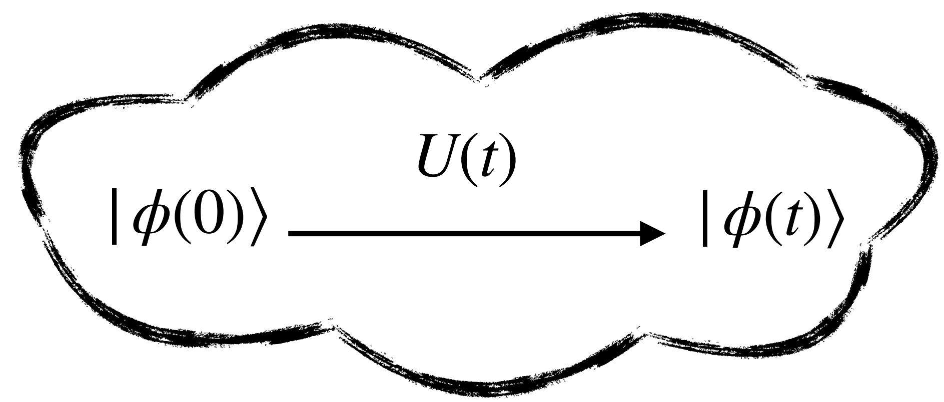
Quantum Simulation,
Rev. Mod. Phys (2014)

# Quantum matter as the basic building block

## Problem to compute




## Quantum system

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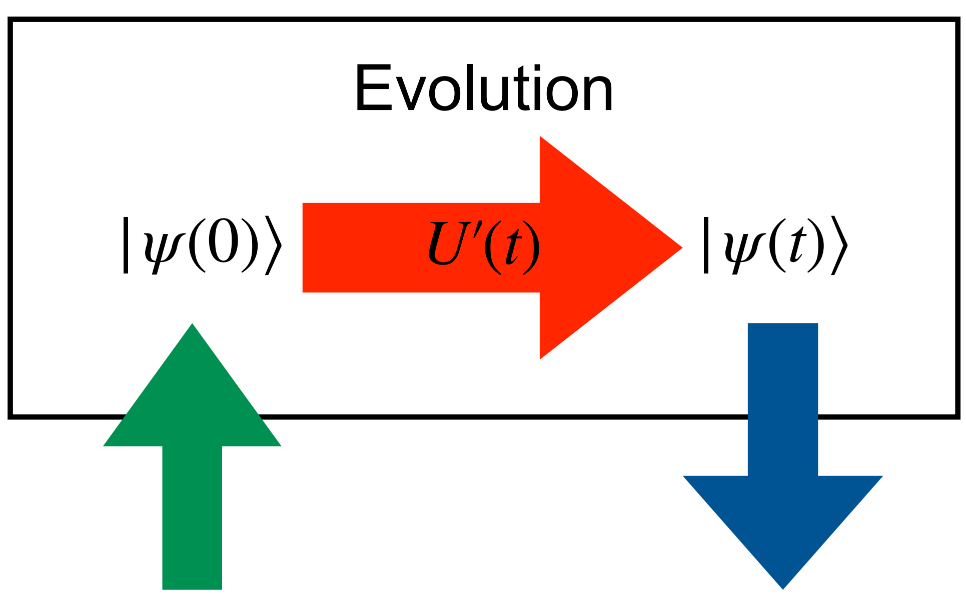
## Quantum simulator




Preparation Measurement

Quantum Simulation, Rev. Mod. Phys (2014)

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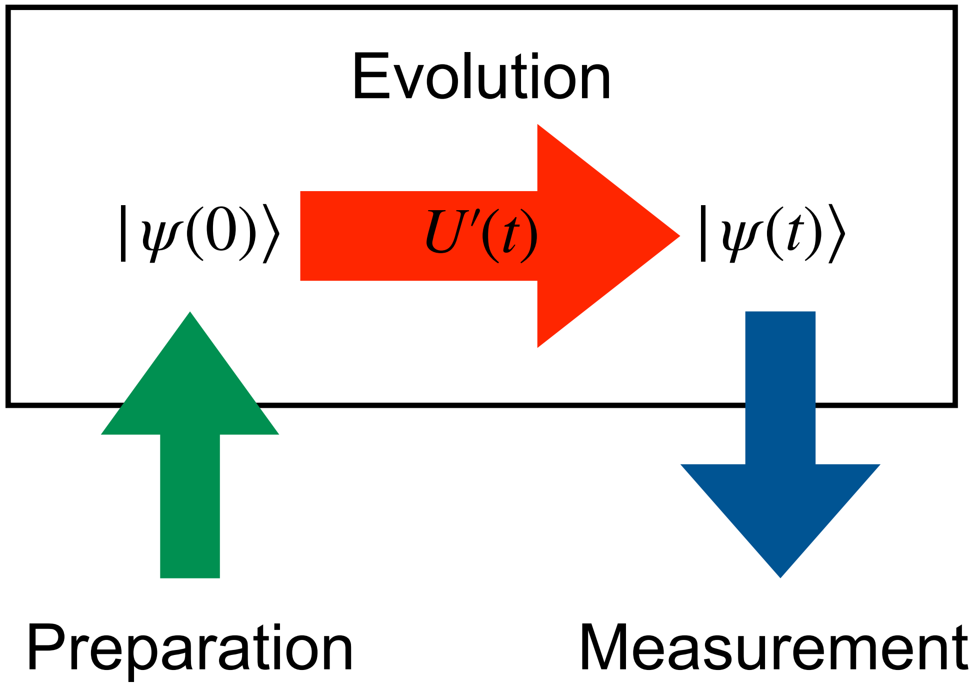
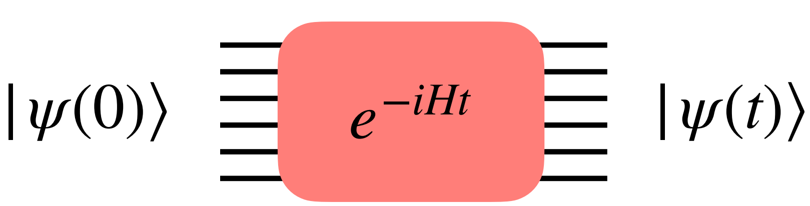
# Quantum matter as the basic building block

## Quantum simulation approaches



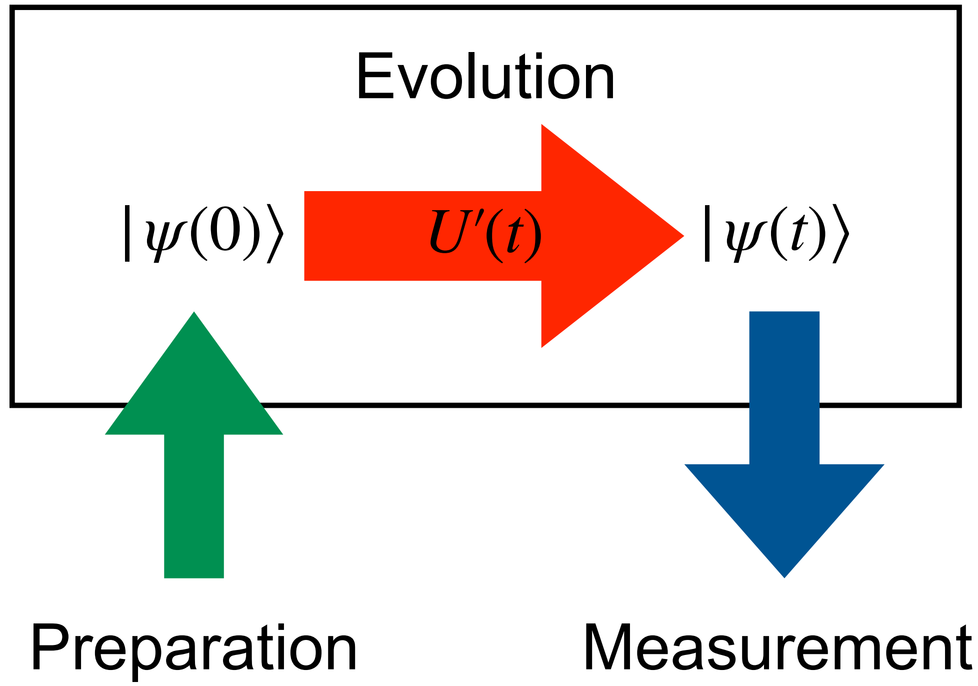

Analog simulation:
Single purposed simulator



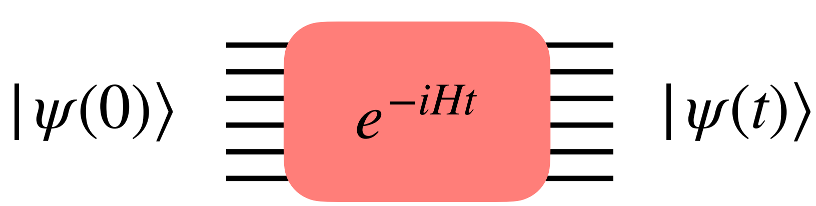

Engineer the interactions to emulate the Hamiltonian of the model

# Quantum matter as the basic building block

## Quantum simulation approaches

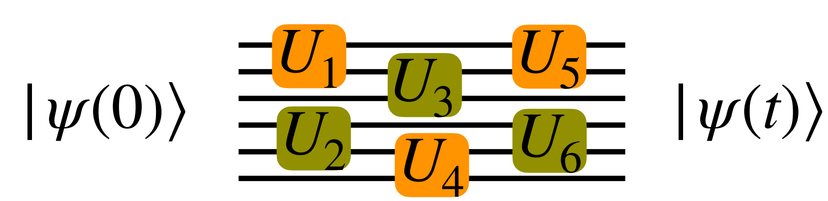



### Analog simulation: Single purposed simulator




Engineer the interactions to emulate the Hamiltonian of the model

### Digital simulation: Universal simulator




Decompose dynamics into sequence of quantum gates

# Quantum matter as the basic building block

**Feynman's universal quantum simulator:**
controlled quantum device which efficiently reproduces the dynamics of any other many-particle quantum system.

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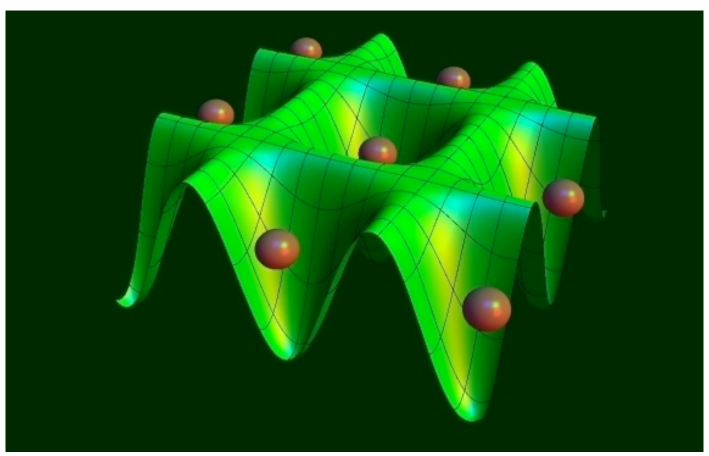
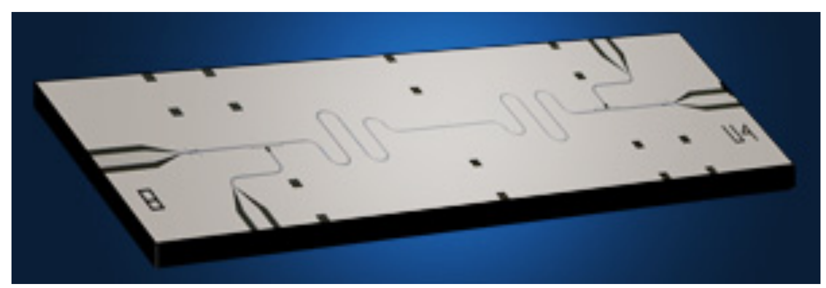
# Quantum matter as the basic building block

**Feynman's universal quantum simulator:**
controlled quantum device which efficiently reproduces the dynamics of any other many-particle quantum system.

How?… cold atoms, ions, photons, superconducting circuit, etc.

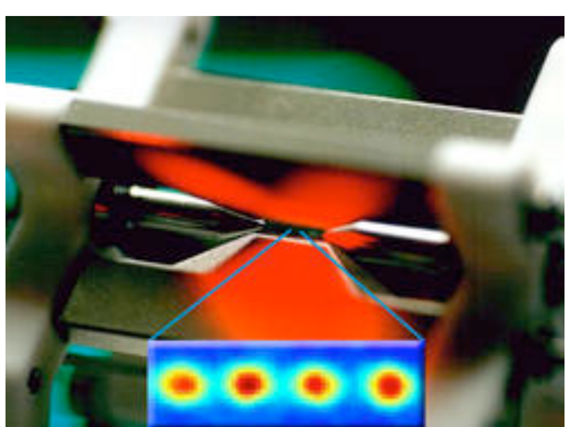


Optical lattices

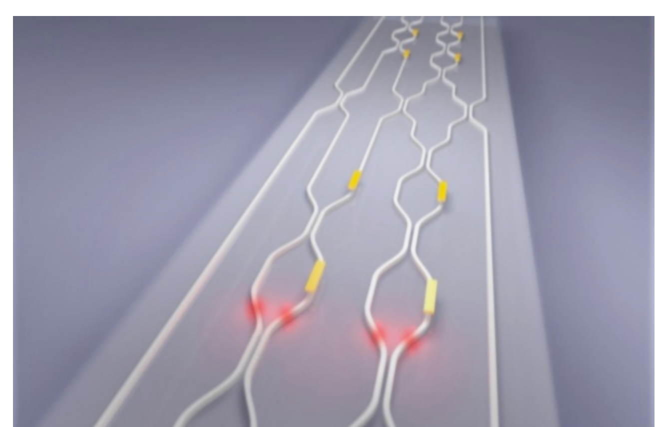


Superconducting circuits

… and several others as quantum dots, NMR, NV centers



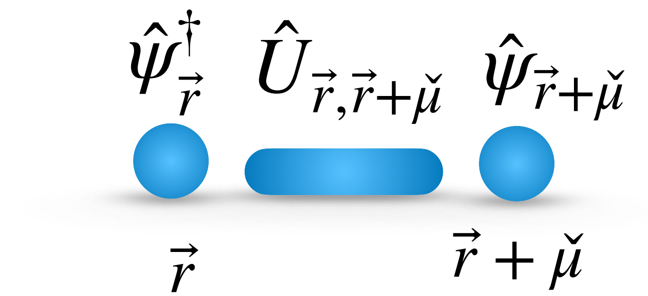
Trapped ions



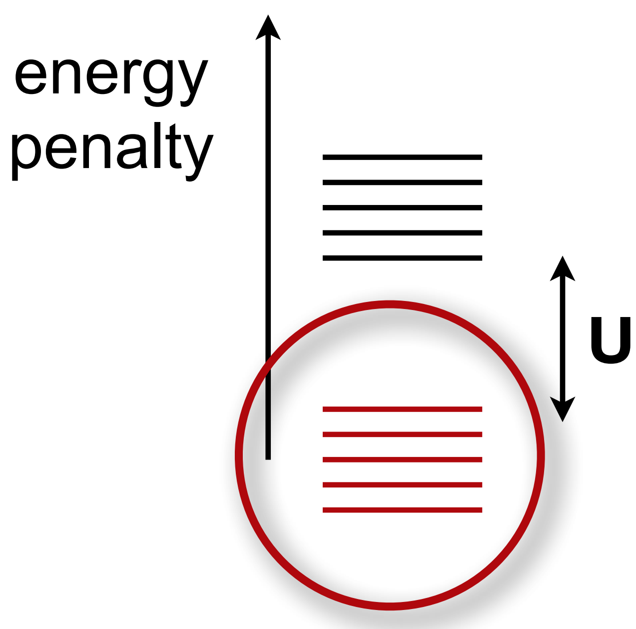
Quantum photonics

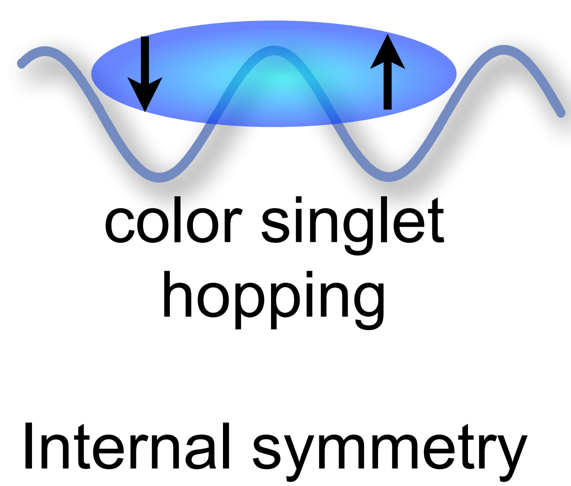
J.I. Cirac, P. Zoller
I. Bloch, J. Dalibard, S. Nascimbène
R. Blatt, C.F. Roos,
A. Aspuru-Guzik, P. Walther
A.A. Hock, H.E. Türeci, J. Koch
Nature Physics Insight - Quantum Simulation (2012)

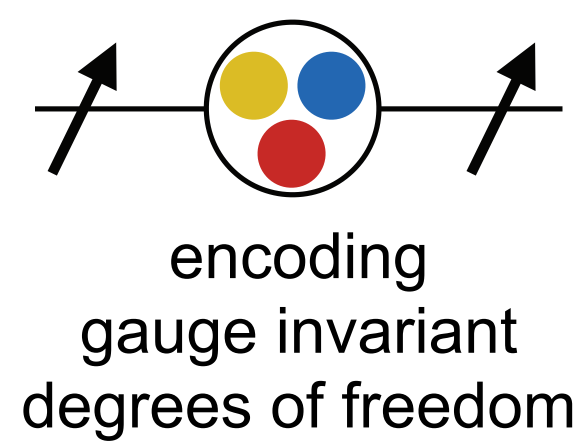
# Simulating lattice gauge theories within quantum technologies



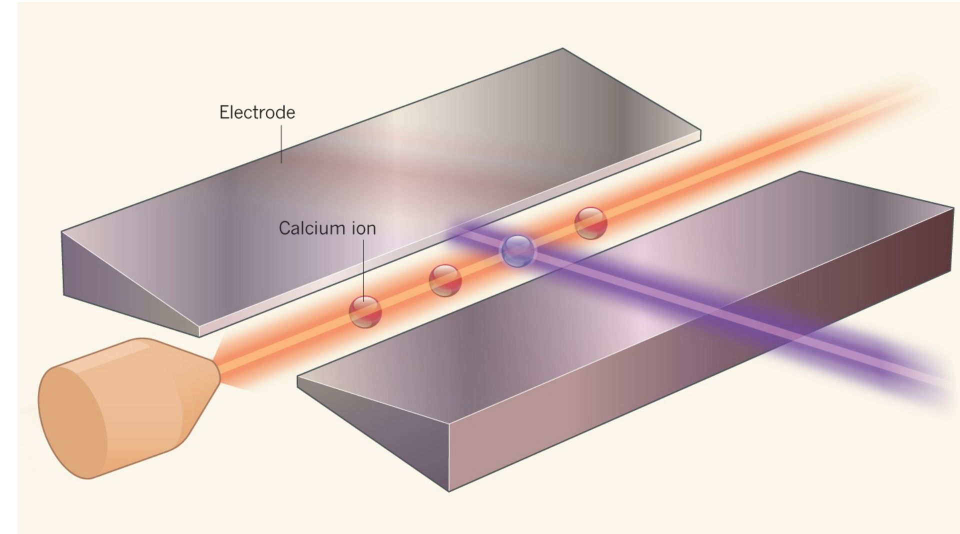

- Implementing the gauge invariant dynamics



# First experimental realisations in trapped ions platform




## Experimental achievements

**Quantum digital simulation**

### Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez, Christine A. Muschik, Philipp Schindler, Daniel Nigg, Alexander Erhard, Markus Heyl, Philipp Hauke, Marcello Dalmonte, Thomas Monz, Peter Zoller & Rainer Blatt

