Coherence of confined matter in lattice gauge theories at the mesoscopic scale

Enrico C. Domanti, Paolo Castorina, Dario Zappalà, Luigi Amico

QuantHEP Conference, Bari, September 2023

Technology Innovation Institute

UNIVERSITÀ degli STUDI di CATANIA

INFN Istituto Nazionale di Fisica Nucleare

Outline

- Motivation
  - Introduction to one dimensional $\mathbb{Z}_2$ lattice gauge theory
- Results
  - Implementation on a ring pierced by a synthetic magnetic flux
  - Ground state current
  - Single meson dynamics in the ring
- Conclusions

Motivation

High energy physics

- Gauge theories are at the basis of our understanding of fundamental interactions
- Lattice gauge theories as tools for studying high-energy phenomena:
    - Confinement, string breaking, etc.

Low energy physics

- High Tc superconductors
- Spin liquids
- Topology

Quantum simulation of LGTs

ARTICLES
https://doi.org/10.1038/s41567-019-0649-7
nature physics

Floquet approach to $\mathbb{Z}_2$ lattice gauge theories with ultracold atoms in optical lattices

Christian Schweizer[1,2,3], Fabian Grusdt[3,4], Moritz Berngruber[1,3], Luca Barbiero[5], Eugene Demler[6], Nathan Goldman[5], Immanuel Bloch[1,2,3] and Monika Aidelsburger[1,2,3*]

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REPORT | QUANTUM SIMULATION

Thermalization dynamics of a gauge theory on a quantum simulator

ZHAO-YU ZHOU, GUO-XIAN SU, JAD C. HALIMEH, ROBERT OTT, HUI SUN, PHILIPP HAUKE, BING YANG, ZHEN-SHENG YUAN, JÜRGEN BERGES, AND JIAN-WEI PAN Authors Info & Affiliations

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Confined Phases of One-Dimensional Spinless Fermions Coupled to Z_2 Gauge Theory

Umberto Borla, Ruben Verresen, Fabian Grusdt, and Sergej Moroz
Phys. Rev. Lett. **124**, 120503 – Published 26 March 2020

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Federica M. Surace, Paolo P. Mazza, Giuliano Giudici, Alessio Lerose, Andrea Gambassi, and Marcello Dalmonte
Phys. Rev. X **10**, 021041 – Published 21 May 2020

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Simulating 2D Effects in Lattice Gauge Theories on a Quantum Computer

Danny Paulson, Luca Dellantonio, Jan F. Haase, Alessio Celi, Angus Kan, Andrew Jena, Christian Kokail, Rick van Bijnen, Karl Jansen, Peter Zoller, and Christine A. Muschik
PRX Quantum **2**, 030334 – Published 25 August 2021

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Nhung H. Nguyen, Minh C. Tran, Yingyue Zhu, Alaina M. Green, C. Huerta Alderete, Zohreh Davoudi, and Norbert M. Linke
PRX Quantum **3**, 020324 – Published 4 May 2022

Quantum Coherence in LGTs at the mesoscopic scale

Goal: address properties of LGTs which emerge in quantum coherent systems at the mesoscopic scale.

Quantum technology to explore properties of coherent mesoscopic systems:

- Superconducting circuits
- Cold atoms: neutral atoms, long coherence times

‘Roadmap on Atomtronics: State of the art and perspective’, Amico, Birkl, Boshier *et al.*, AVS Quantum Science (2021).

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Probe of quantum coherence: Persistent Current

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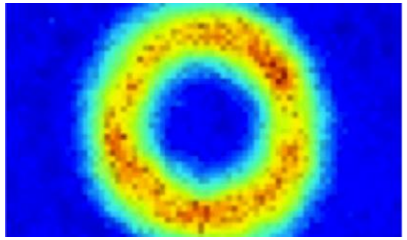
‘Probing the BCS-BEC crossover with persistent currents’, Pecci, Naldesi *et al.*, PRR (2021).

‘Probe for bound states of SU(3) fermions and colour deconfinement’, Chetcuti, Polo *et al.*, Communication Physics (2023).



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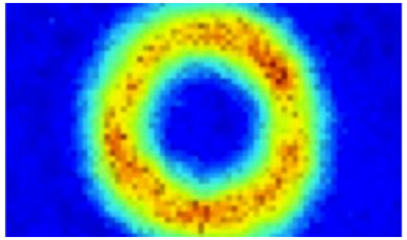

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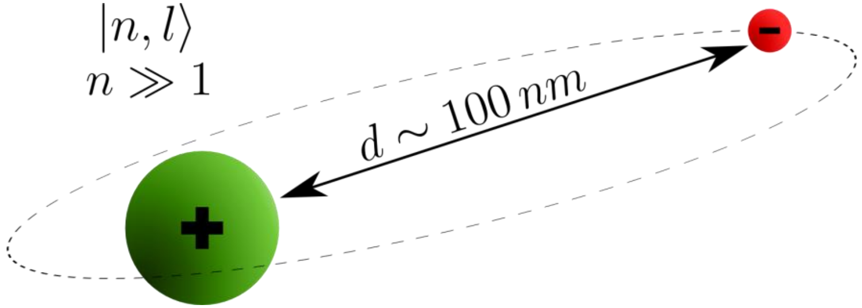
More recently:

- Rydberg atoms: coherent transport of excitations

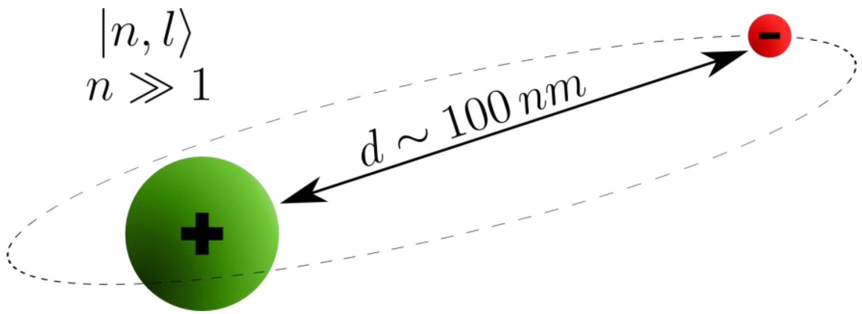
‘Controlled flow of excitations in a ring-shaped network of Rydberg atoms ’, Perciavalle, Rossini *et al.*, PRA (2023).

Rydberg atoms

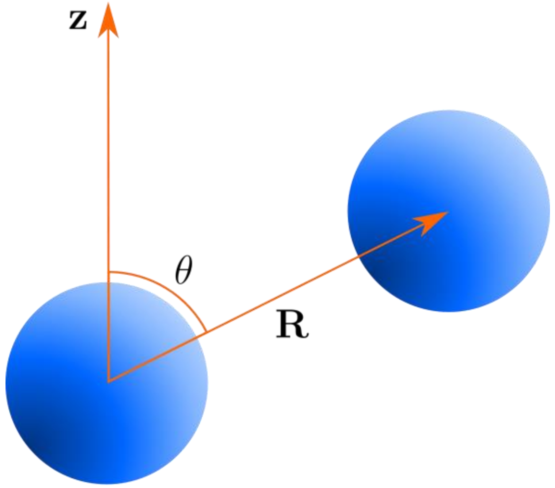


D. Barredo, et al. 2015 *PRL* **114**, 113002
S. Ravets, et al. 2015 *PRA* **92**, 020701(R)
A. Browaeys & T. Lahaye 2020 *Nature Physics* **16**, 132-142

Rydberg atoms



$$V_{dd} = \frac{\mathbf{p_1} \cdot \mathbf{p_2} - 3\,(\mathbf{p_1} \cdot \mathbf{n})(\mathbf{p_2} \cdot \mathbf{n})}{R^3}$$



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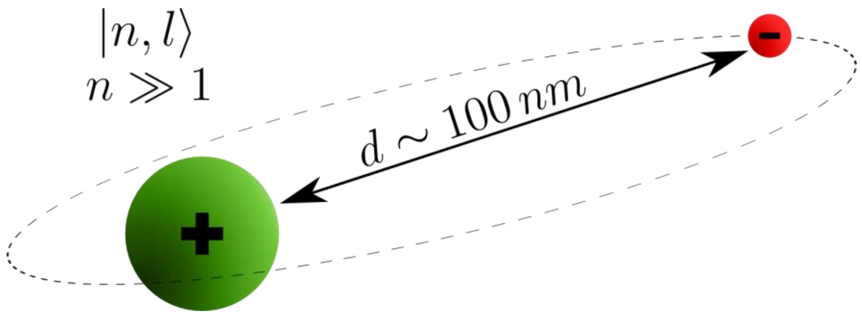

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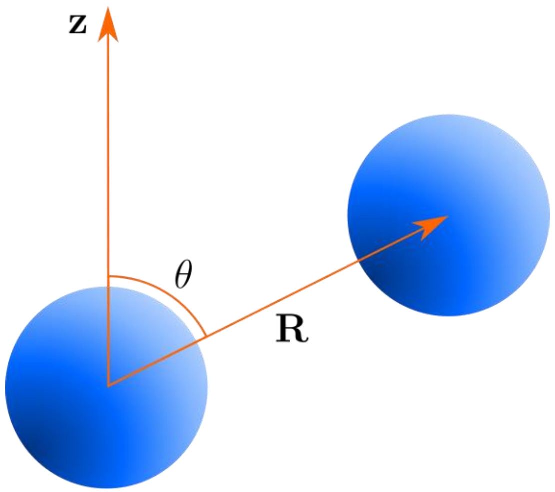

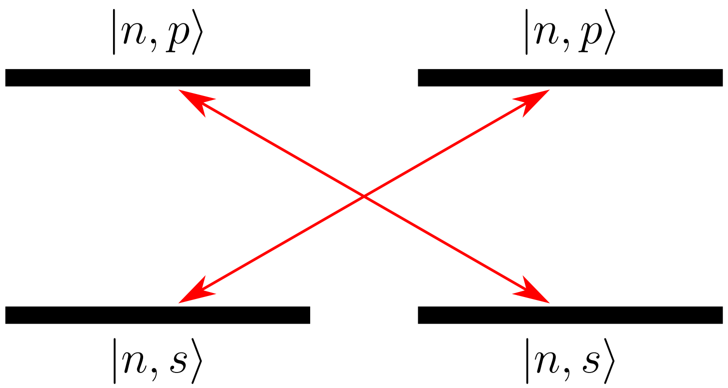

$$\mathcal{H}_{\mathrm{XY}} = \sum_{i \neq j} \frac{C_3(\theta_{ij})}{R_{ij}^3}\, \sigma_i^+ \sigma_j^-$$