*Nature* **534**, 516–519 (23 June 2016) | Download Citation

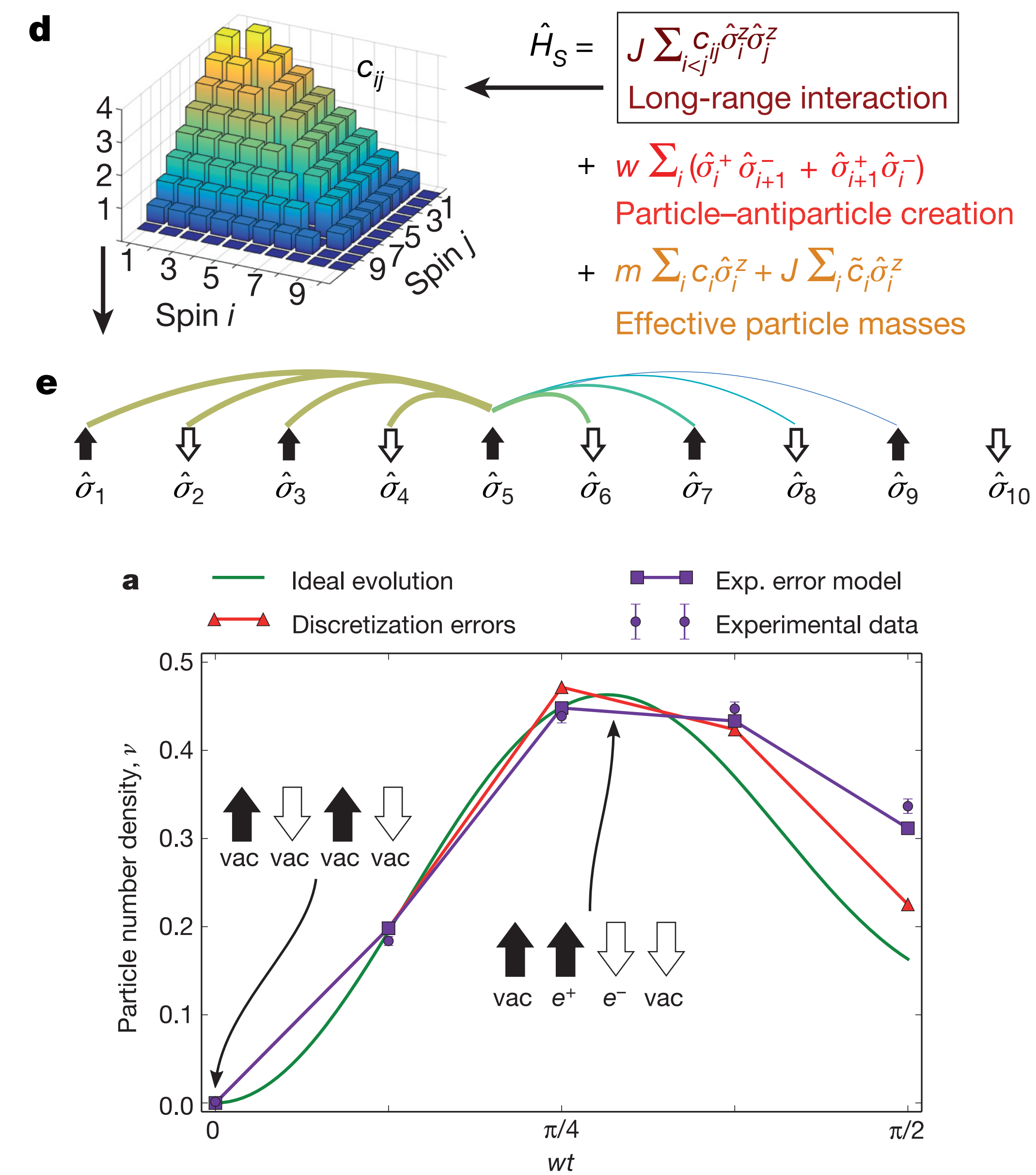
**Hybrid (quantum-classical) approach**

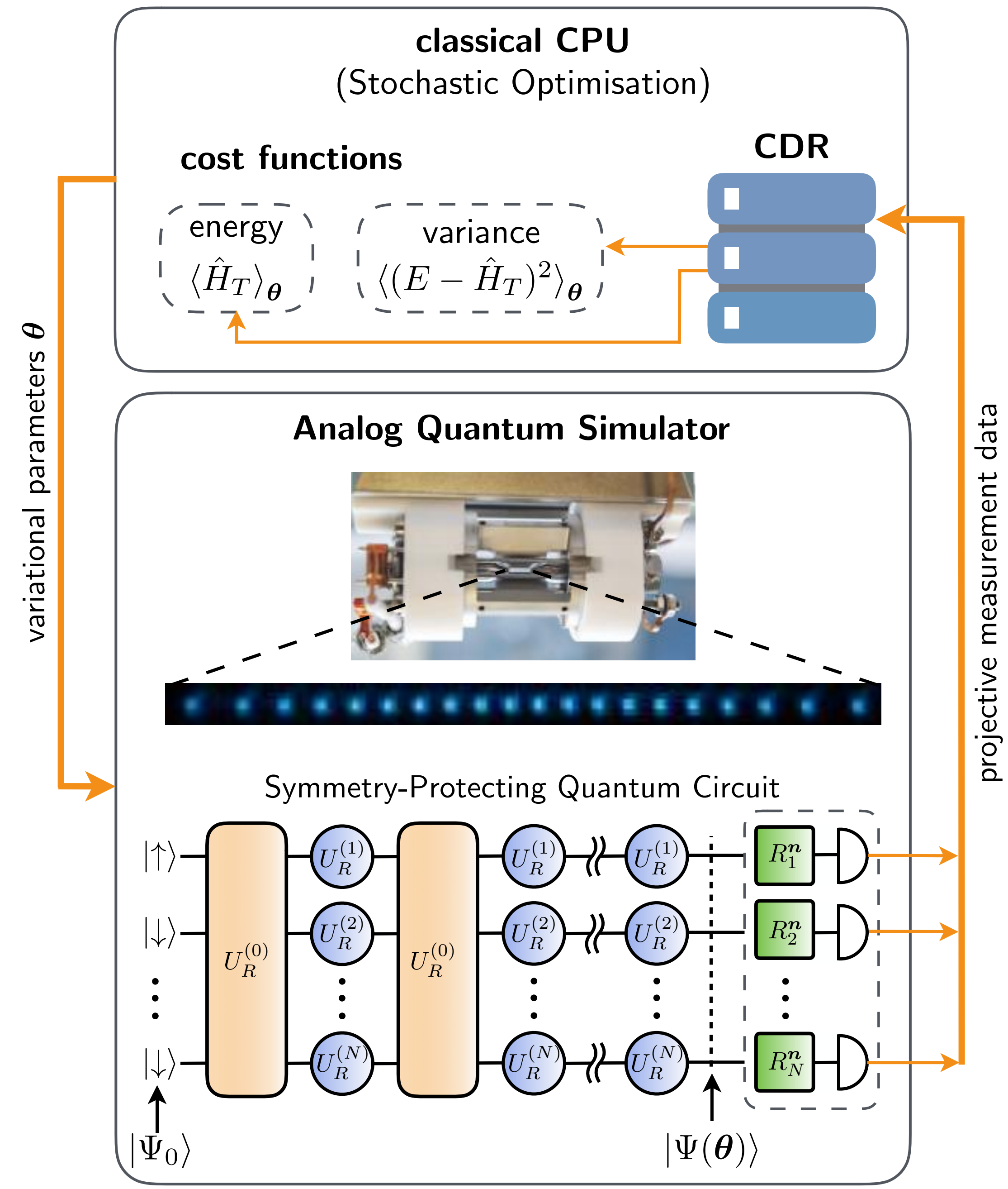
### Self-verifying variational quantum simulation of lattice models

C. Kokail, C. Maier, R. van Bijnen, T. Brydges, M. K. Joshi, P. Jurcevic, C. A. Muschik, P. Silvi, R. Blatt, C. F. Roos & P. Zoller

*Nature* **569**, 355–360 (2019) | Download Citation

# QUANTUM SIMULATIONS OF THE SCHWINGER MODEL




*IQOQI Innsbruck*

*21 lattice sites!*

*R. Blatt and P. Zoller's groups*

*Nature (2016), arXiv:1810.03421*

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# Simulating lattice gauge theories within quantum technologies

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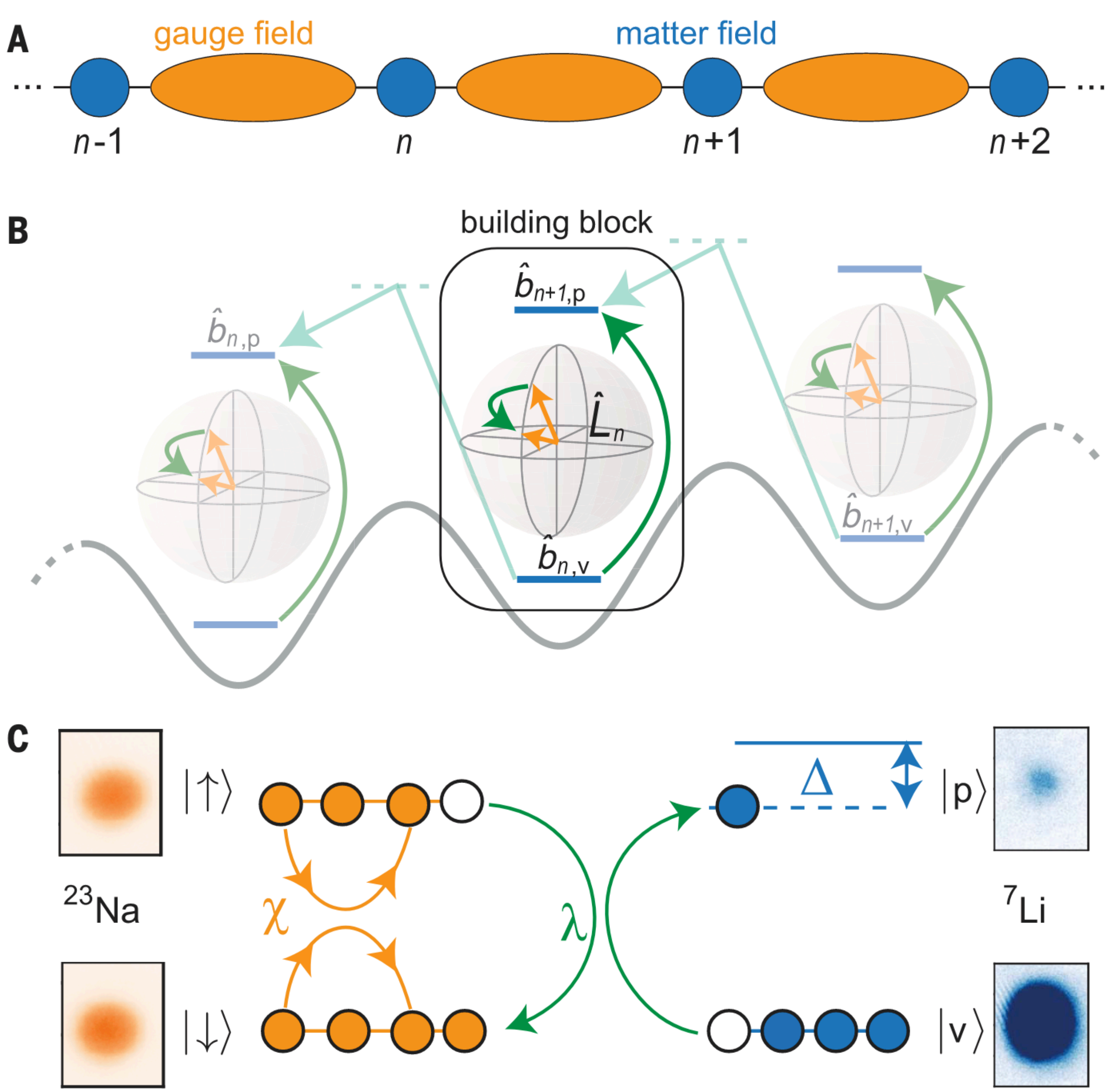
## A scalable realization of local U(1) gauge invariance in cold atomic mixtures

*Science* **367**, 1128–1130 (2020)

Alexander Mil[1*], Torsten V. Zache[2], Apoorva Hegde[1], Andy Xia[1], Rohit P. Bhatt[1], Markus K. Oberthaler[1], Philipp Hauke[1,2,3], Jürgen Berges[2], Fred Jendrzejewski[1]



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# Simulating lattice gauge theories within quantum technologies

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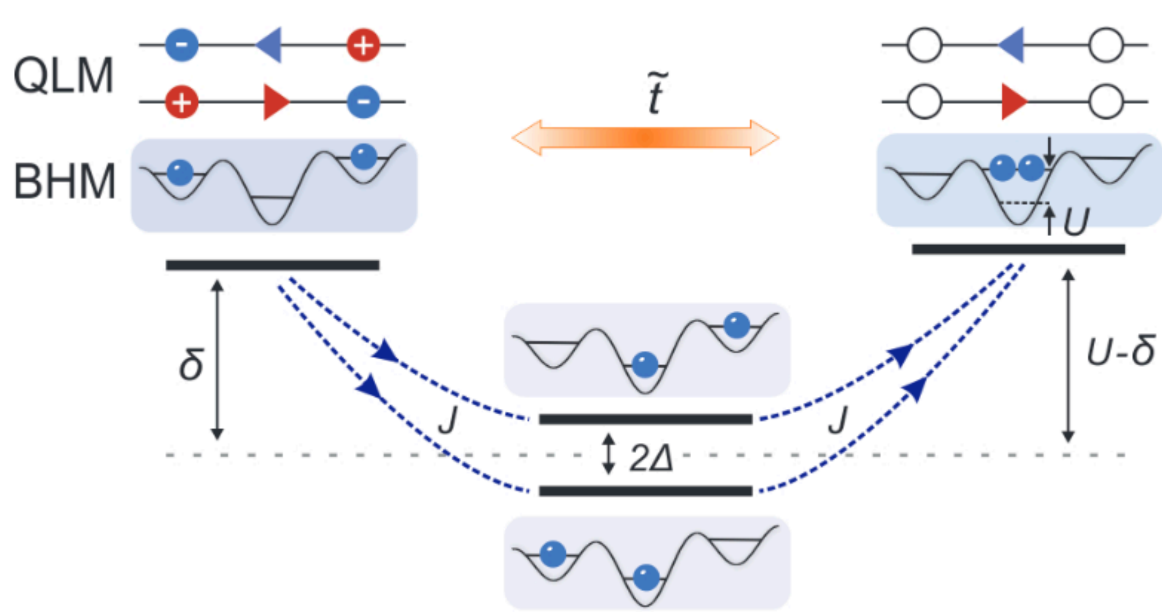
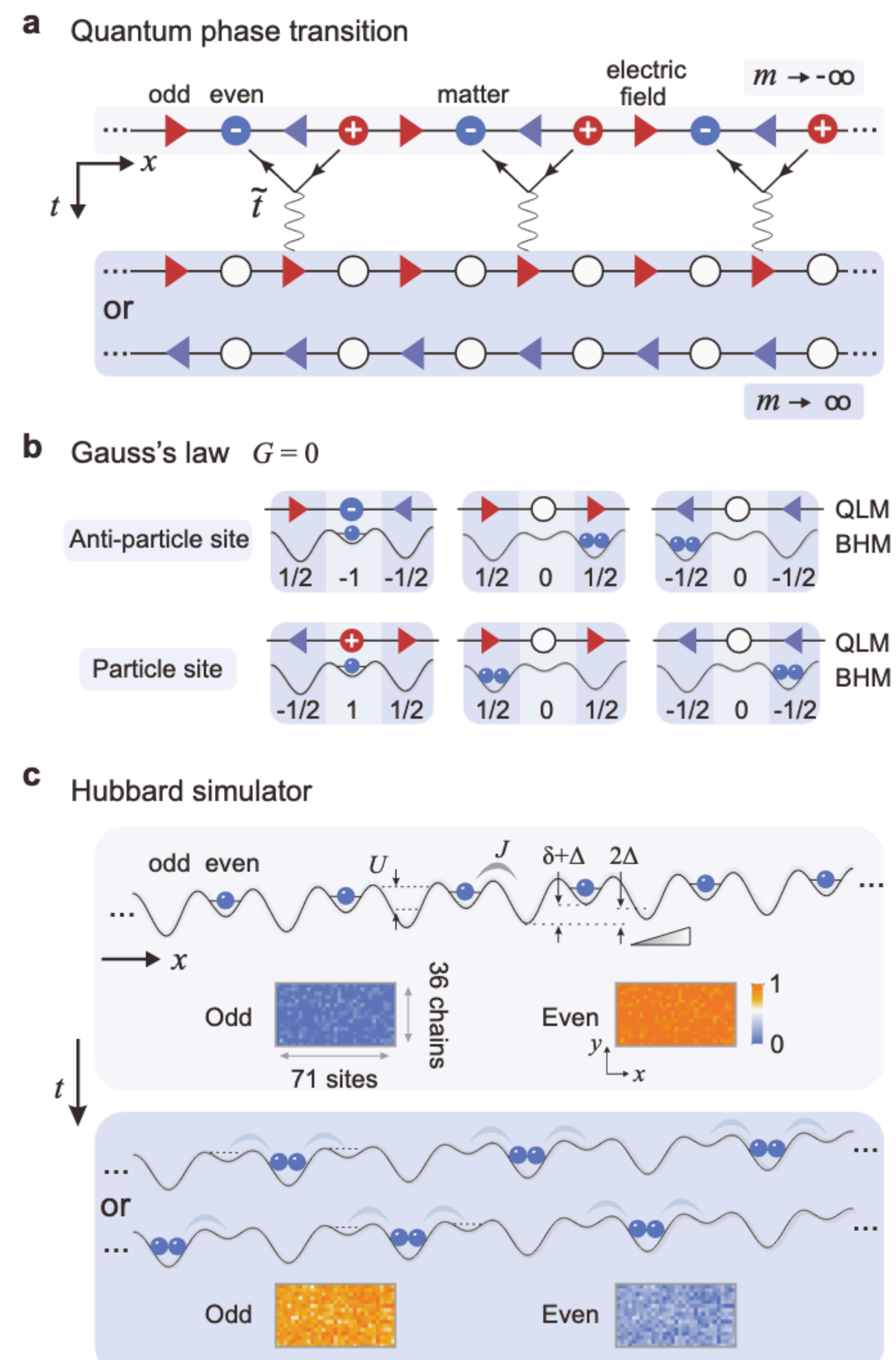
## Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator

Bing Yang, Hui Sun, Robert Ott, Han-Yi Wang, Torsten V. Zache, Jad C. Halimeh, Zhen-Sheng Yuan ✉, Philipp Hauke ✉ & Jian-Wei Pan ✉

*Nature* **587**, 392–396 (2020) | Cite this article



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# Simulating lattice gauge theories within quantum technologies

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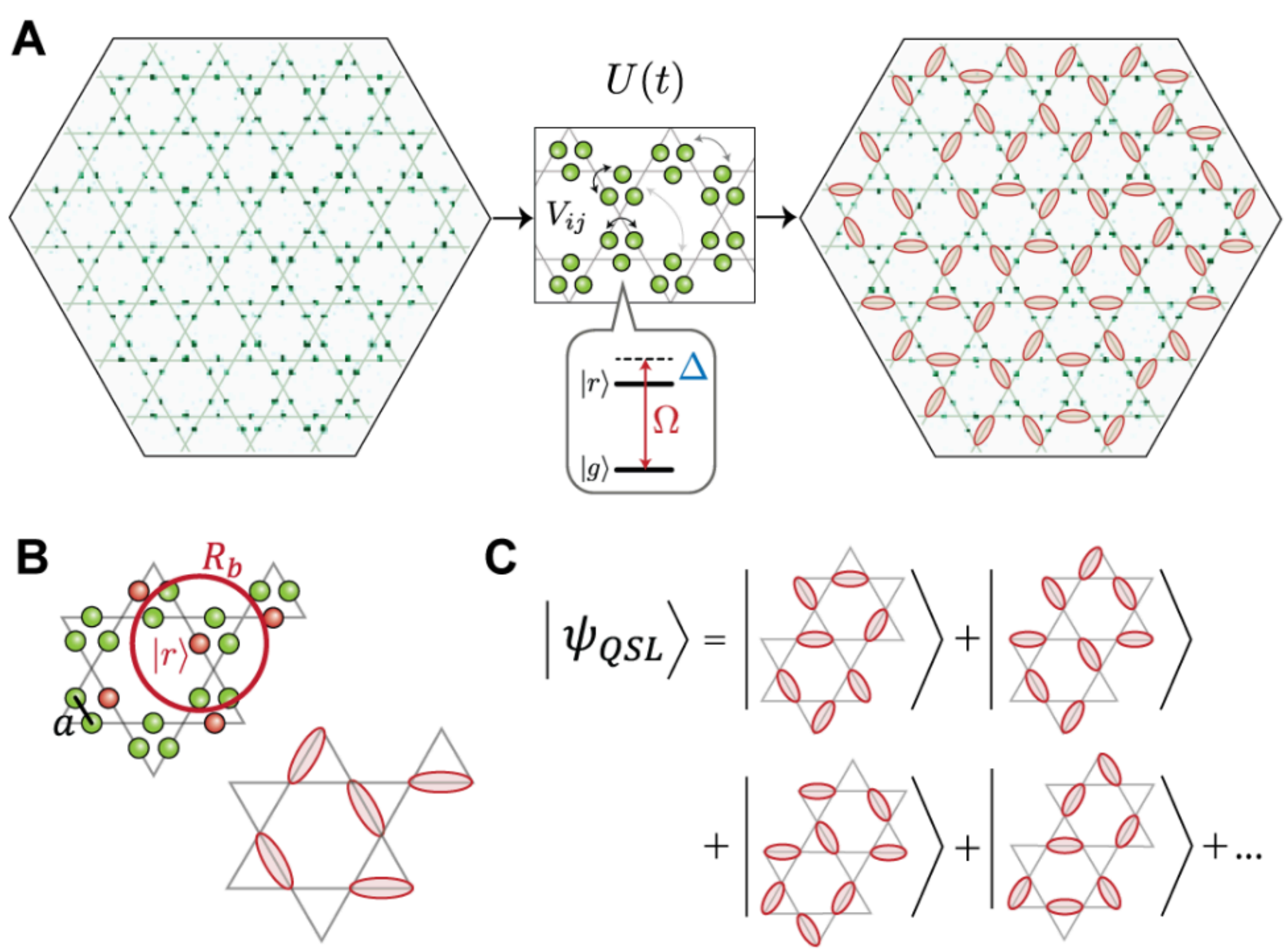
## Probing topological spin liquids on a programmable quantum simulator

G. SEMEGHINI, H. LEVINE, A. KEESLING, S. EBADI, T. T. WANG, D. BLUVSTEIN, R. VERRESEN, H. PICHLER, M. KALINOWSKI, R. SAMAJDAR, A. OMRAN, S. SACHDEV, A. VISHWANATH, M. GREINER, V. VULETIĆ, AND M. D. LUKIN fewer Authors Info & Affiliations

SCIENCE • 2 Dec 2021 • Vol 374, Issue 6572 • pp. 1242-1247 • DOI: 10.1126/science.abi8794

Gauss law = Dimer Constraint = Rydberg blockade

219 atoms



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# Simulating lattice gauge theories within quantum technologies

## Quantum Computing for High-Energy Physics
## State of the Art and Challenges
## Summary of the QC4HEP Working Group

arXiv:2307.03236 (2023)

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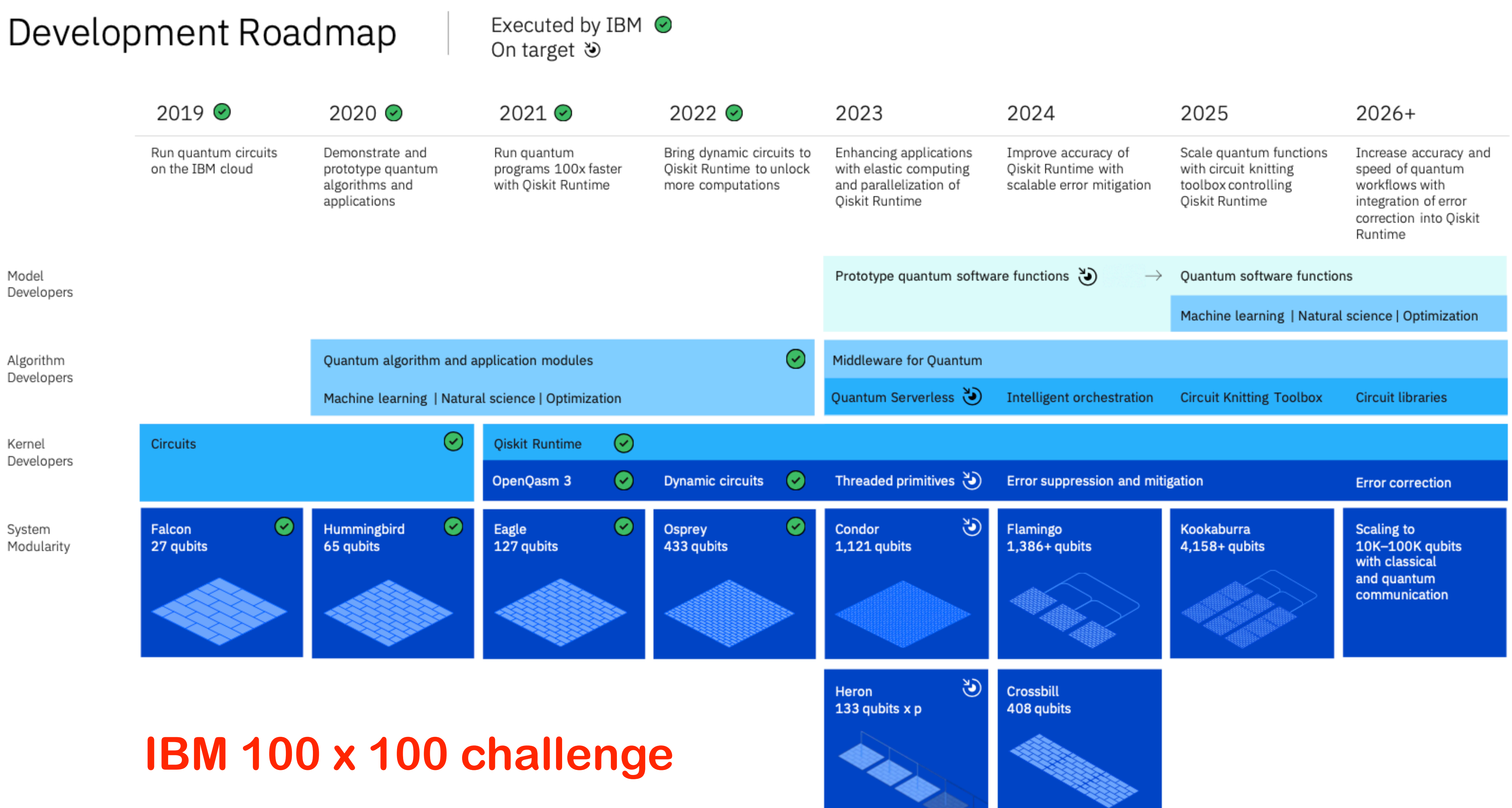
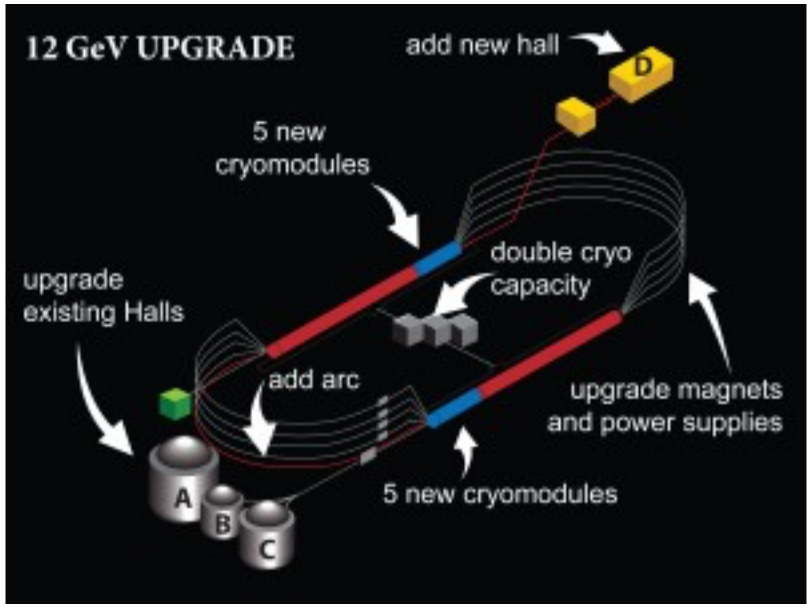
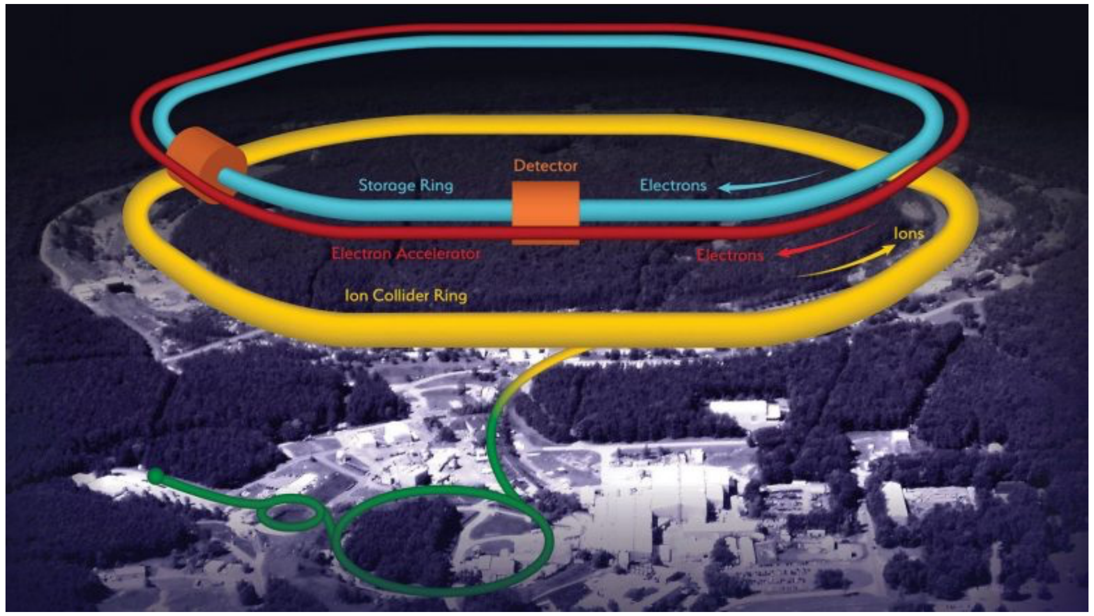


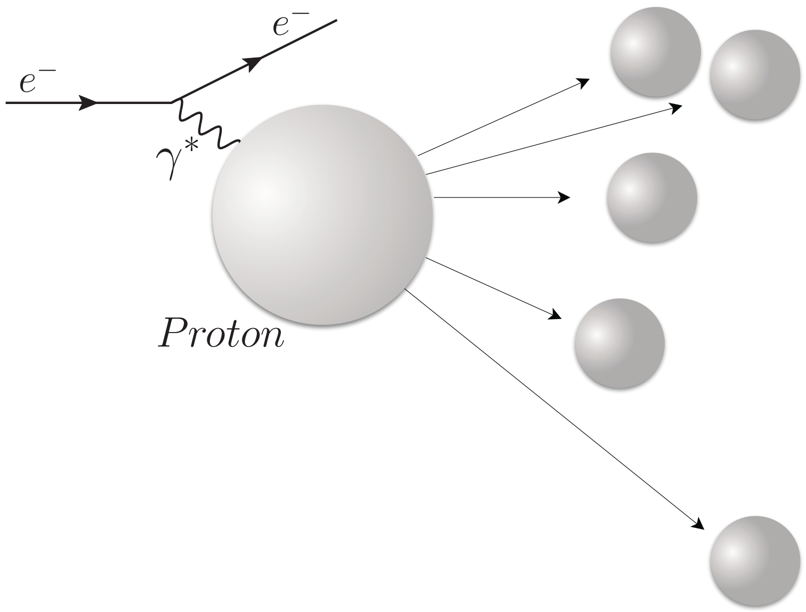

**IBM 100 x 100 challenge**

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators



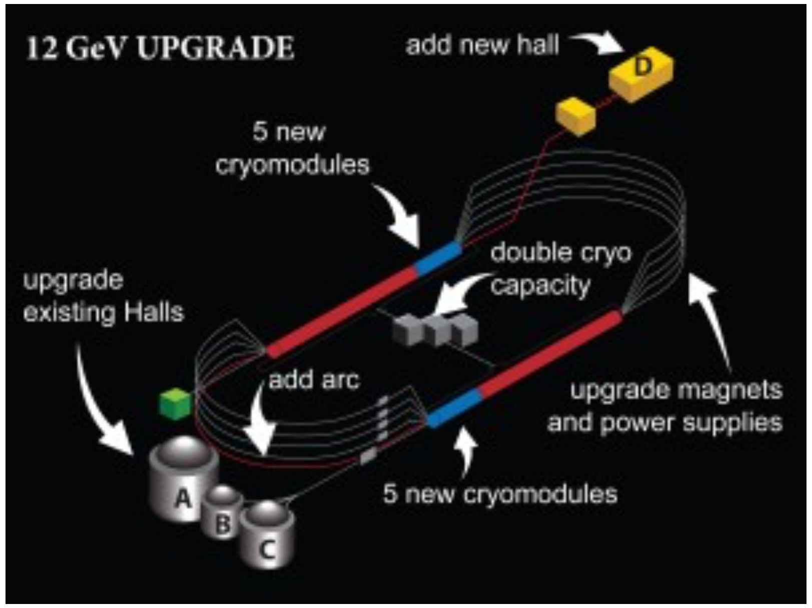

modern microscopes

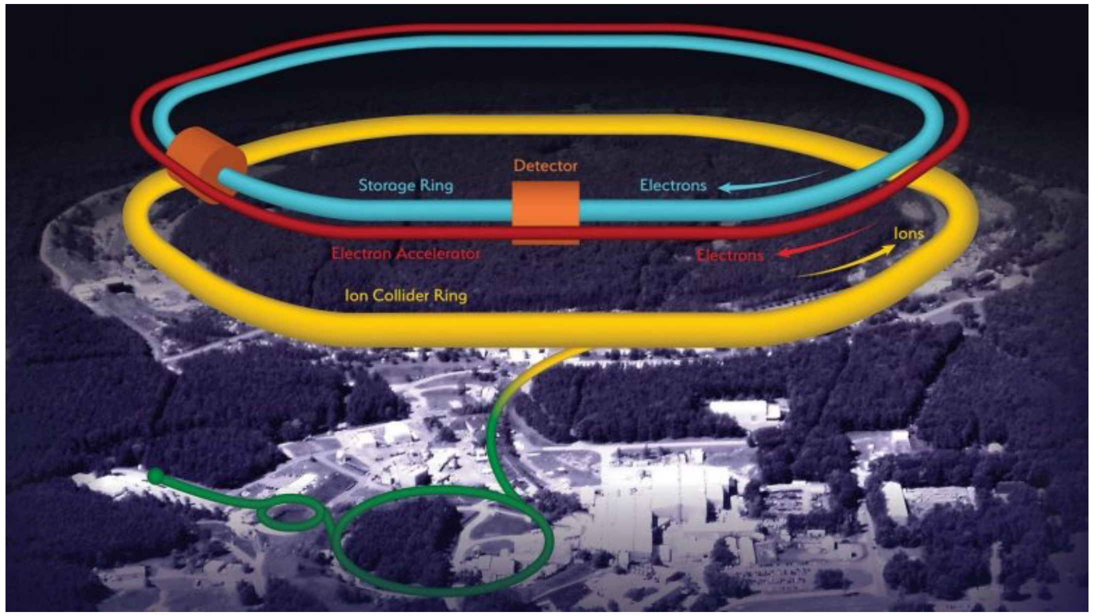



(semi-inclusive) deep-inelastic lepton scattering

# Hybrid algorithms (classical/quantum):
# Real time evolution and light front parton correlators



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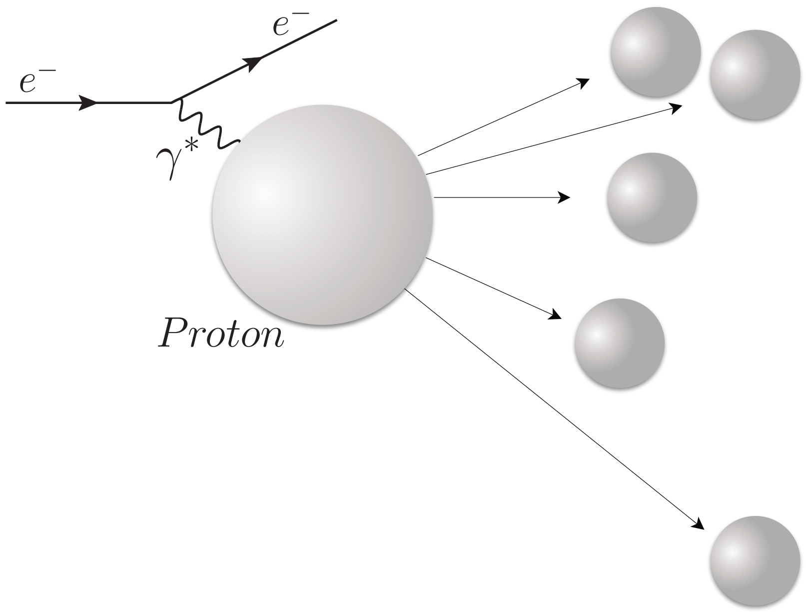


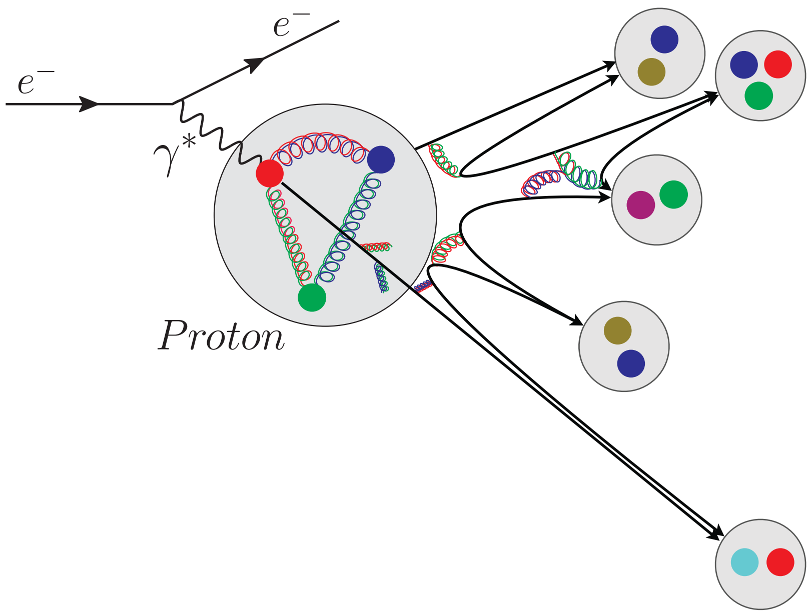


(semi-inclusive) deep-inelastic lepton scattering

highly virtual photons resolve inner (partonic) structure

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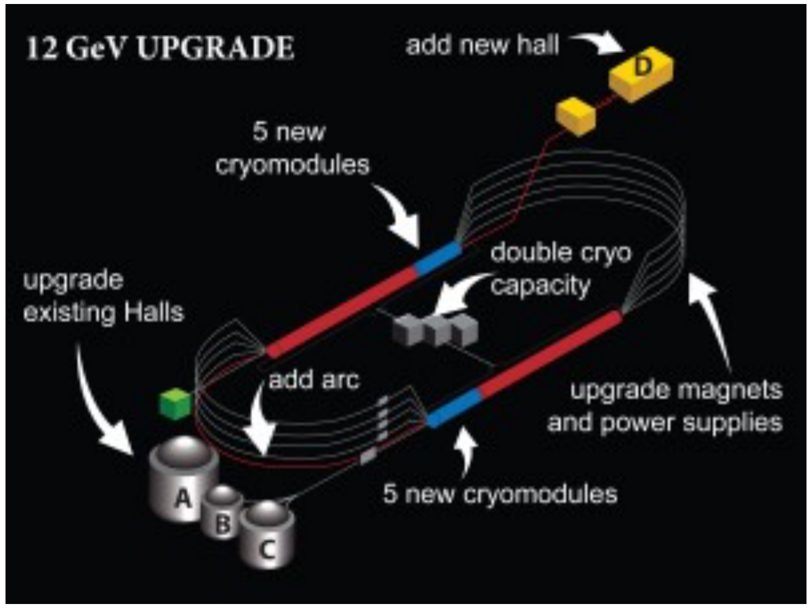