$$C_3(\theta) = C_3\,(1 - 3\cos^2\theta)$$

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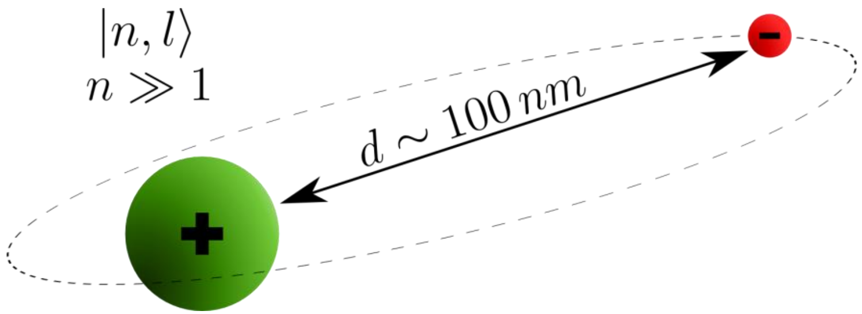
Rydberg atoms



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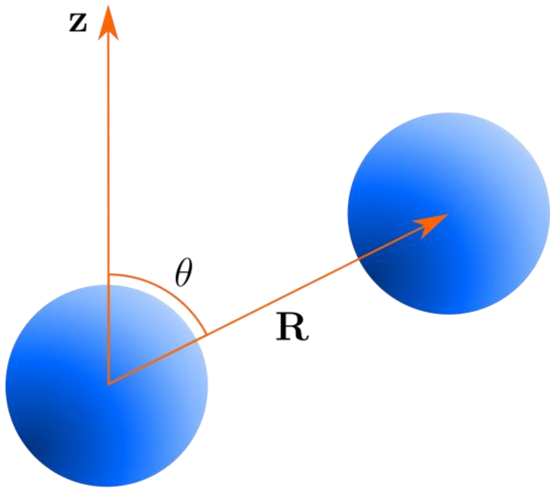

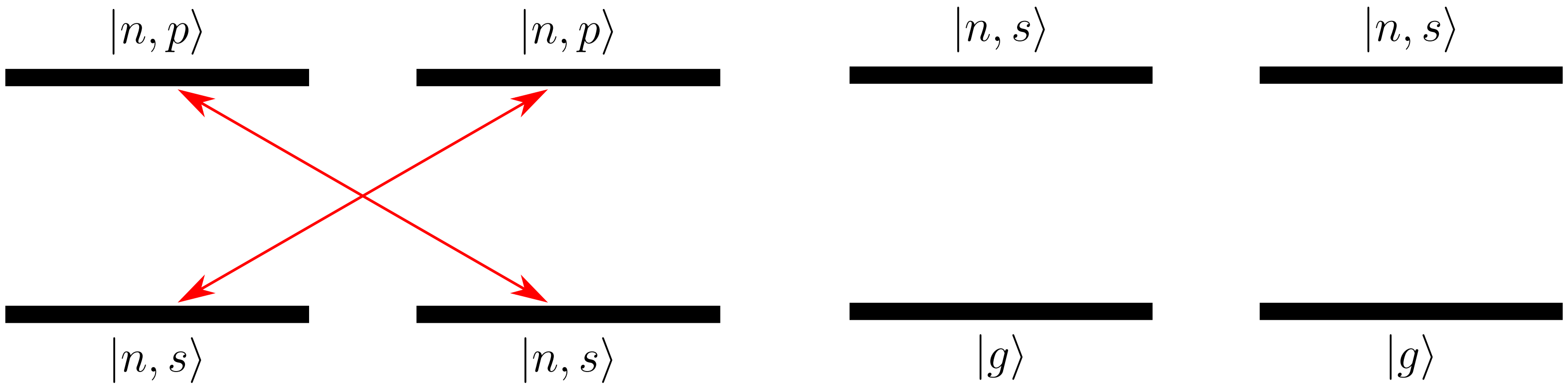

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Gauge theories

Lattice Gauge Theories

(Hamiltonian approach)

Gauge theories

$$S(\psi, A) = \int d^d x\, \mathcal{L}(\psi(x), A(x))$$

QED

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu(\partial_\mu - ieA^\mu) - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

The action is invariant under local gauge transformations.

$$A_\mu(x) \to A_\mu(x) + \partial_\mu \Lambda(x)$$

$$\psi(x) \to e^{ie\,\Lambda(x)}\psi(x)$$

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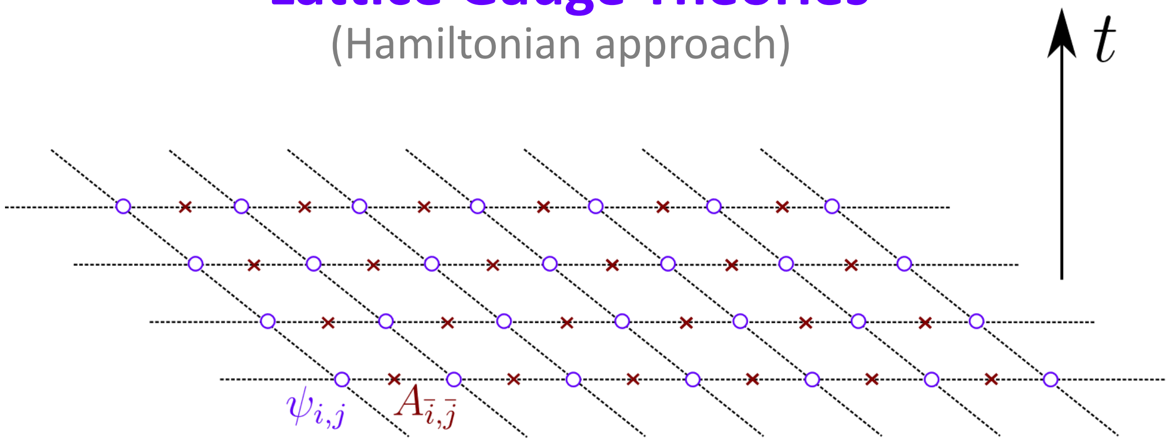

$$\mathcal{H}(\psi_{i,j}, A_{\bar{i},\bar{j}})$$

The Hamiltonian commutes with the generators of local gauge transformations, at each site of the lattice:

$$[\mathcal{H}, G_{i,j}] = 0$$

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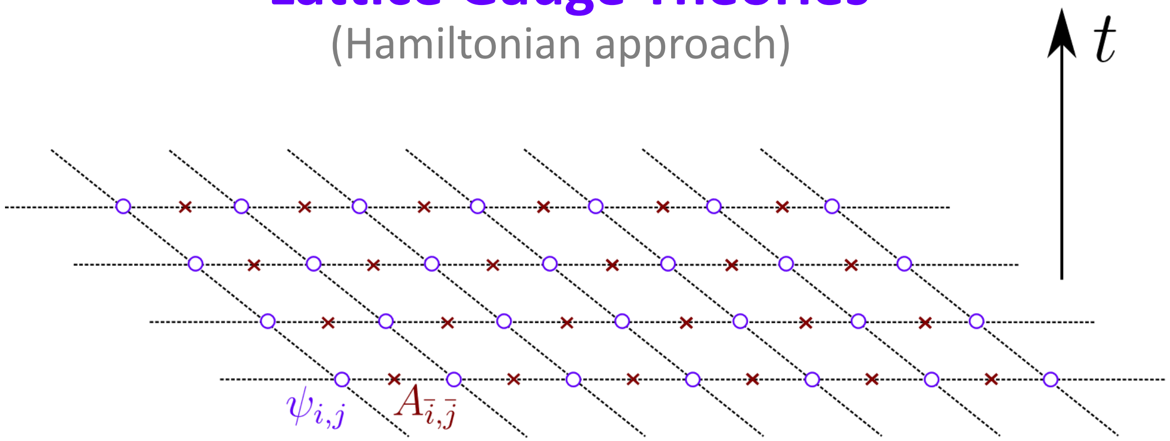

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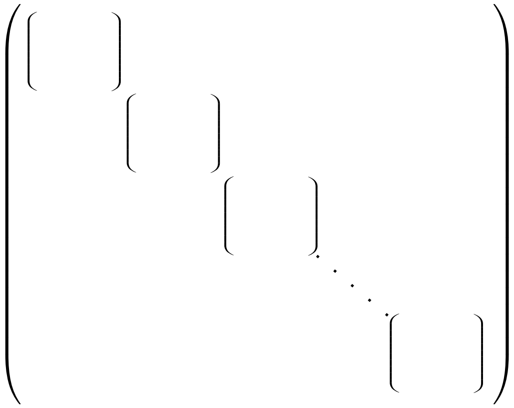

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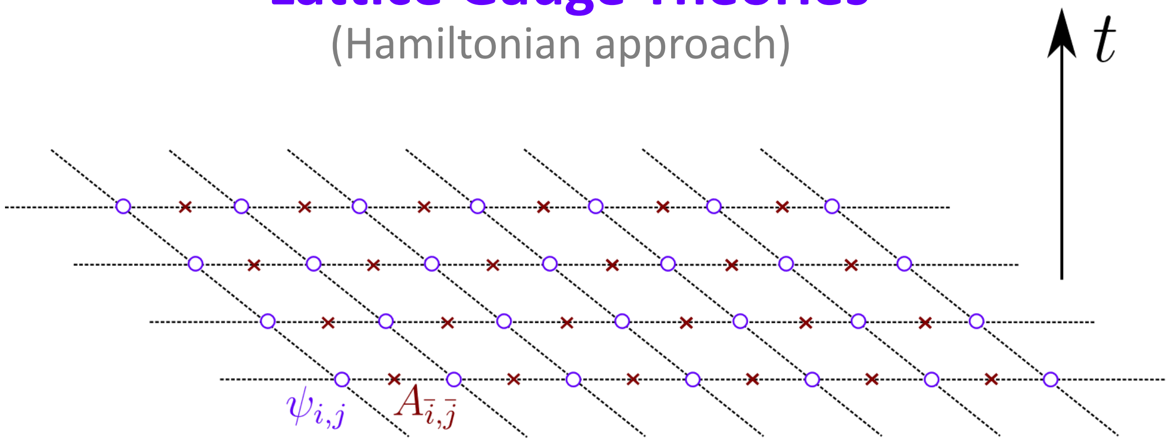