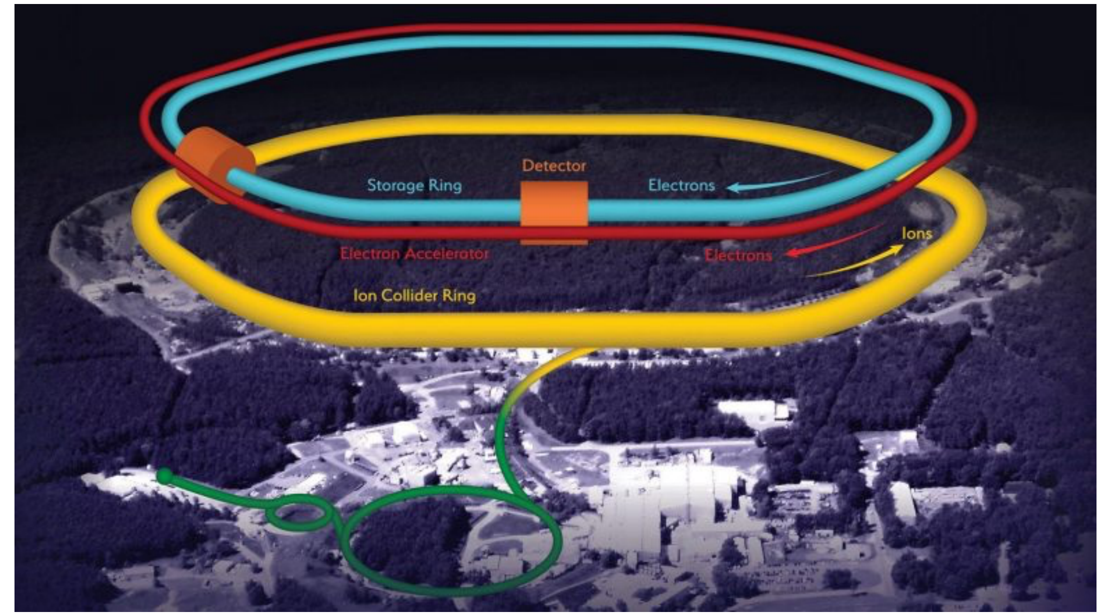


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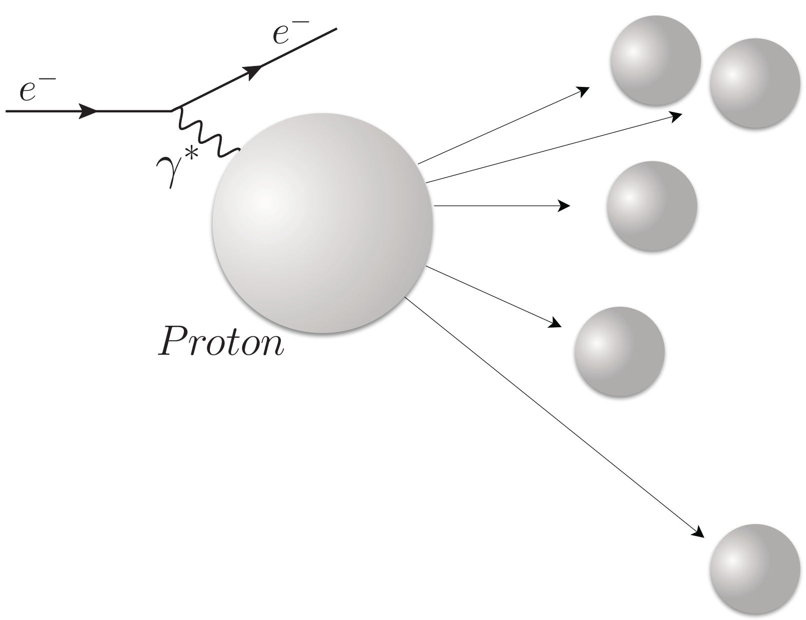
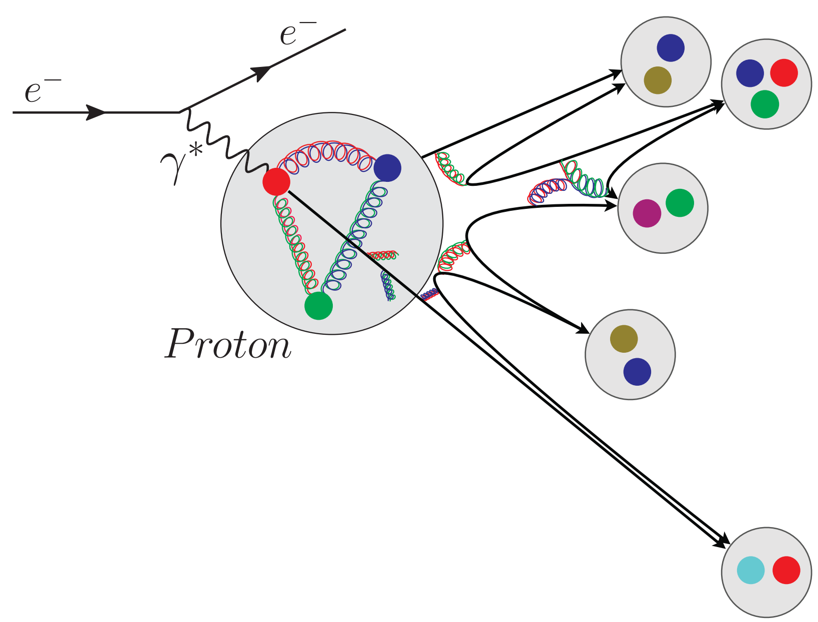
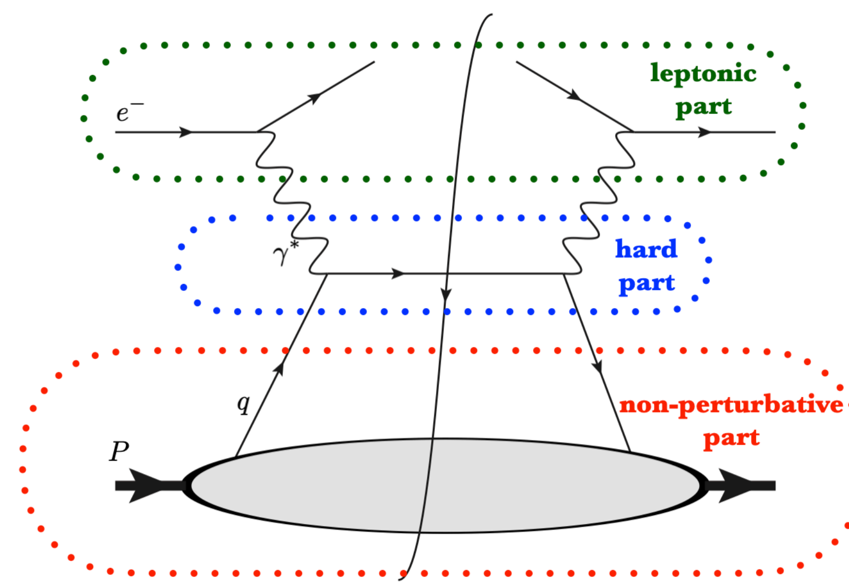



(semi-inclusive) deep-inelastic lepton scattering

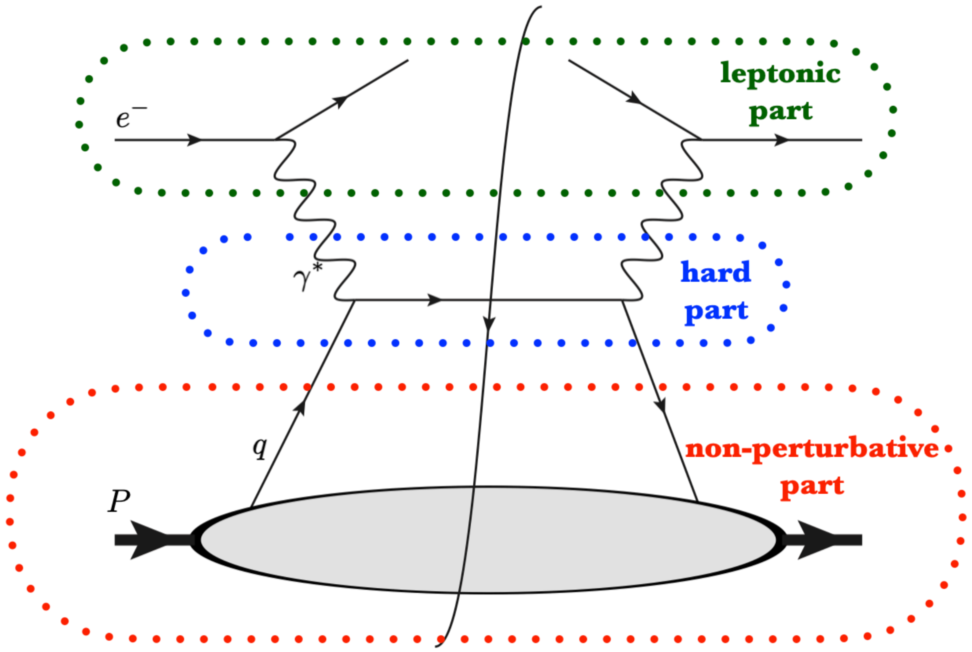
highly virtual photons resolve inner (partonic) structure

factorization theorems separate non-calculable from calculable parts

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

cross section:

$$\sigma(\xi, Q^2) = \sum_f \int_\xi^1 \mathrm{d}\bar{\xi}\, \hat{\sigma}(\bar{\xi}, Q^2)\, f_{f/P}(\xi/\bar{\xi}) \quad + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$

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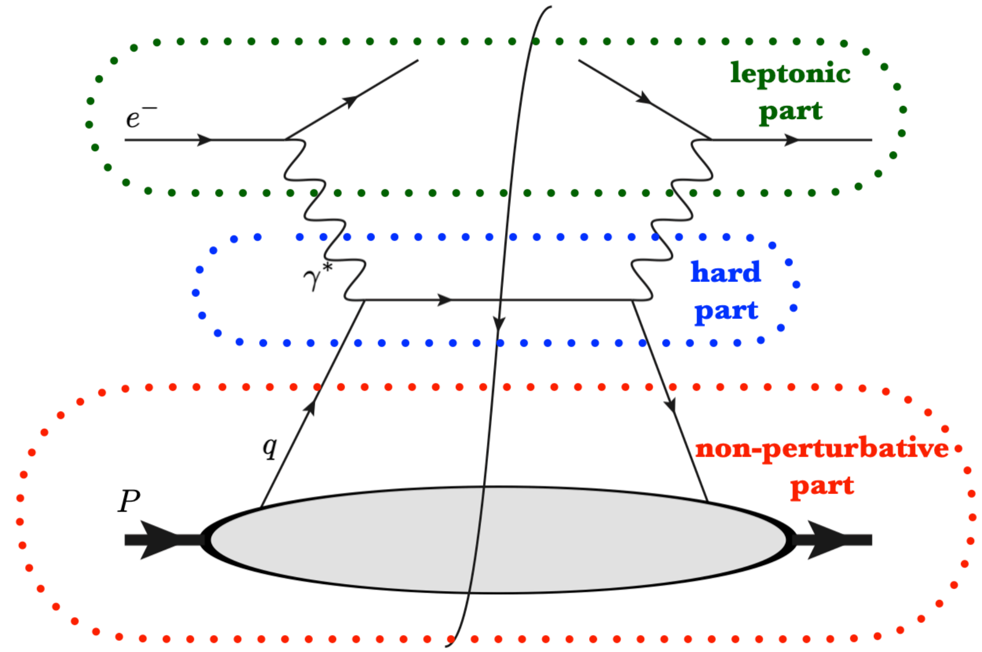


partonic cross section:
calculable

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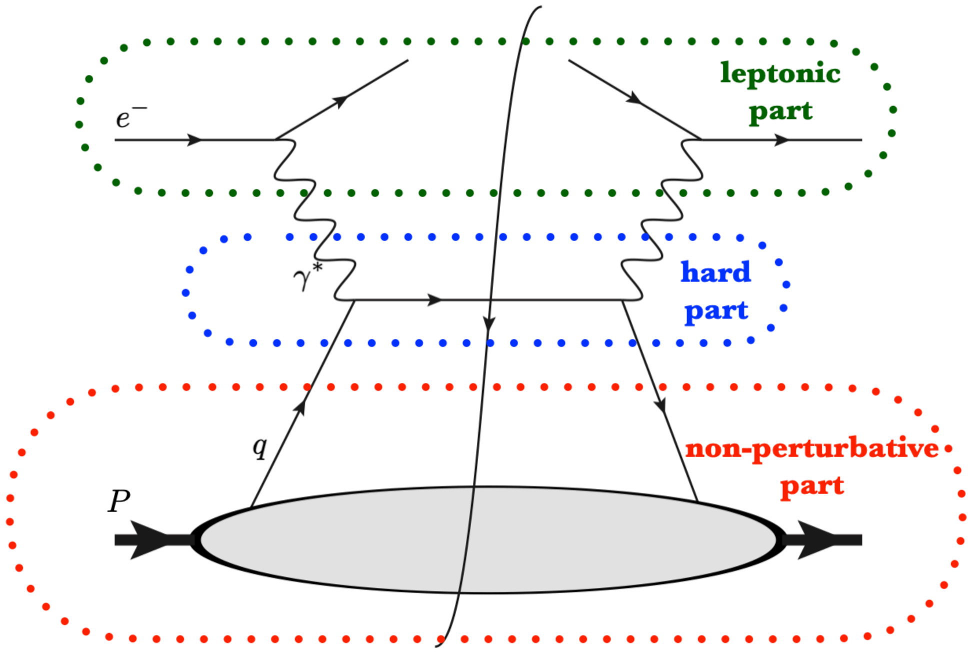


partonic cross section: calculable

non-perturbative parametrization of nucleon: PDFs, TMDs etc.

factorization theorems separate non-calculable from calculable parts

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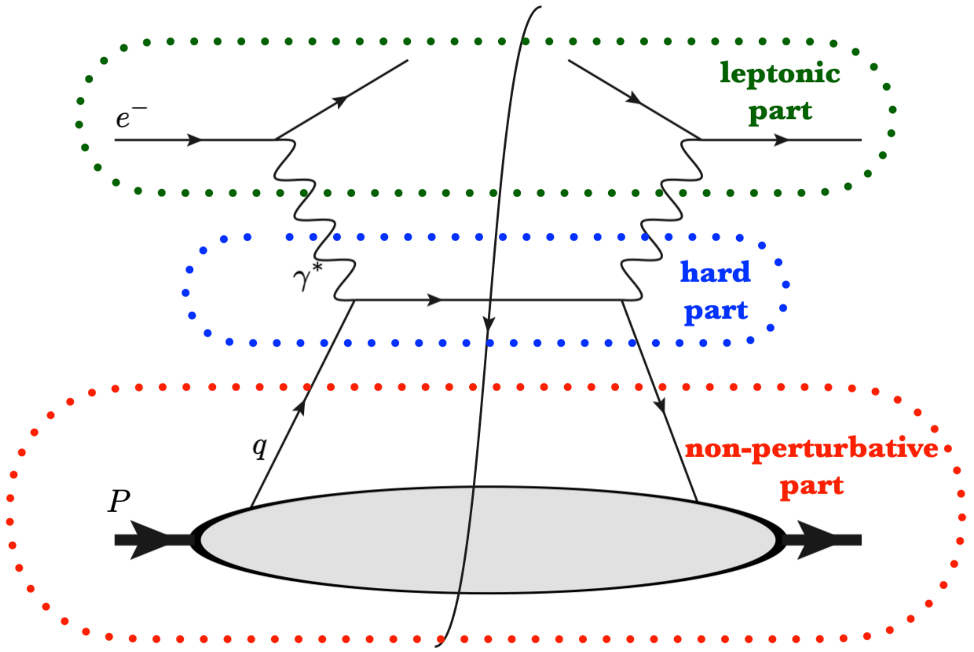


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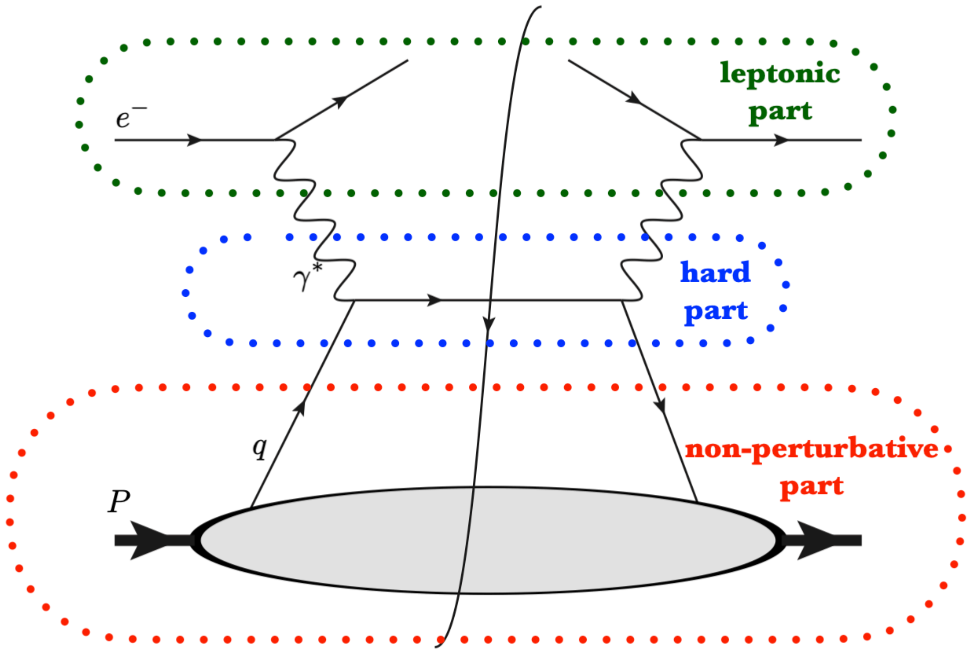


factorization theorems separate non-calculable from calculable parts

$$f_{f/P}(\xi) = \sum_S \int \frac{dy^-}{2\pi} e^{-i\xi p^+ y^-} \langle PS | \left[\bar{\psi}\mathcal{U}\right](y^-) \frac{\gamma^+}{2} \left[\mathcal{U}^\dagger \psi\right](0) | PS \rangle$$

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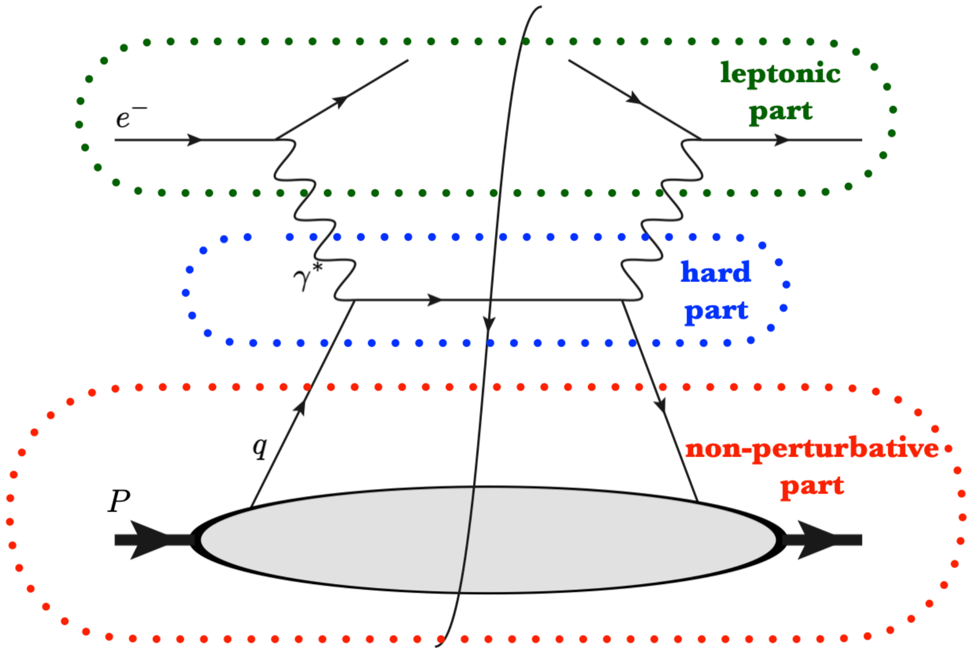


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Non-local (space-time) matrix elements require Wilson lines for gauge invariance

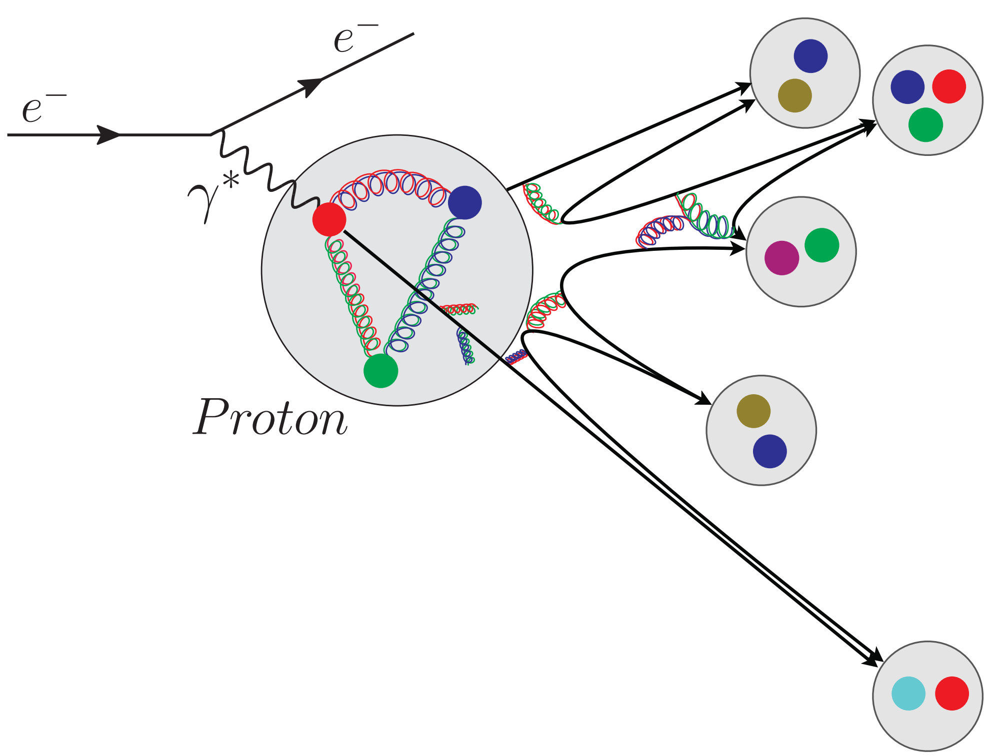
We study the quantum simulation of Wilson loops in space and real-time