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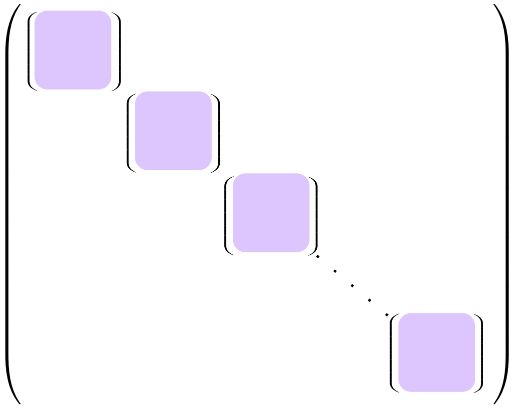
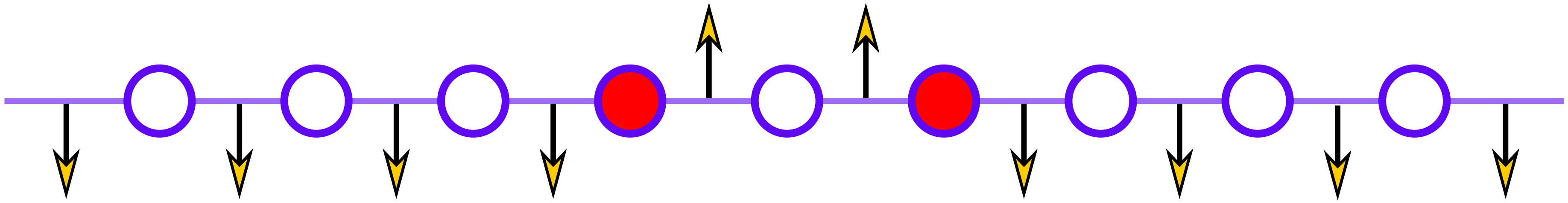


GAUGE SECTORS

$\mathbb{Z}_2$ Lattice gauge theory

$$\mathcal{H} = \sum_j \left[w(c_j^\dagger \, \sigma^x_{j+\frac{1}{2}} \, c_{j+1} + h.c.) + \frac{\tau}{2} \sigma^z_{j+\frac{1}{2}} \right]$$

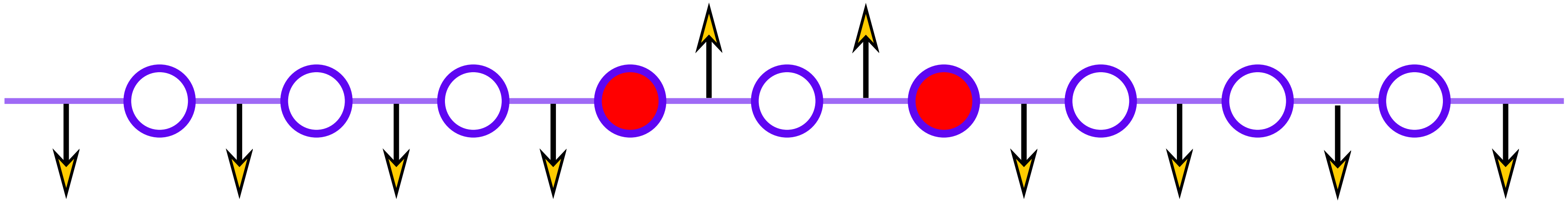


$\mathbb{Z}_2$ Lattice gauge theory

Fermionic operators

$$\mathcal{H} = \sum_j \left[w(c_j^\dagger \sigma^x_{j+\frac{1}{2}} c_{j+1} + h.c.) + \frac{\tau}{2} \sigma^z_{j+\frac{1}{2}} \right]$$

Gauge variables



$\mathbb{Z}_2$ Lattice gauge theory

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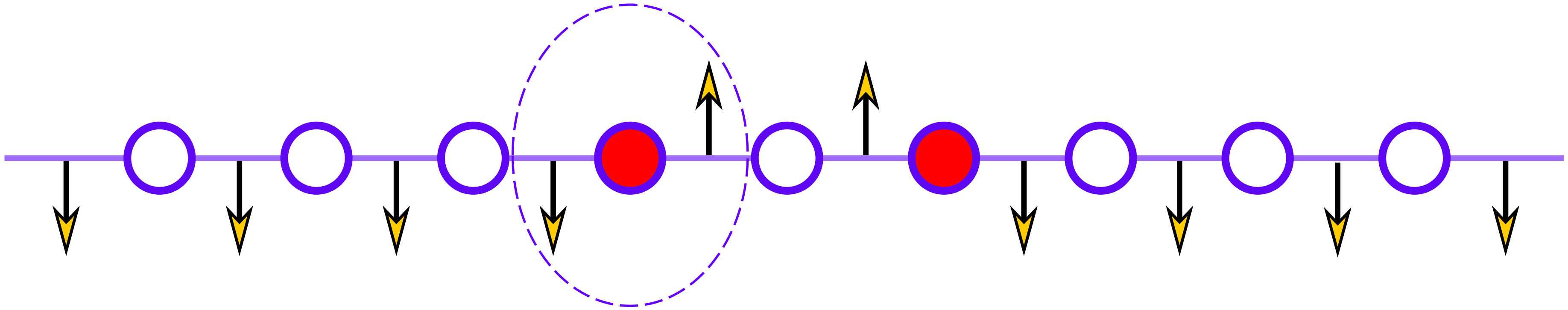