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,§]

arXiv:2011.01275
Phys. Rev. D 104, 014512 (2021)




Quantum simulation of light-front parton correlators

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

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Requirements for the quantum simulation of parton correlators:

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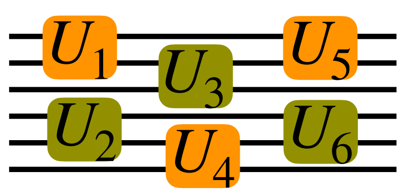
Requirements for the quantum simulation of parton correlators:

- encode in quantum degrees of freedom both matter and gauge fields
- preparation of a reference state, e.g., vacuum, proton, glue-ball
- simulate gauge-invariant quantities, e.g., minimal gauge-matter coupling
- real-time evolution, since the Wilson line is non-local in time
- carry out measurements after the evolution, i.e., quantum interferometer

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

## Digital simulation: Universal simulator

$|\psi(0)\rangle$



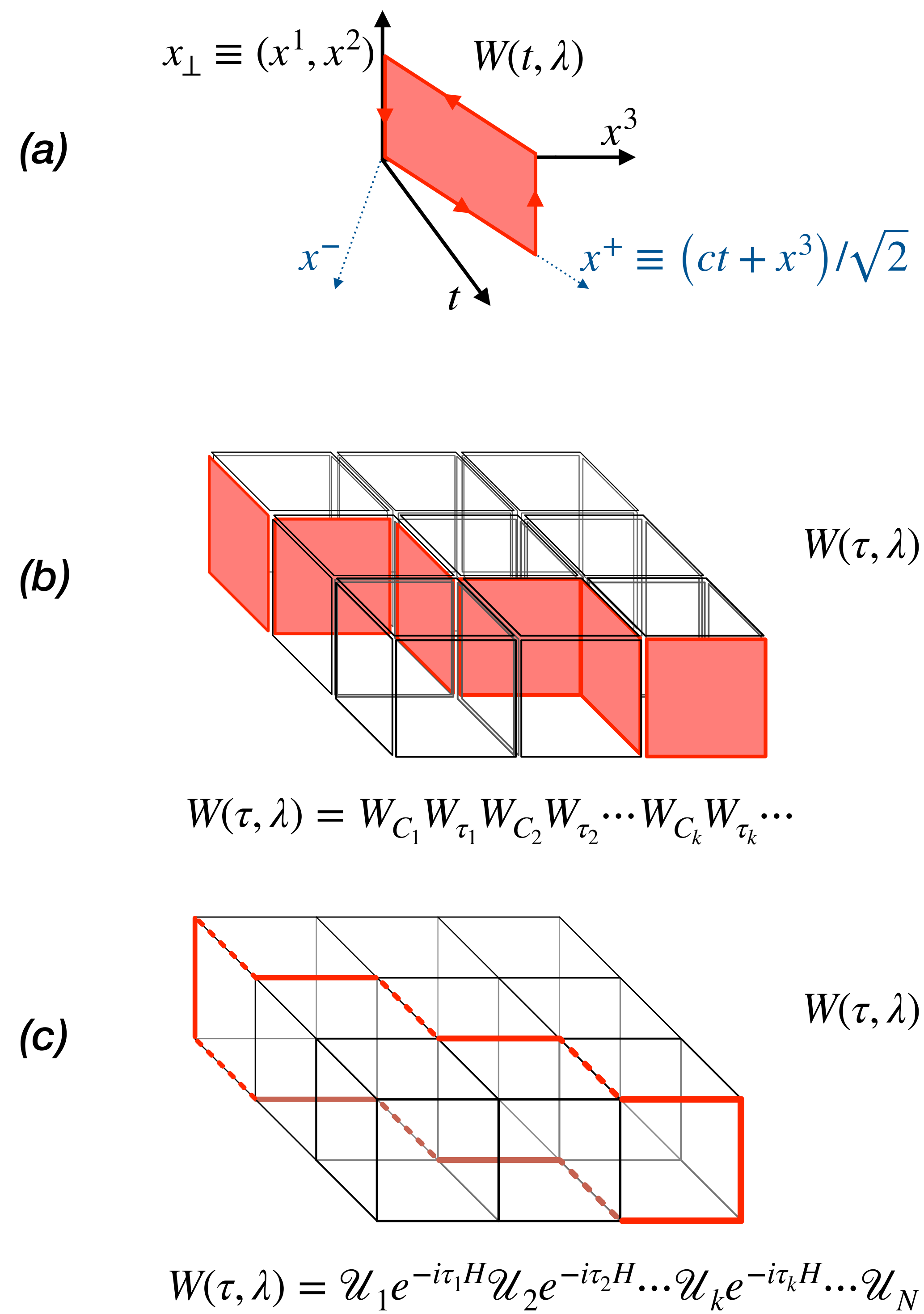

$|\psi(t)\rangle$

Decompose dynamics into sequence of quantum gates

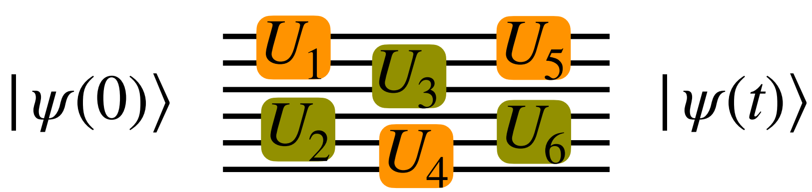
Stroboscopic simulation in an analog simulator

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

## Discretisation of space-time in a Hamiltonian formulation




## Digital simulation: Universal simulator

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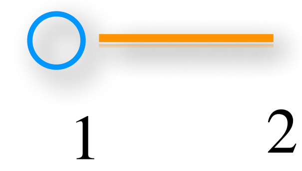
Note: in the Hamiltonian formulation the temporal gauge $A_0=0$ is chosen

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

## Moving a single quark:

$$u_{12} = \exp\left\{ \frac{-i\pi}{2} \sum_{\alpha\beta} \left[ \psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right] \right\}$$

$$\rightarrow (-i)\left[ \psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right],$$



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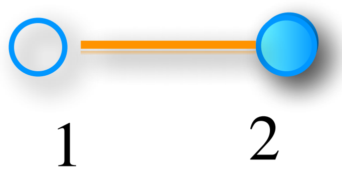

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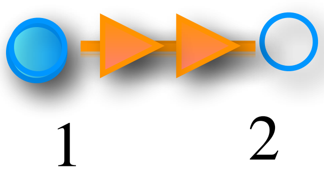

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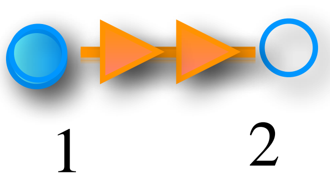


Starting from a "meson" state:

$$|\,\mathrm{m}\rangle \equiv \frac{1}{\mathrm{N}^{1/2}}\sum_{\alpha=1}^{\mathrm{N}} |\,\alpha(1), \bar{\alpha}(2)\rangle$$

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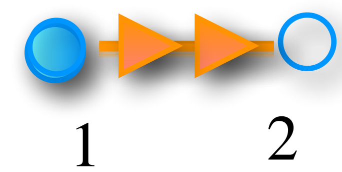


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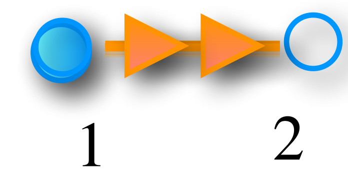


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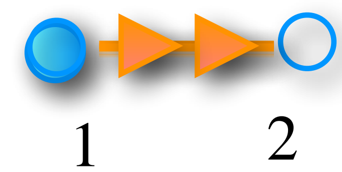


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$$\mathcal{U}(A_1, B_L) = \frac{1}{N^{1/2}} \sum_{\alpha\beta\cdots\mu\nu\omega\cdots\theta\phi} |\,\alpha(A_1)\rangle U_{\alpha\beta}(e_1)\cdots U_{\mu\nu}(e_{L/2-1}) U^{*}_{\omega\nu}(e_{L/2})\cdots U^{*}_{\phi\theta}(e_{L-1})\,|\,\bar{\phi}(B_L)\rangle$$

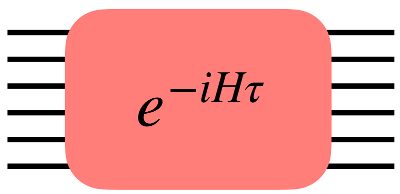
$$= \frac{1}{N^{1/2}} \sum_{\alpha\phi} |\,\alpha(A_1)\rangle \mathcal{U}_{\alpha\phi}(e_1, \cdots, e_{L-1})\,|\,\bar{\phi}(B_L)\rangle$$

we built a spatial Wilson line

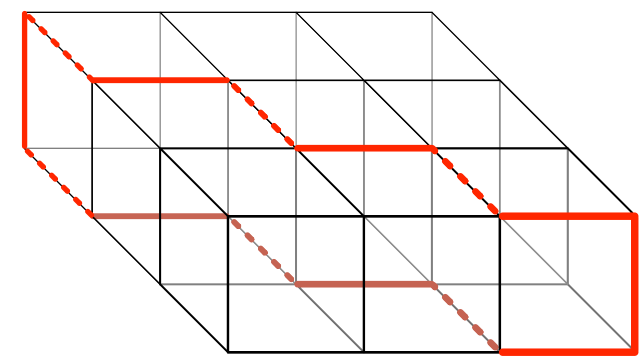
# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

Time-evolution by a single time step

$|\psi(0)\rangle$




$|\psi(\tau)\rangle$



$W(\tau, \lambda)$

$$W(\tau,\lambda) = \mathcal{U}_1 e^{-i\tau_1 H}\mathcal{U}_2 e^{-i\tau_2 H}\cdots\mathcal{U}_k e^{-i\tau_k H}\cdots\mathcal{U}_N$$

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

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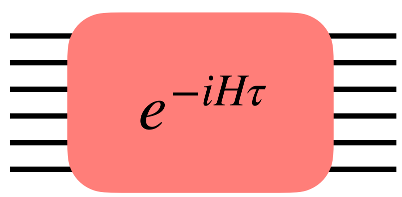
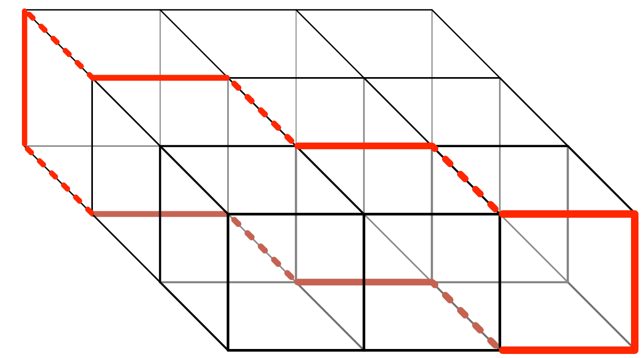
$|\psi(0)\rangle$  $|\psi(\tau)\rangle$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Decompose dynamics induced by systems' Hamiltonian into sequence of quantum gates

Digital simulation can simulate any model but requires many gate operations

Stroboscopic simulation in an analog simulator

$$H = H_{\rm el} + H_{\rm mag}$$

Efficient for local interactions

$$e^{-iH} \simeq \left[ e^{-iH_{\rm el}/2n_T} e^{-i\lambda H_{\rm mag}/n_T} e^{-iH_{\rm el}/2n_T} \right]^{n_T}$$

Trotter-Suzuki approximation

S. Lloyd, Science (1996)

# Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

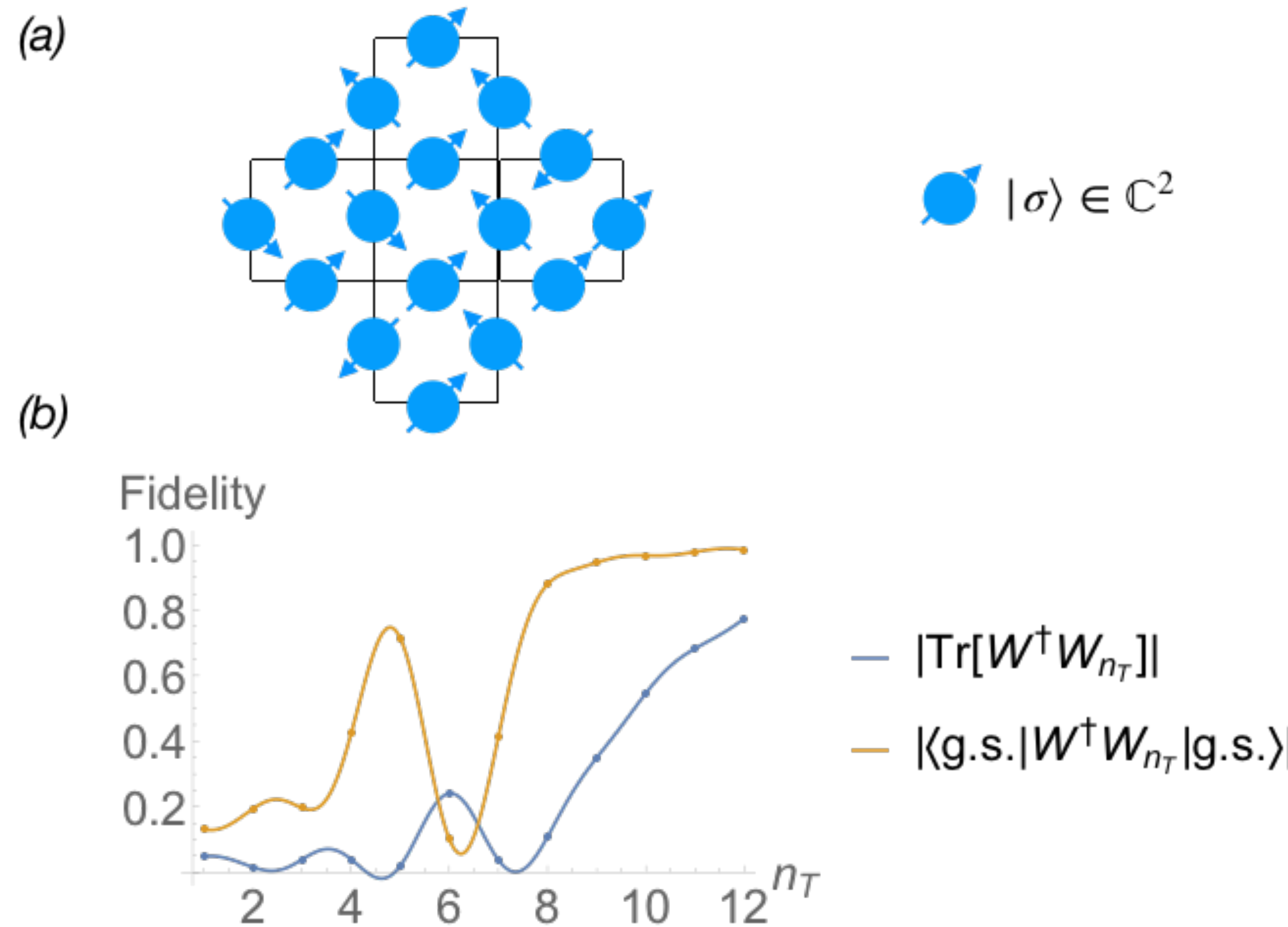
## Proof of principle: $Z_2$ pure gauge model

operator norm:

$$\left| \mathrm{Tr}\left[ \mathscr{W}^{\dagger} \mathscr{W}_{n_T} \right] \right|$$

ground state fidelity:

$$\left| \langle g.s.| \mathscr{W}^{\dagger} \mathscr{W}_{n_T} | g.s. \rangle \right|$$




within a few Trotter steps a fidelity closed to one is achieved

# CERN’s new Next Generation Triggers Project (NGT), supported by a grant from the E&W Schmidt Fund for Strategic Innovation.



***Core objectives for Quantum Simulation:***

*Quantum Simulations on Classical Hardware:* quantum algorithms for state preparation and real-time dynamics simulations, including quantum simulation of parton distribution functions from first principles. Initially, I plan to utilise classical hardware to achieve a hybrid simulation, blending classical and quantum approaches seamlessly.

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ikerbasque Basque Foundation for Science

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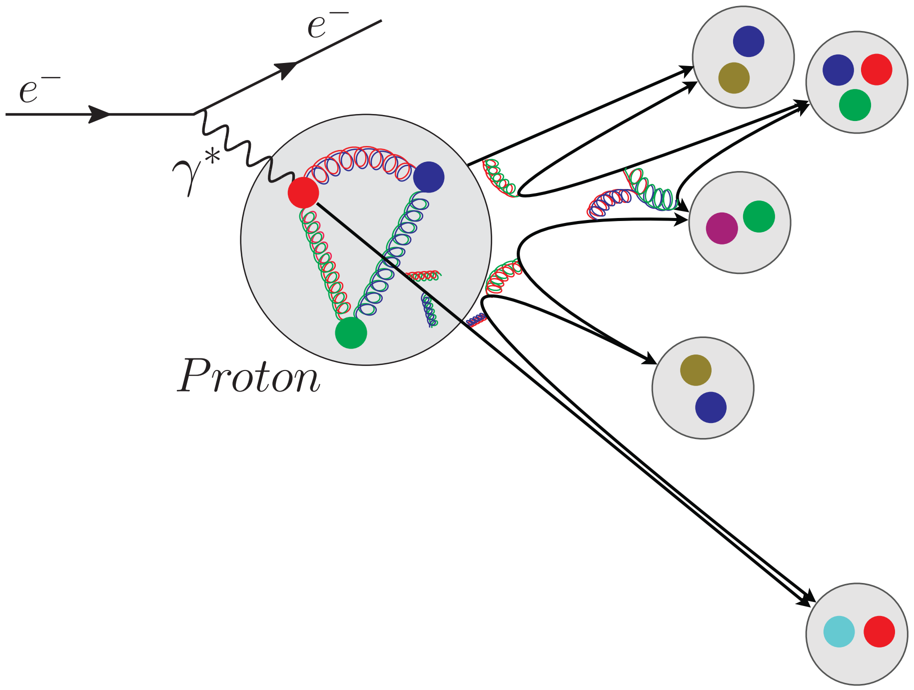
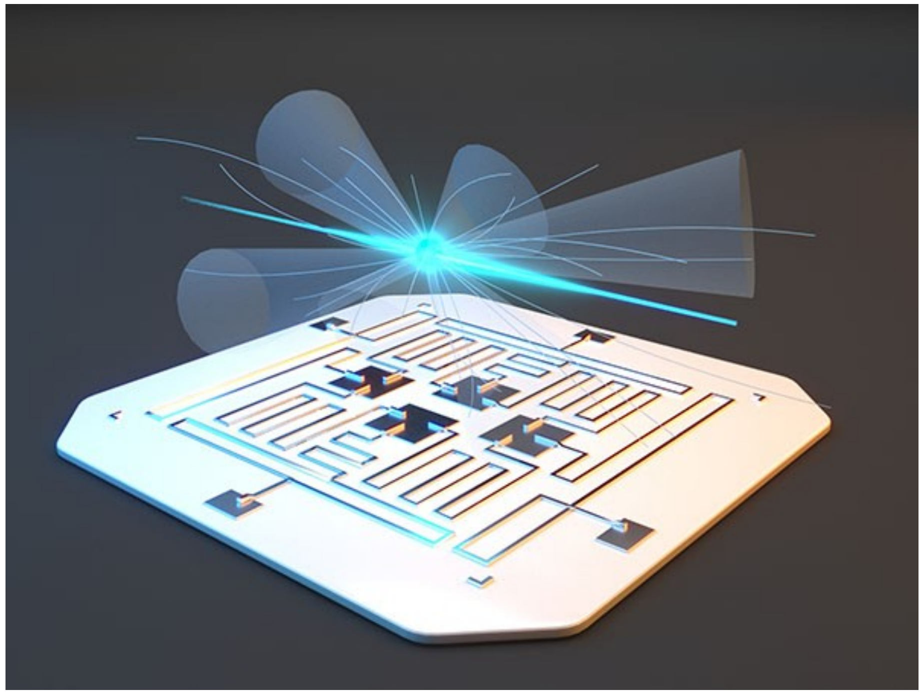
*Quantum Simulations on Quantum Hardware:* exploring Rydberg quantum platforms and strengthening collaborations with experimentalists in superconducting circuits to advance the quantum simulation of high-energy problems, extending existing partnerships from projects such as QuantERA.

# A fruitful dialogue (two-way communication)




High-Energy and Nuclear Physics



Quantum Information Science and Technology

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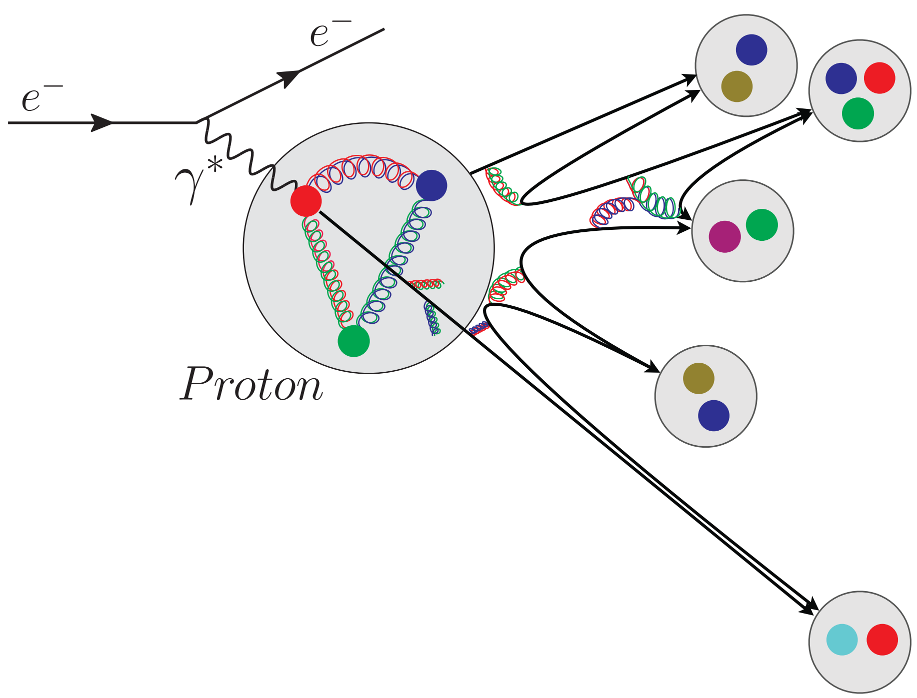


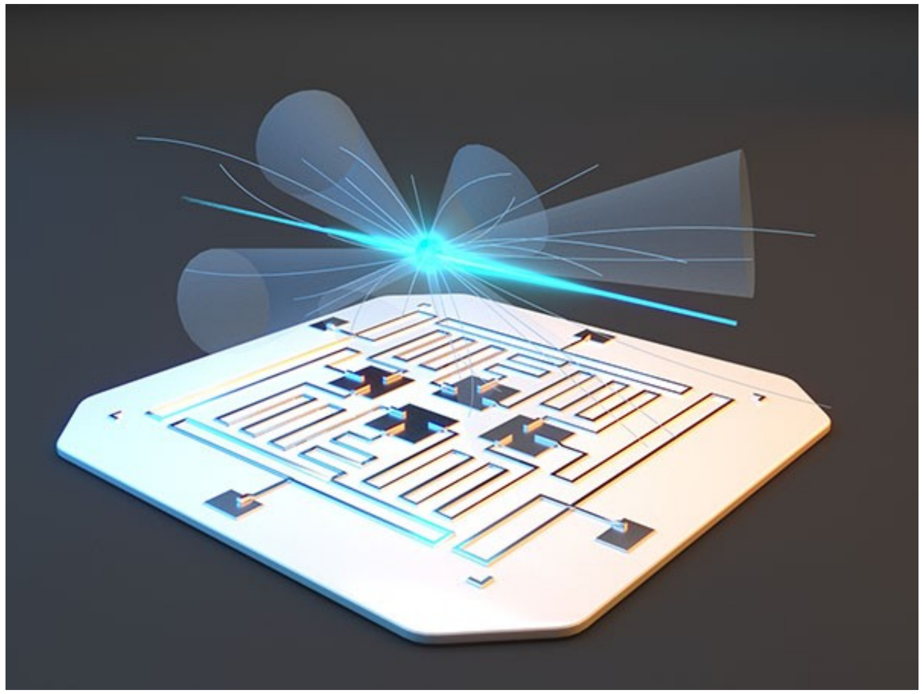

High-Energy and Nuclear Physics

Quantum Information Science and Technology

PHYSICAL REVIEW B **105**, L201104 (2022)

Letter

## Role of anomalous symmetry in 0-$\pi$ qubits

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[2]*EHU Quantum Center, University of the Basque Country, UPV/EHU, Barrio Sarriena s/n, 48940 Leioa, Biscay, Spain*

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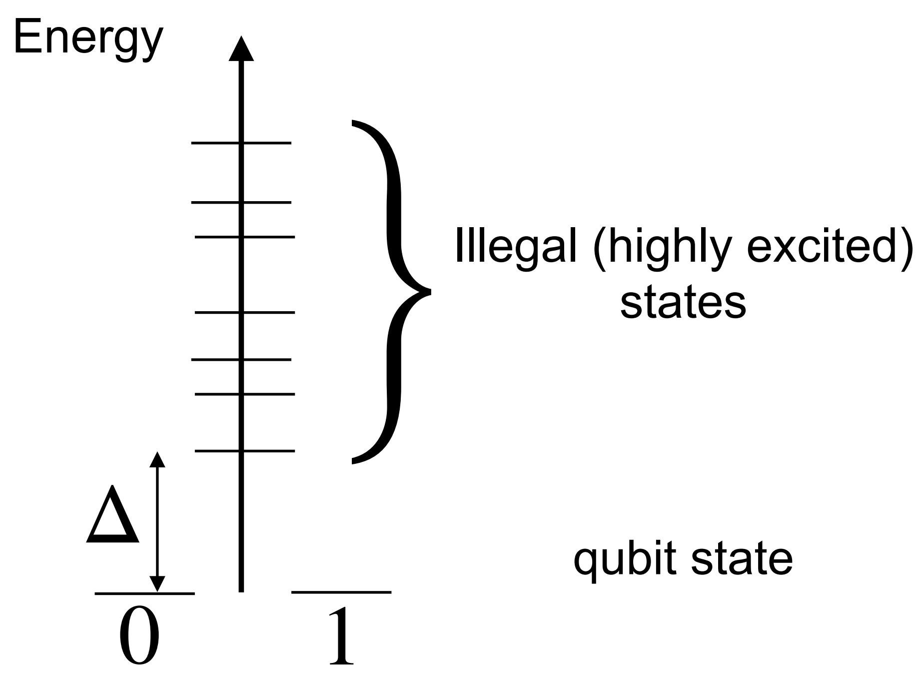
[5]*IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain*

# 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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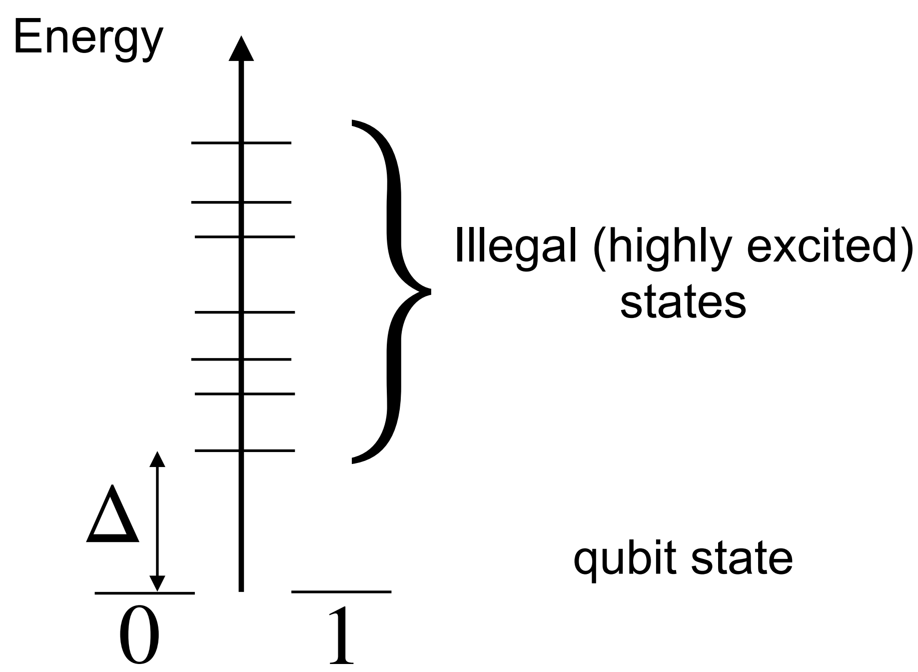


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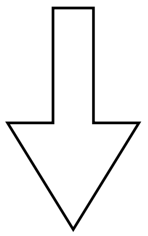

$$\hat{H} \propto \epsilon \mathbb{I}$$

**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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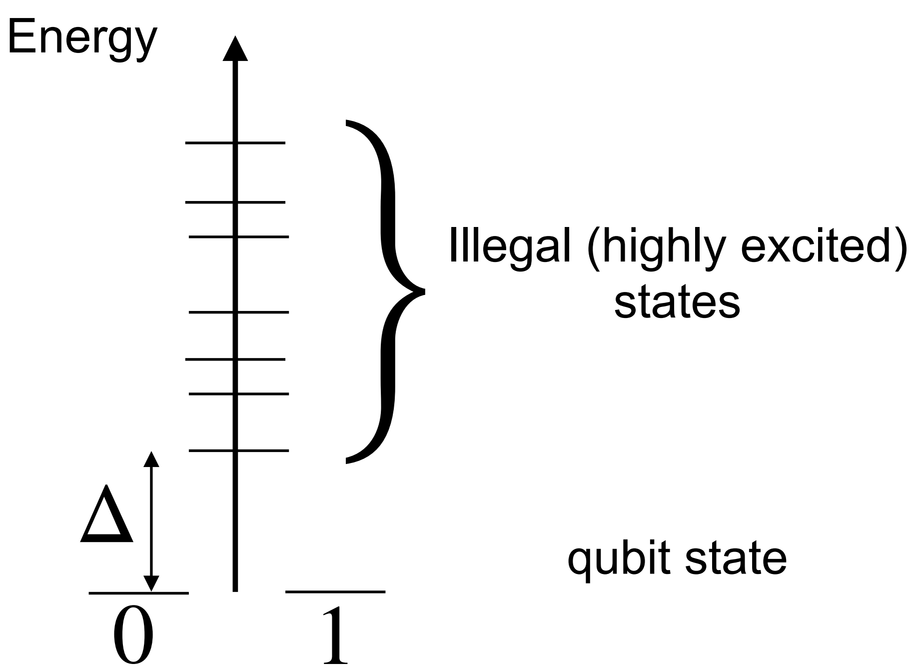


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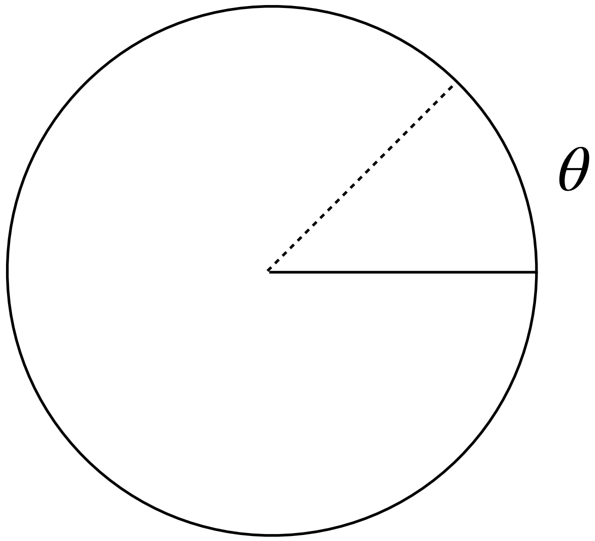
The degeneracies in the protected regime of the $0-\pi$ qubit are a remnant of the anomalous symmetry.
Degeneracies independent of energy parameters

# 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

Reflexion by an axis

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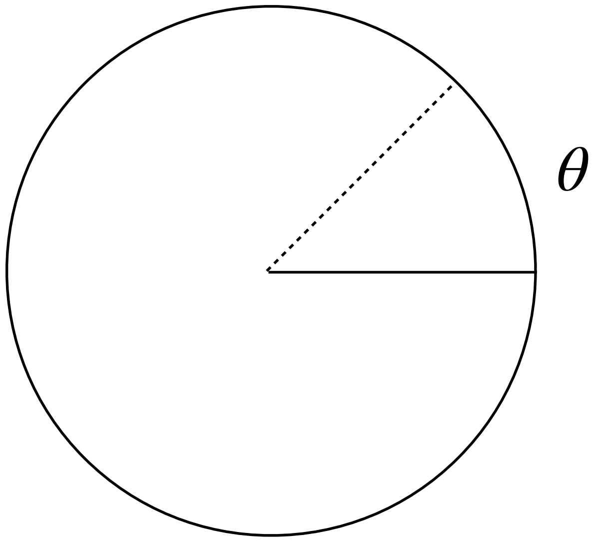


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Rotation by any angle ($SO(2)$)

Reflexion by an axis ($\mathbb{Z}_2$)

## 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: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$  $SO(2) \sim U(1)$

# The role of the anomaly on decoherence robust qubits



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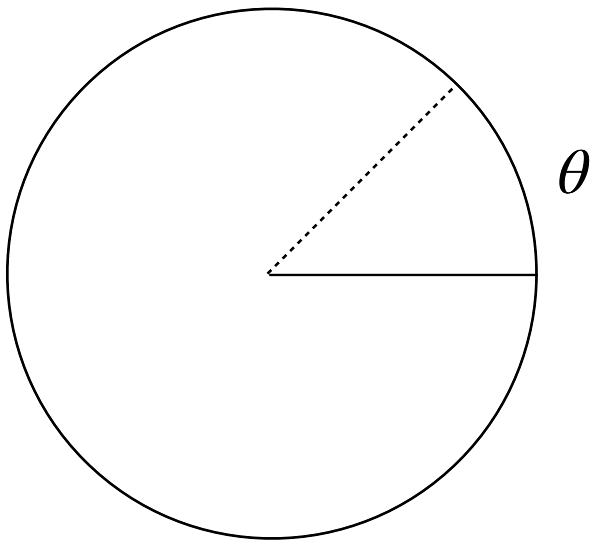


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Rotation by any angle → $SO(2)$

Reflexion by an axis → $\mathbb{Z}_2$

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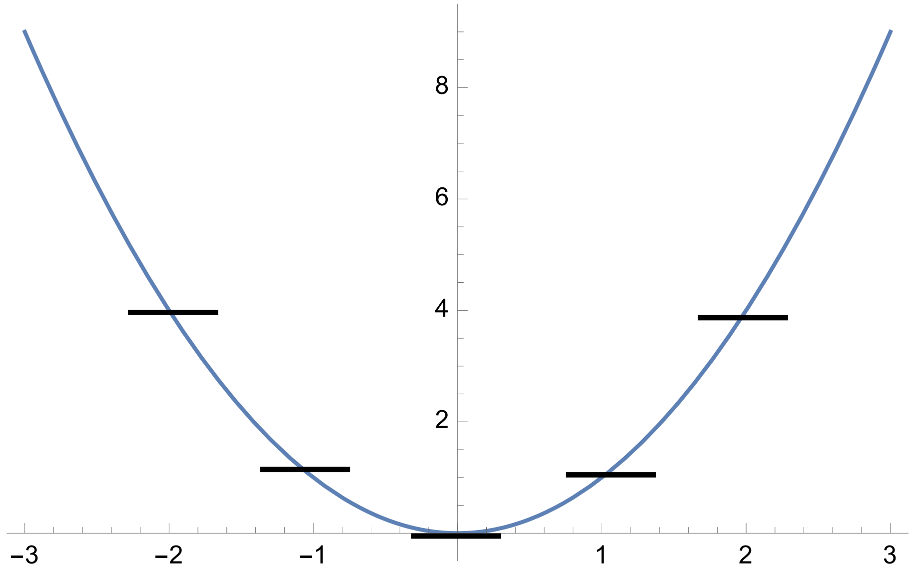
About the reflexion symmetry…

$n_g = 0$

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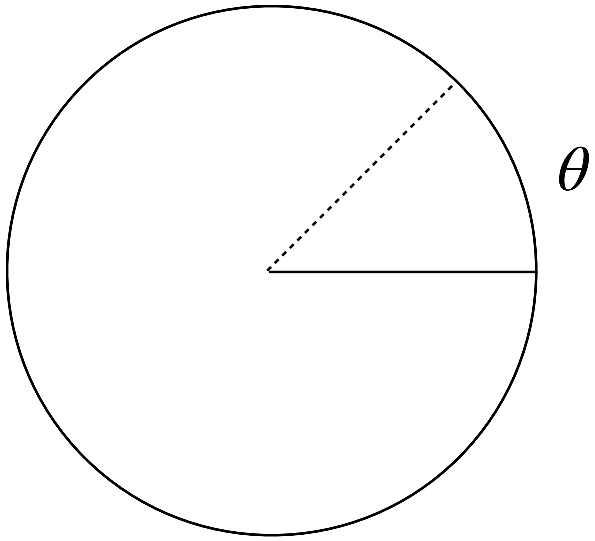