Gauge Constraints: Gauss Law

$$G_j = \sigma^z_{j-1/2} \, (-1)^{n_j} \, \sigma^z_{j+1/2} = 1 \; \forall j$$

$\mathbb{Z}_2$ Lattice gauge theory

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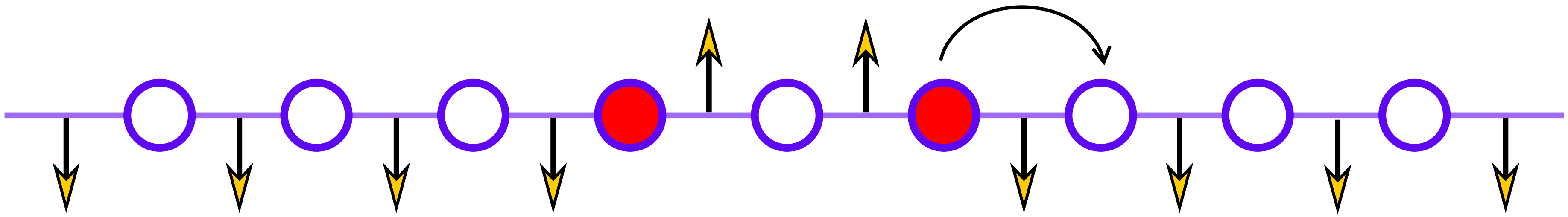
Gauge invariant hopping



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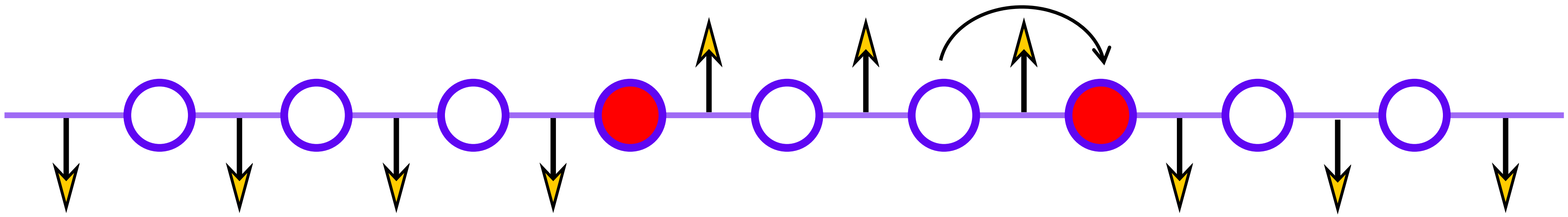

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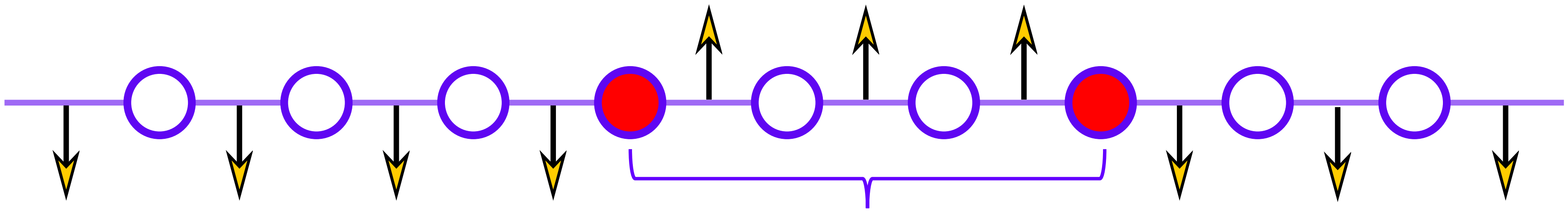
$$\mathcal{H} = \sum_j \left[w(c_j^\dagger \, \sigma^x_{j+\frac{1}{2}} \, c_{j+1} + h.c.) + \boxed{\frac{\tau}{2}\sigma^z_{j+\frac{1}{2}}} \right]$$

String tension /
electric field term



$R \equiv$ length of a string of spin $\uparrow$

$$V(R) = \tau \, R$$

CONFINING POTENTIAL

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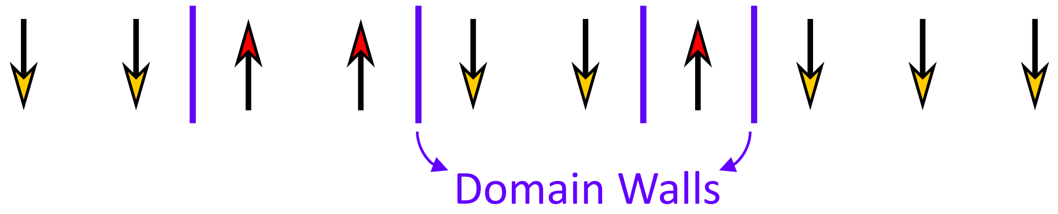
Implementation on a ring pierced by a synthetic magnetic field

In a **fixed gauge sector**, a $\mathbb{Z}_2$ Lattice Gauge Theory dynamics can be mapped in an Ising model in transverse & longitudinal fields

$$\mathcal{H} = \sum_j \left[-(m/2)\, s_j^z s_{j+1}^z + w\, s_j^x + (\tau/2)\, s_j^z \right]$$