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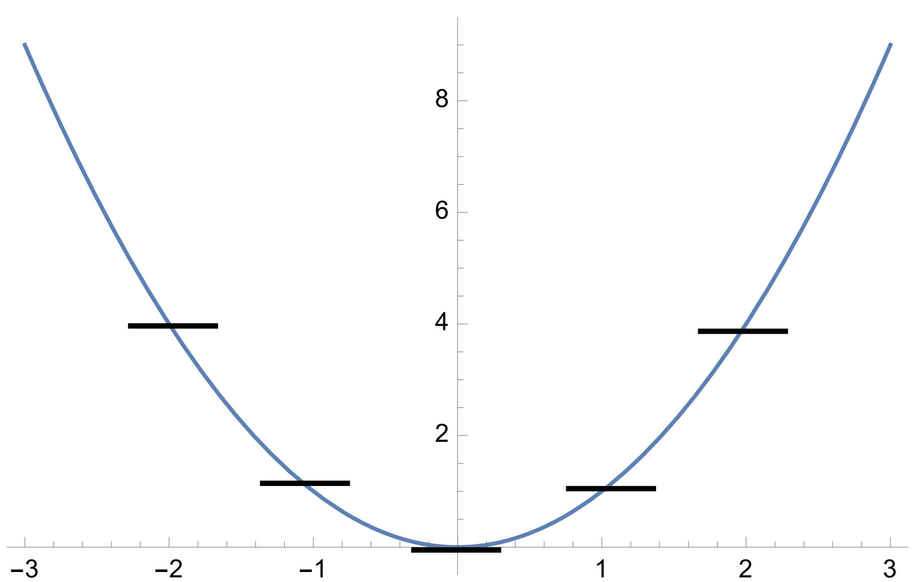
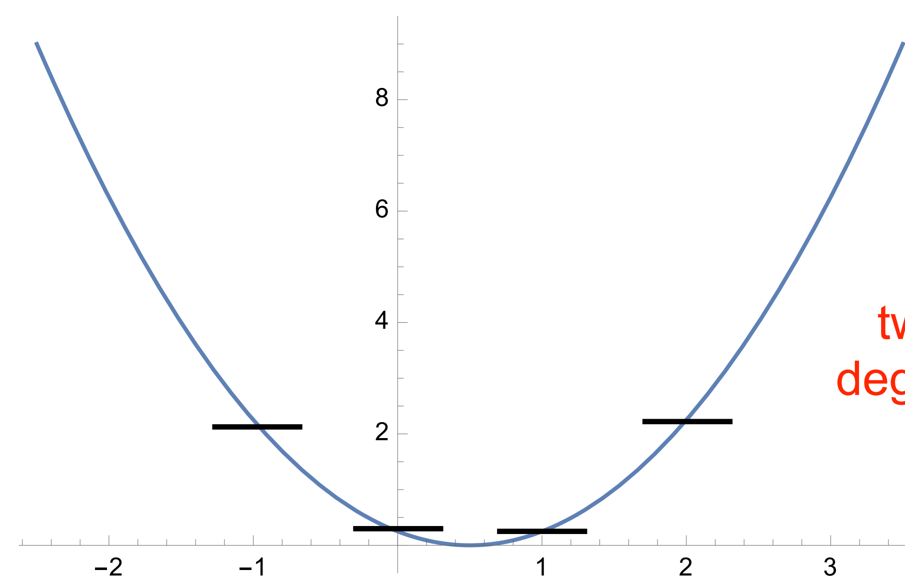



$$O(2) = SO(2) \times \mathbb{Z}_2$$

$n_g = 1/2$



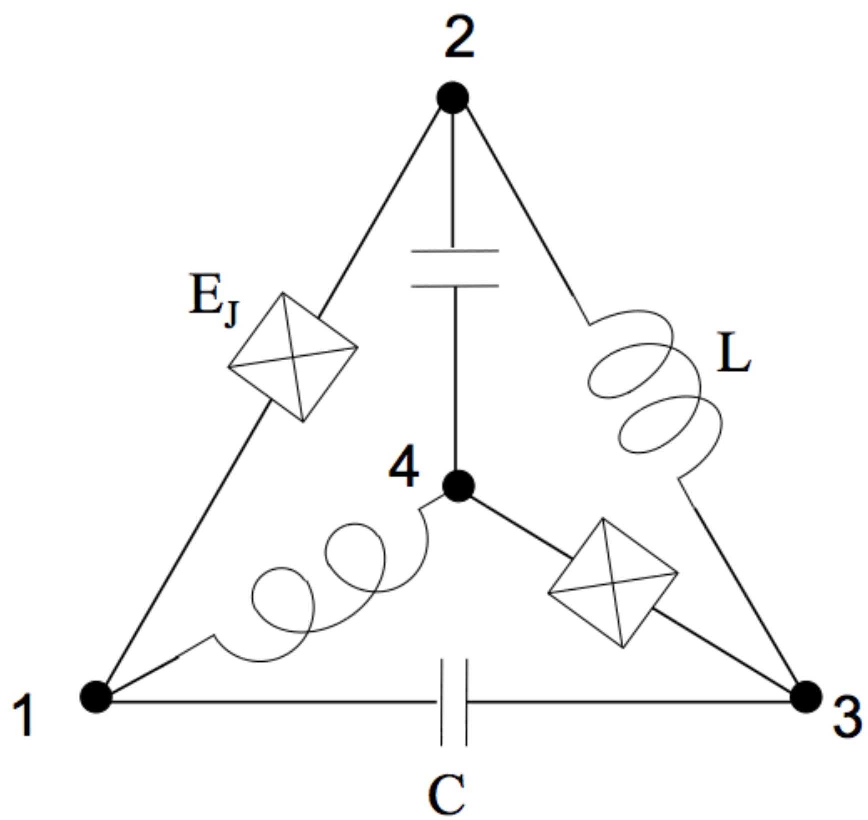

two-fold degeneracy

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

# The role of the anomaly on decoherence robust qubits



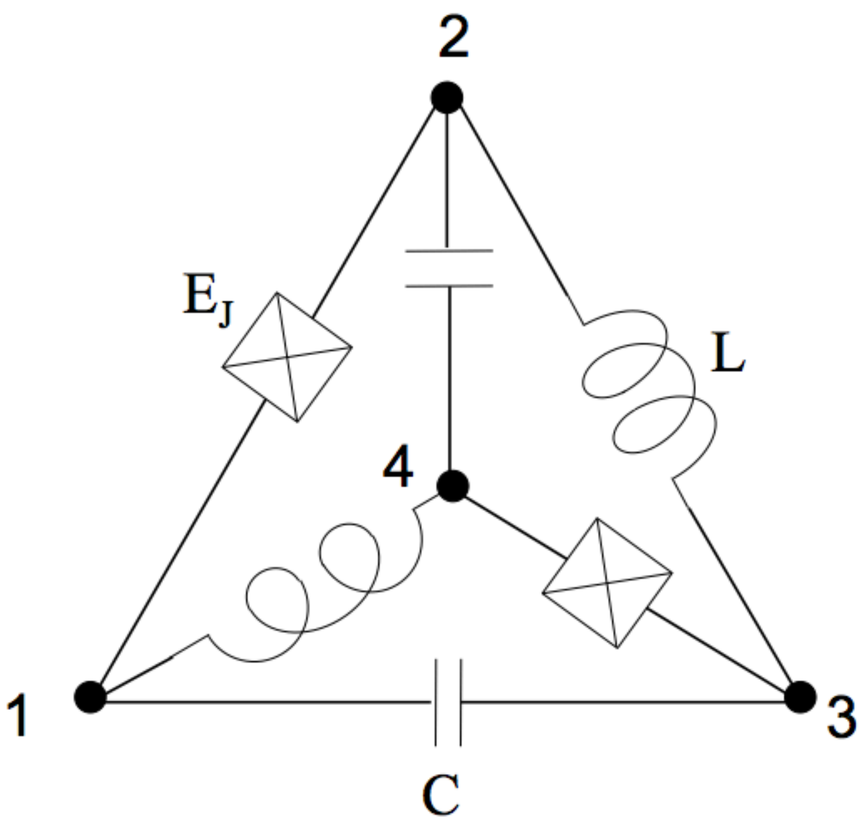
## $0-\pi$ Hamiltonian




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

# The role of the anomaly on decoherence robust qubits






## $0 - \pi$ Hamiltonian

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

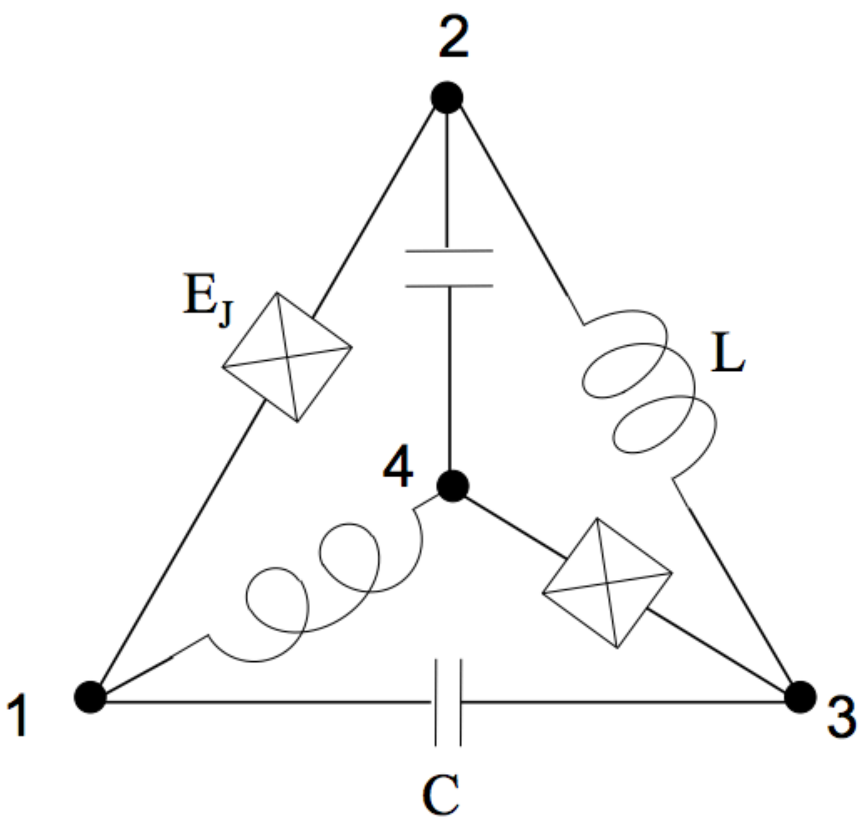
$$\left[\hat{\theta}, \hat{n}_\theta\right] = i \qquad \theta \in (-\pi, +\pi] \qquad \text{spect}\left(\hat{\mathrm{n}}\right) \in \mathbb{Z}$$

$$\left[\hat{\phi}, \hat{Q}_\phi\right] = i \qquad \phi \in \mathbb{R} \qquad \hat{Q}_\phi \in \mathbb{R}$$

# The role of the anomaly on decoherence robust qubits



## $0-\pi$ Hamiltonian




***high symmetry point***

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

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

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

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harmonic oscillator — diagonal — interaction

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# The role of the anomaly on decoherence robust qubits



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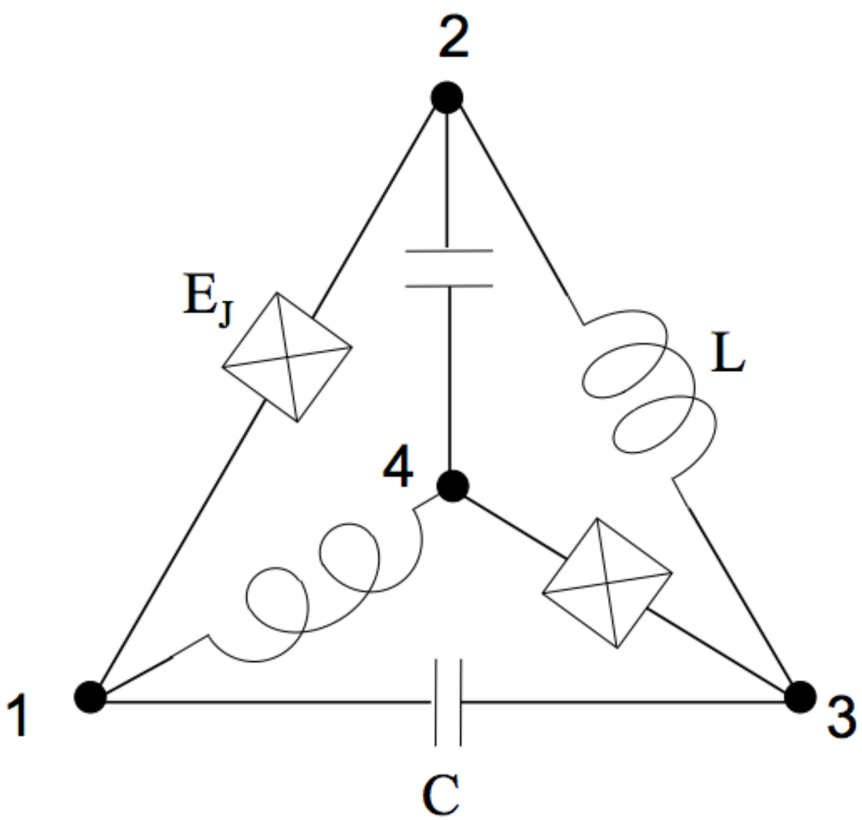


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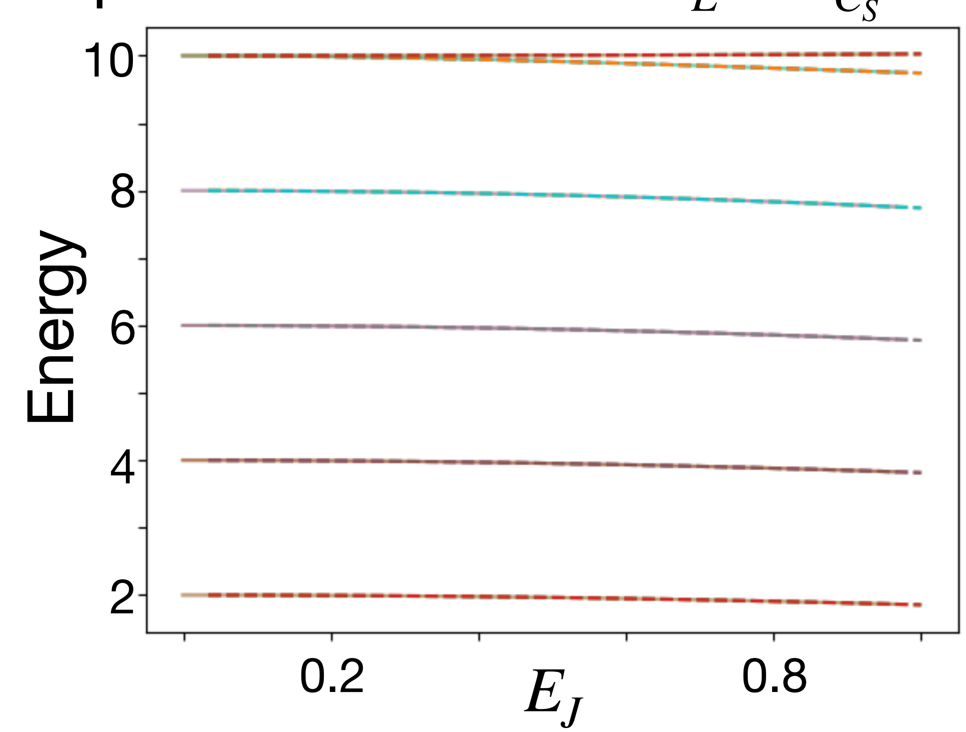
Spectrum in units of $E_L = E_{C_S} = E_{C_J}$




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

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# The role of the anomaly on decoherence robust qubits

0 - $\pi$ qubit


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J. M. Dempster, B. Fu, D. G. Ferguson, D. I. Schuster, and J. Koch, Understanding degenerate ground-states of a protected quantum circuit in the presence of disorder, Phys. Rev. B **90**, 094518 (2014).

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P. Groszkowski, A. Di Paolo, A. L. Grimsmo, A. Blais, D. I. Schuster, A. A. Houck, and J. Koch, Coherence properties of the 0-$\pi$ qubit, New J. Phys. **20**, 043053 (2018).

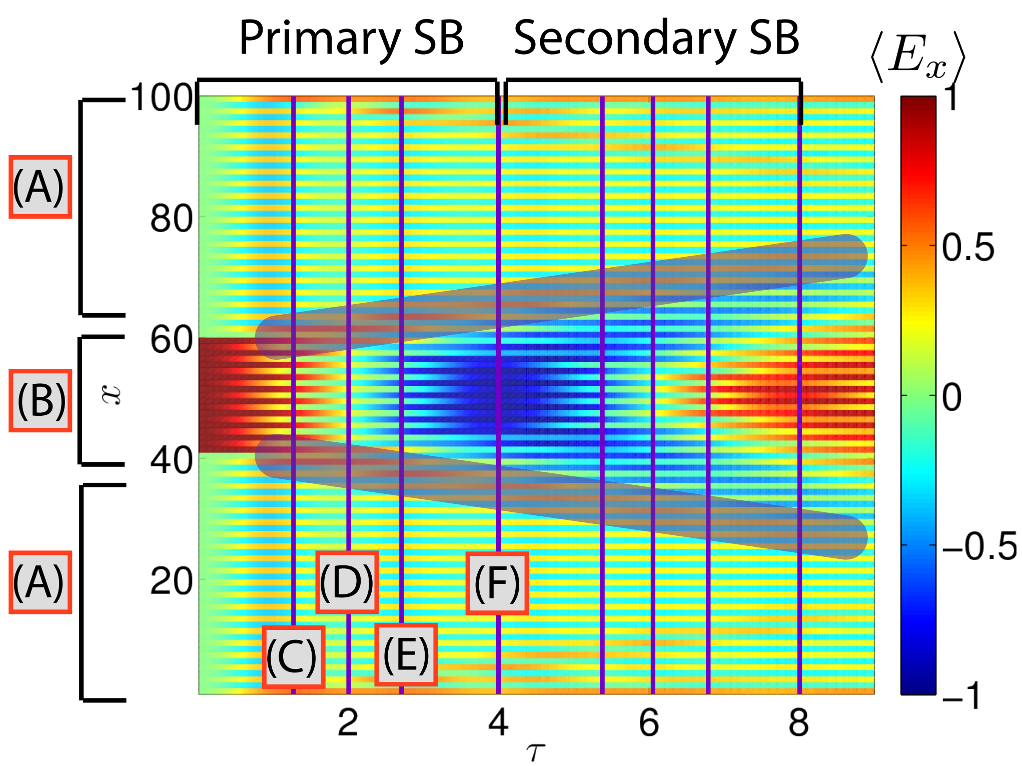
A. Di Paolo, A. L. Grimsmo, P. Groszkowski, J. Koch, and A. Blais, Control and coherence time enhancement of the 0-$\pi$ qubit, New J. Phys. **21**, 043002 (2019).

A. Gyenis, P. S. Mundada, A. Di Paolo, T. M. Hazard, X. You, D. I. Schuster, J. Koch, A. Blais, and A. A. Houck, Experimental realization of a protected superconducting circuit derived from the 0-$\pi$ qubit, PRX Quantum **2**, 010339 (2021).

# Three (take-home) messages



## Tensor network algorithms: dynamical string breaking and hadronization



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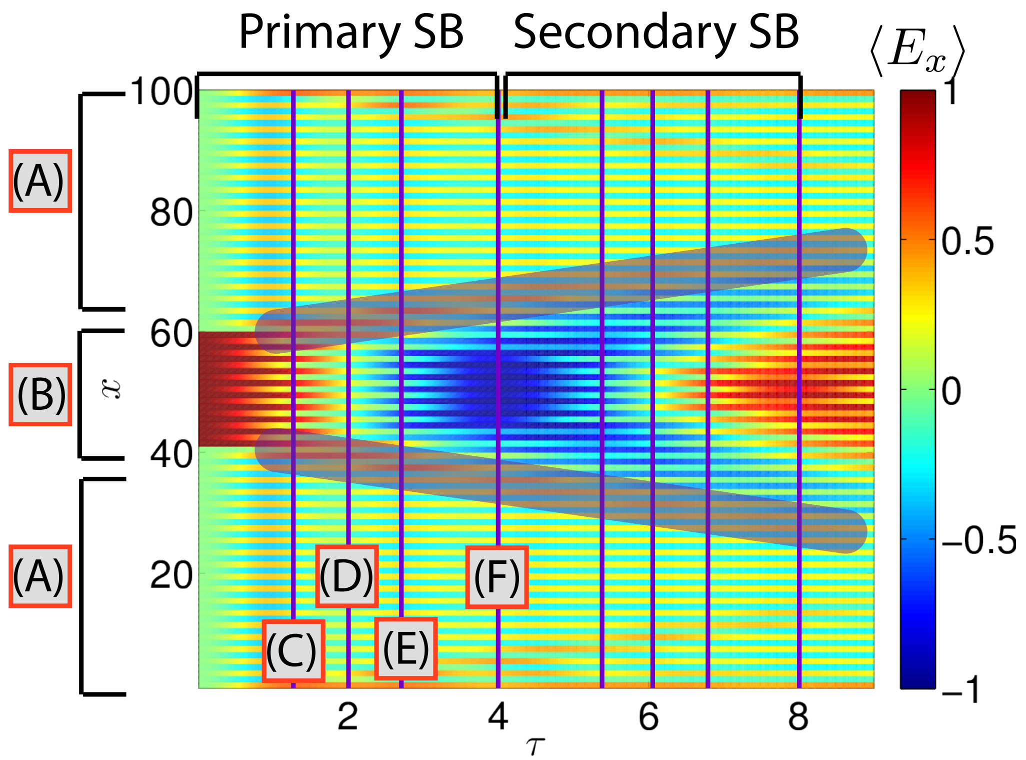
## Tensor network algorithms: dynamical string breaking and hadronization




## Hybrid algorithms (classical/quantum): Real time evolution and light front parton correlators

$$f_{f/P}(\xi) = \sum_S \int \frac{dy^-}{2\pi} e^{-i\xi p^+ y^-} \langle PS | [\bar{\psi}\mathcal{U}](y^-) \frac{\gamma^+}{2} [\mathcal{U}^\dagger \psi](0) | PS \rangle$$