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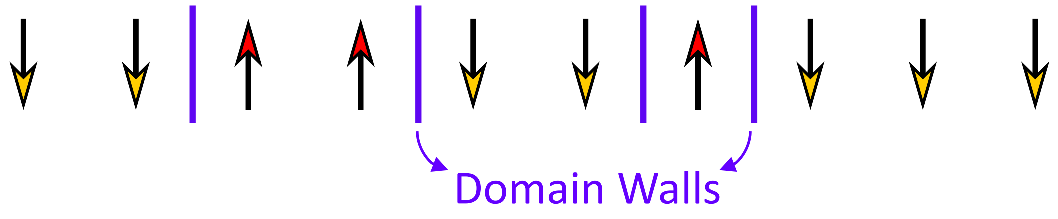

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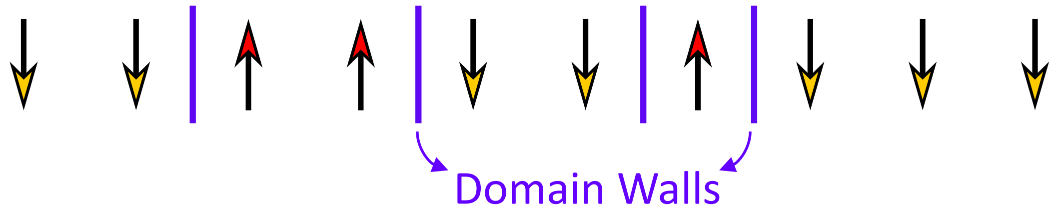

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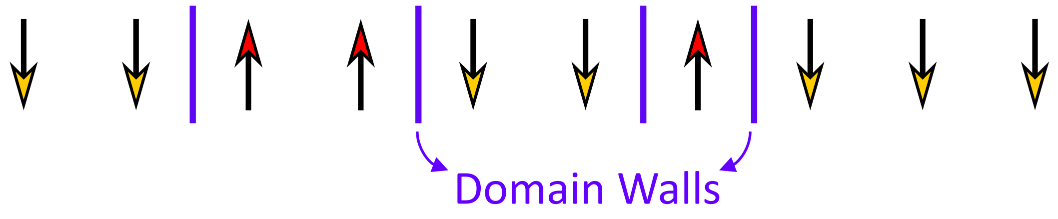

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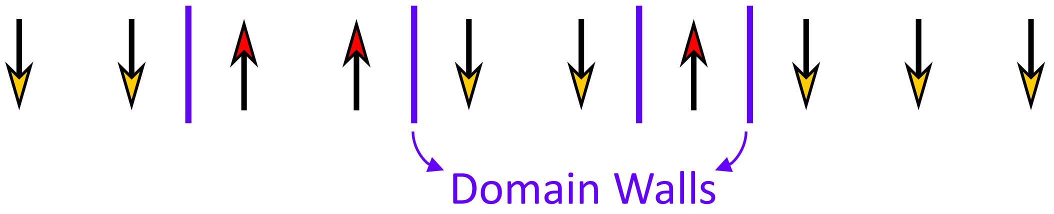

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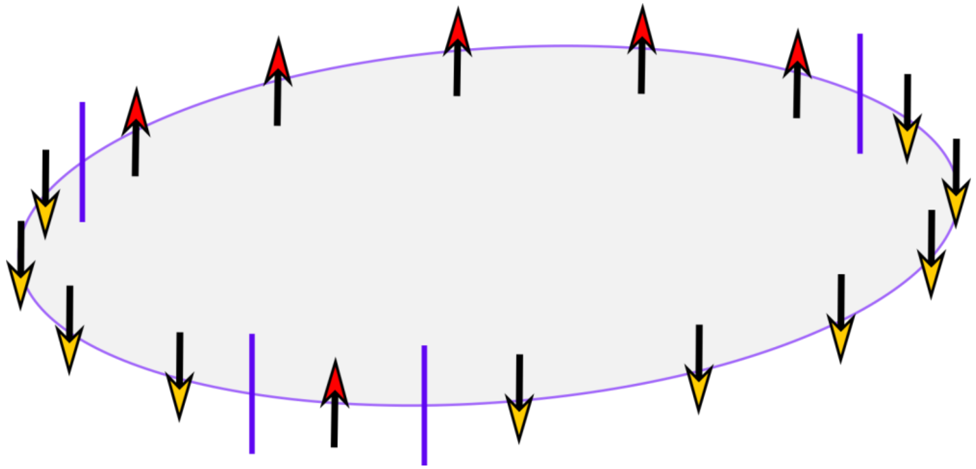
Floquet engineering → Synthetic magnetic flux

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{drive}(t)$$

$$\mathcal{H}_0 = \sum_j \left[(\tau/2)\, s_j^z + w\, s_j^x + (-1)^j\, V\, s_j^z s_{j+1}^z \right]$$

$$\mathcal{H}_{drive}(t) = \sum_j (A/2) \cos(\Omega\, t + (-1)^j \varphi)\, s_j^z$$



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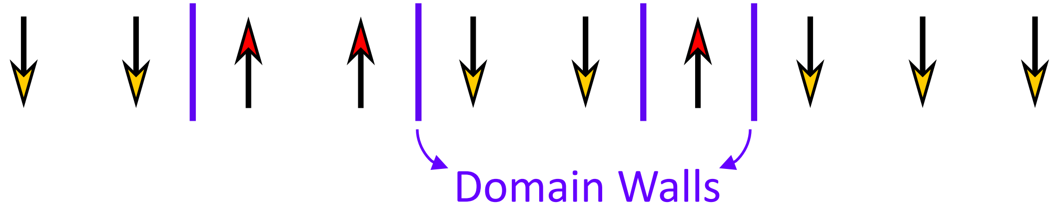