We show how to quantum simulate non-local Wilson loops in space and real-time

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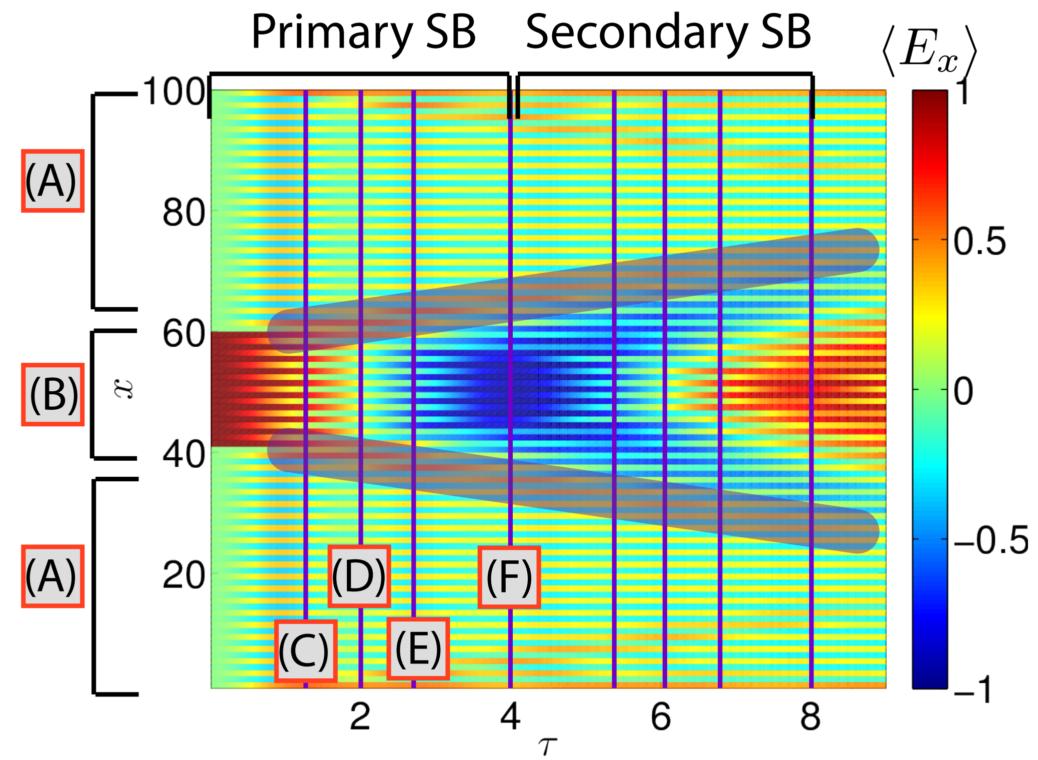


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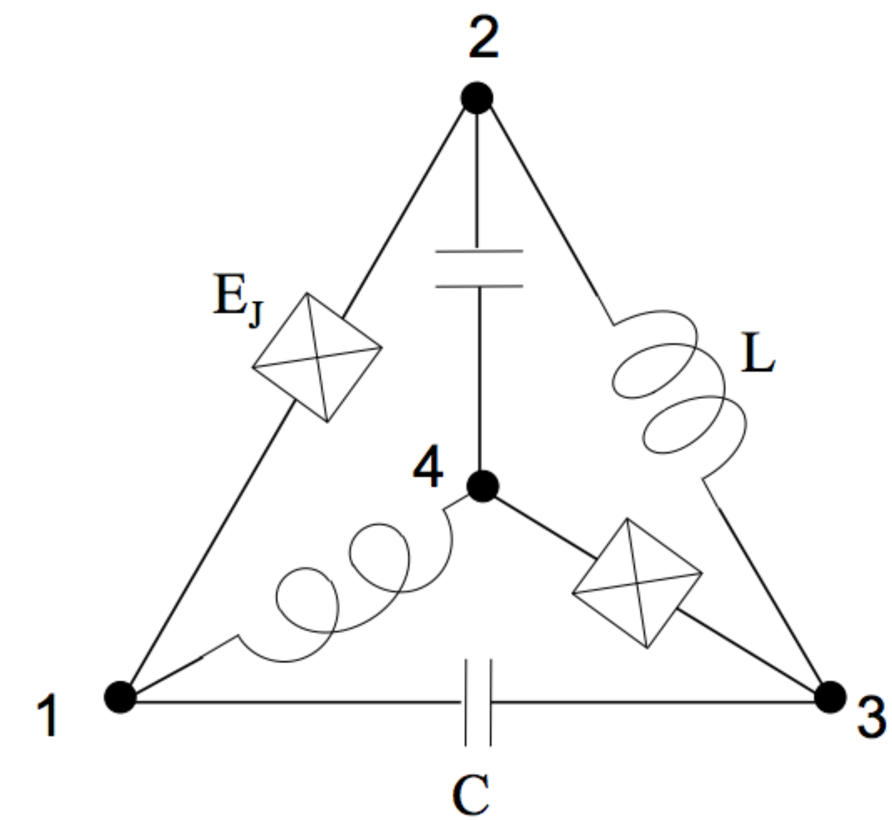


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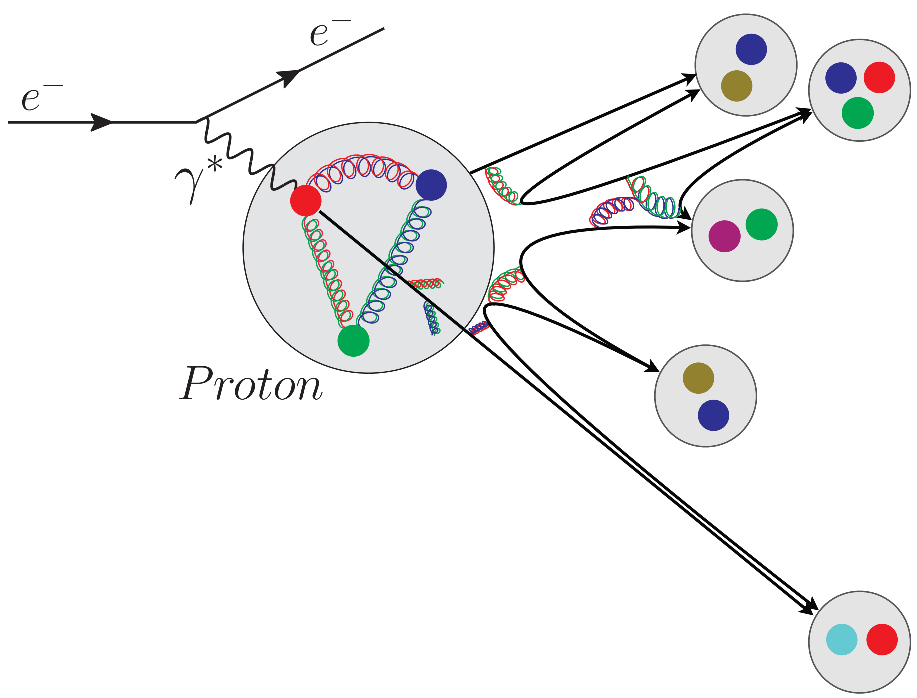
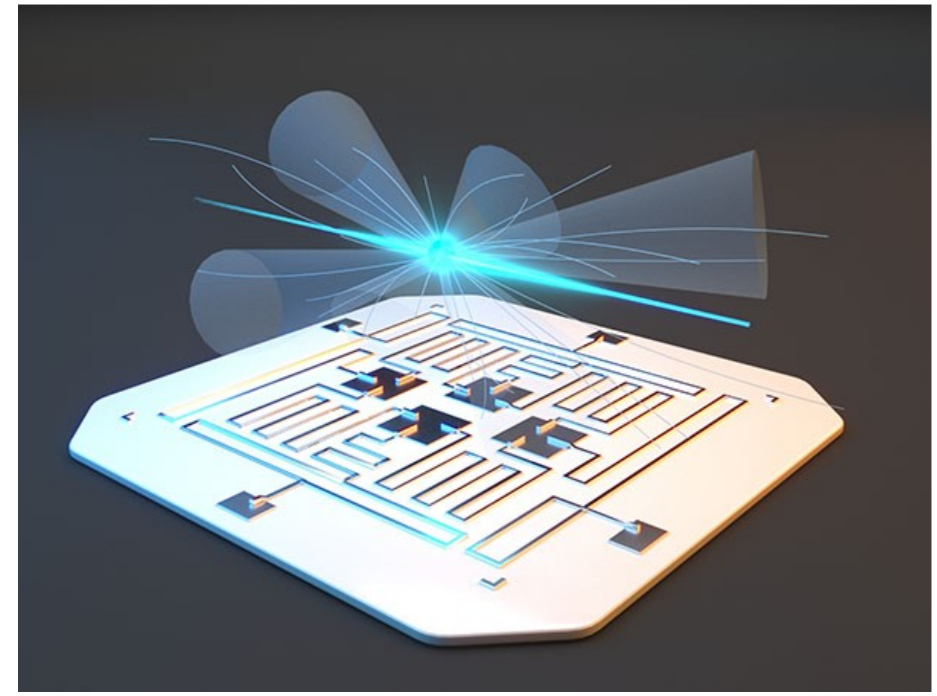



High-Energy and Nuclear Physics



Quantum Information Science and Technology

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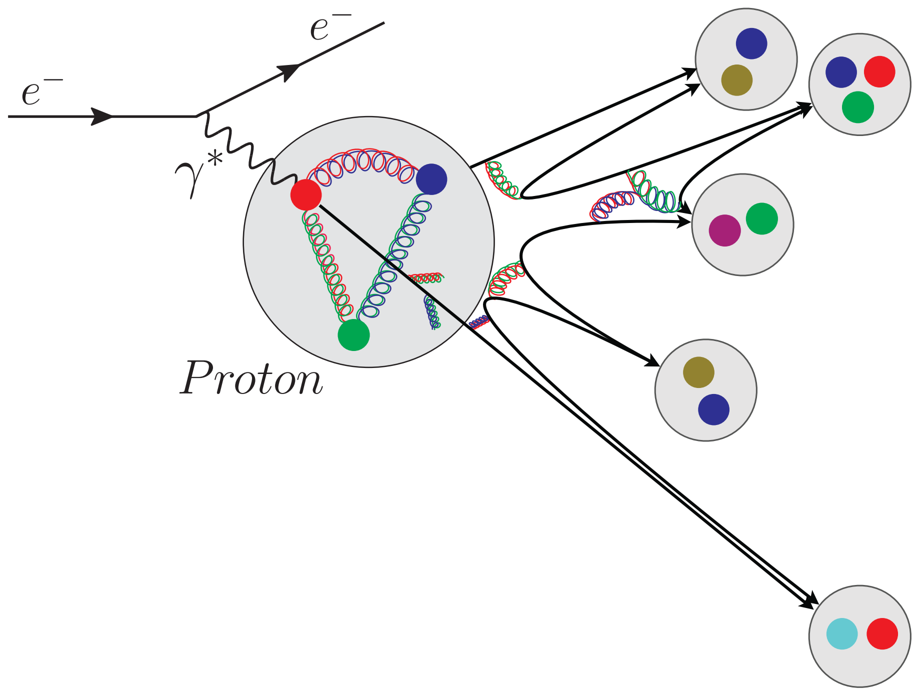


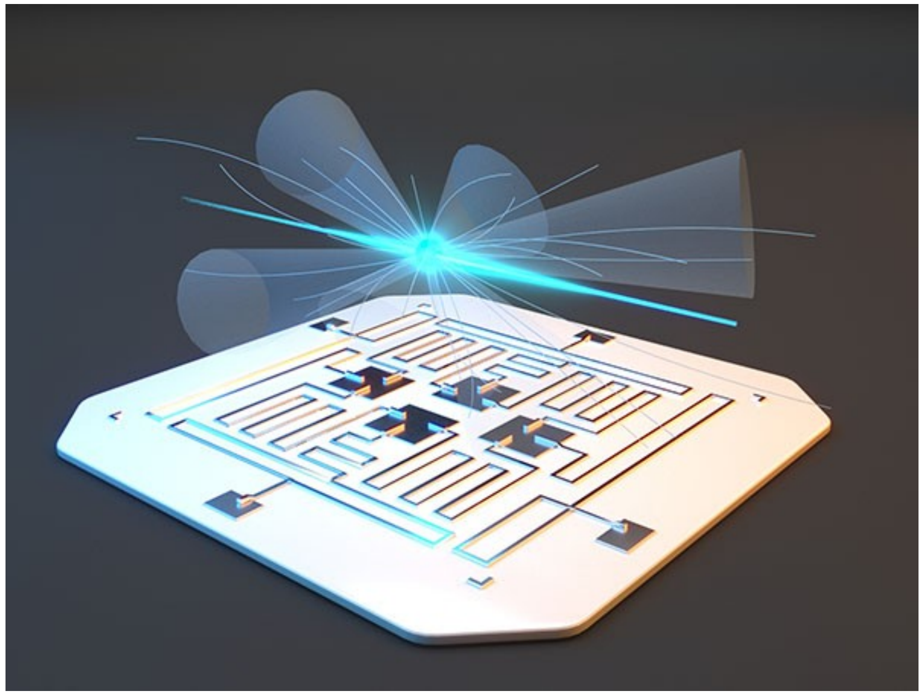

## High-Energy and Nuclear Physics

## Quantum Information Science and Technology

***Theory development:***

Formulate QCD in the Hamiltonian language
Optimal bases towards the continuum limit
Importance of gauge invariance
Systematics: finite volume, space-time discretisation

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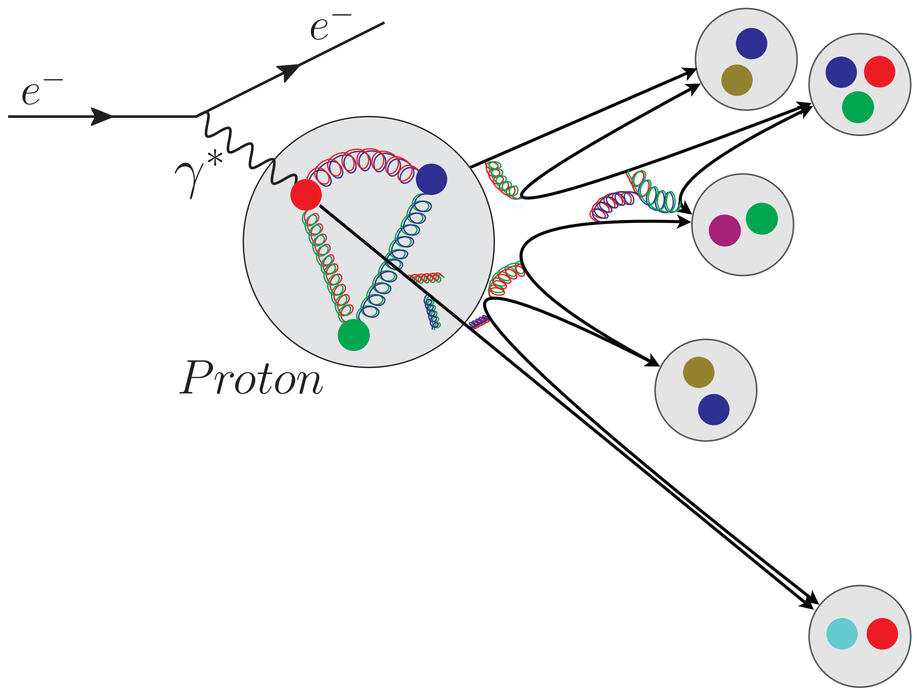


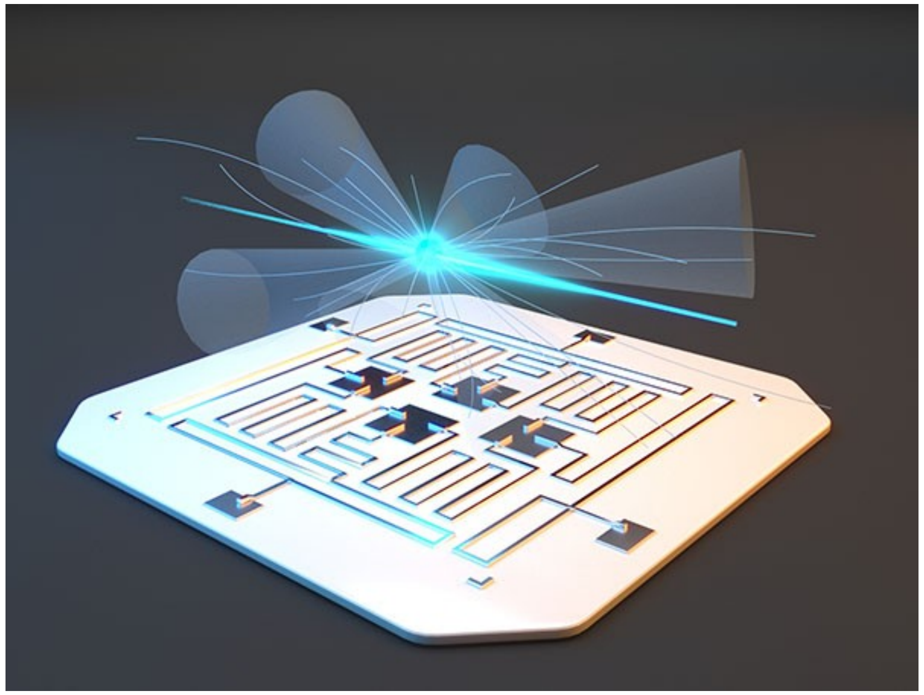

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***Algorithmic developments:***

Resources for gauge theories in quantum algorithm
Simulation of higher-dimensional non-abelian theories
Computation of observables like scattering amplitudes
Quantum state preparation
Data analysis with Quantum Machine Learning

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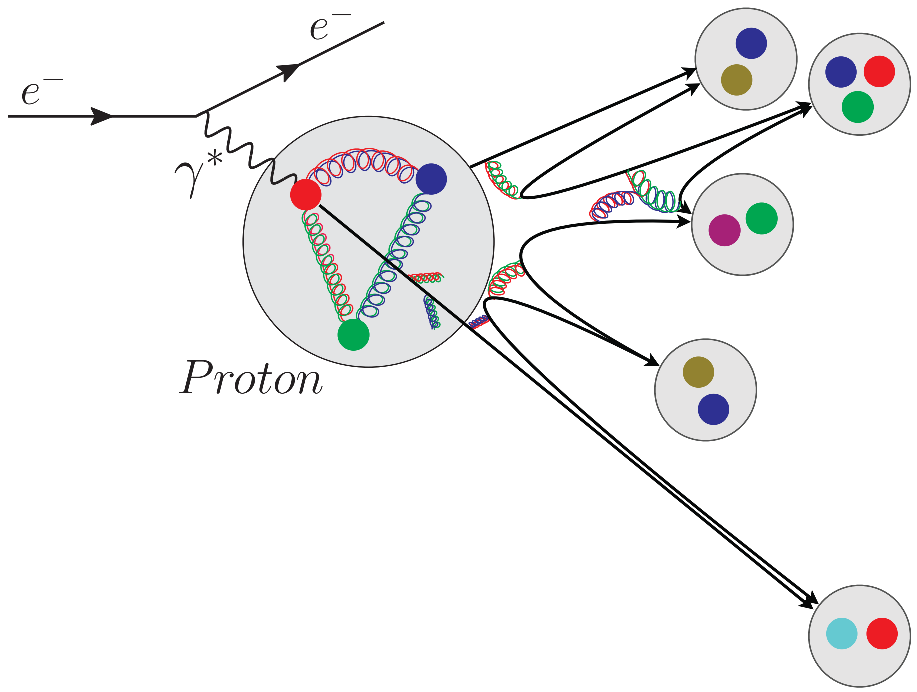


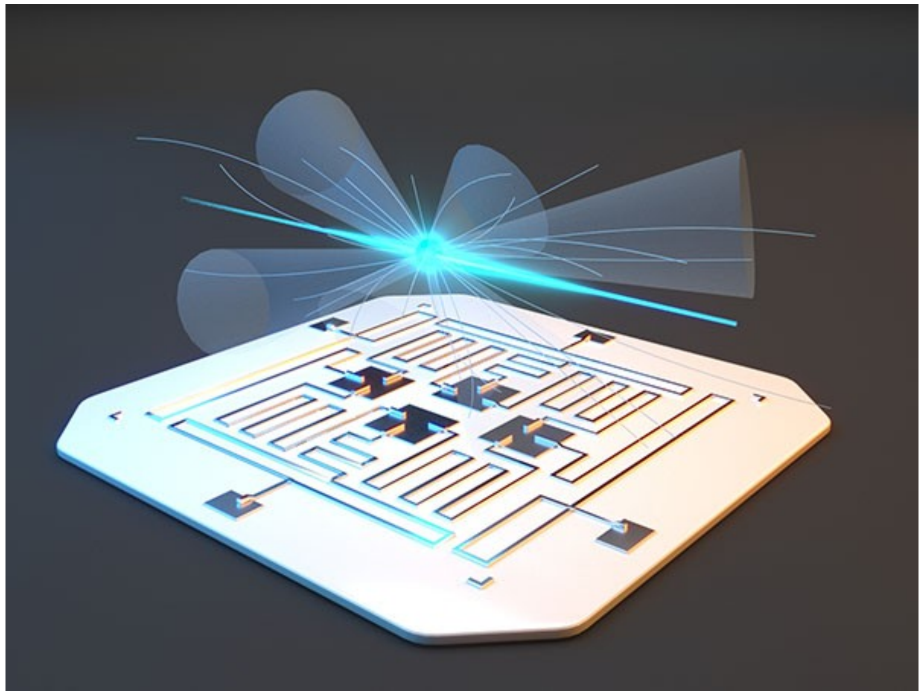

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Quantum state preparation
Data analysis with Quantum Machine Learning

***Implementation, benchmark, and co-development:***

Limits of actual hardware for gauge-theory quantum simulation
Nature of noise in actual hardware and ways to mitigate it
Co-design and co-develop quantum hardware for gauge theory simulations
Digital, analog and hybrid ideas to simulate field theories.