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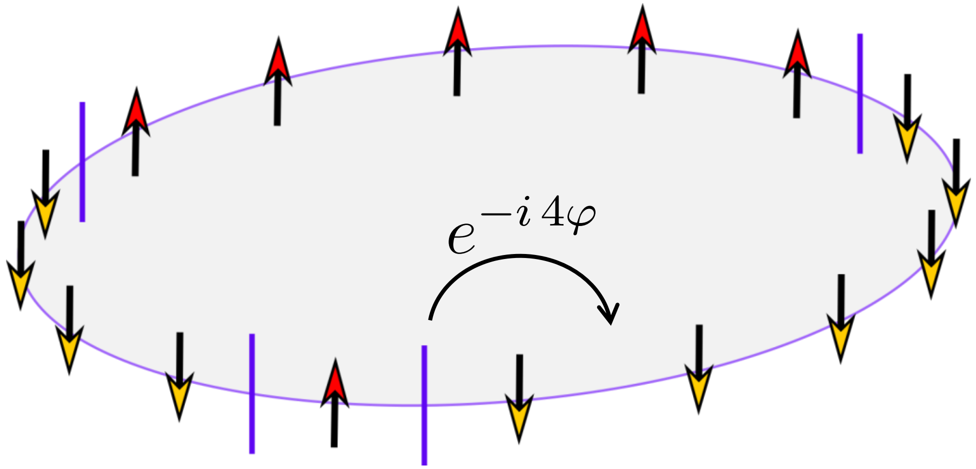
$$\mathcal{H}_0 = \sum_j \left[(\tau/2)\, s^z_j + w\, s^x_j + (-1)^j\, V\, s^z_j s^z_{j+1} \right]$$

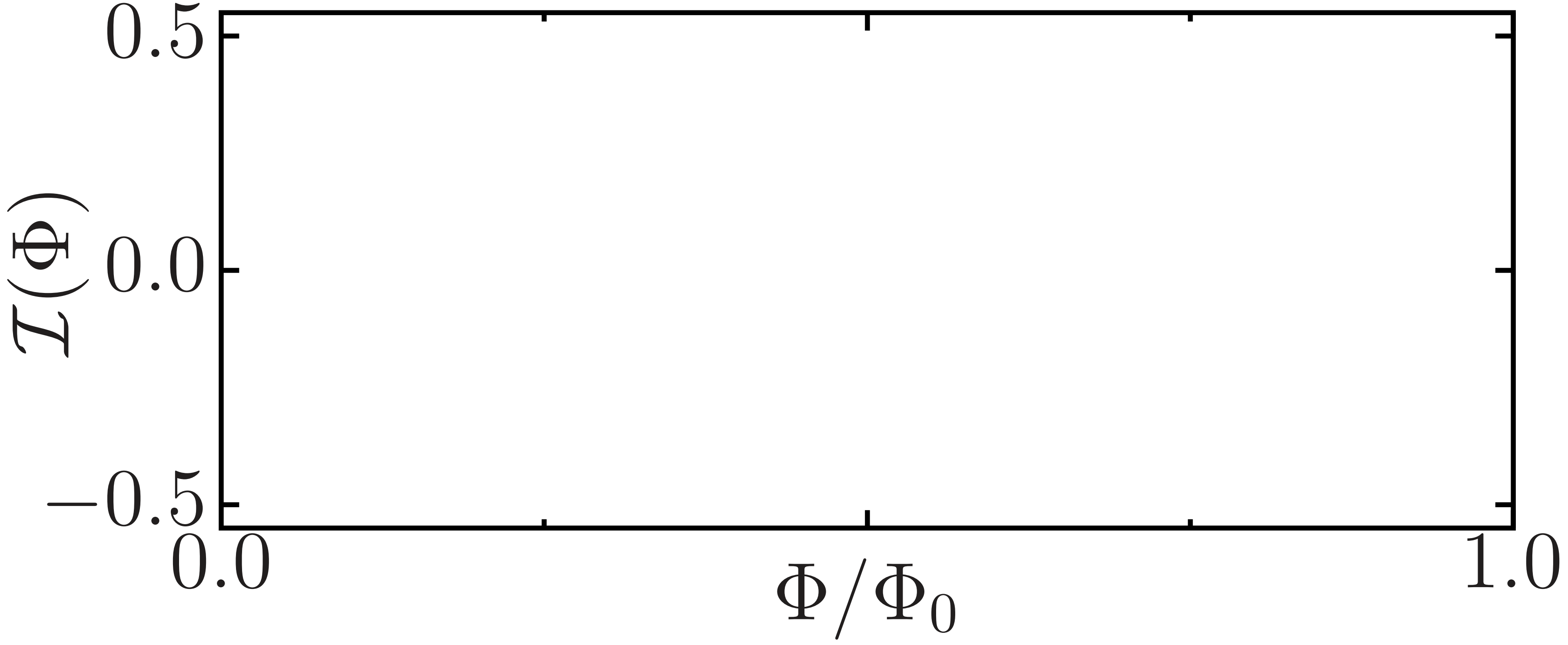
$$\mathcal{H}_{drive}(t) = \sum_j (A/2) \cos(\Omega\, t + (-1)^j \varphi)\, s^z_j$$



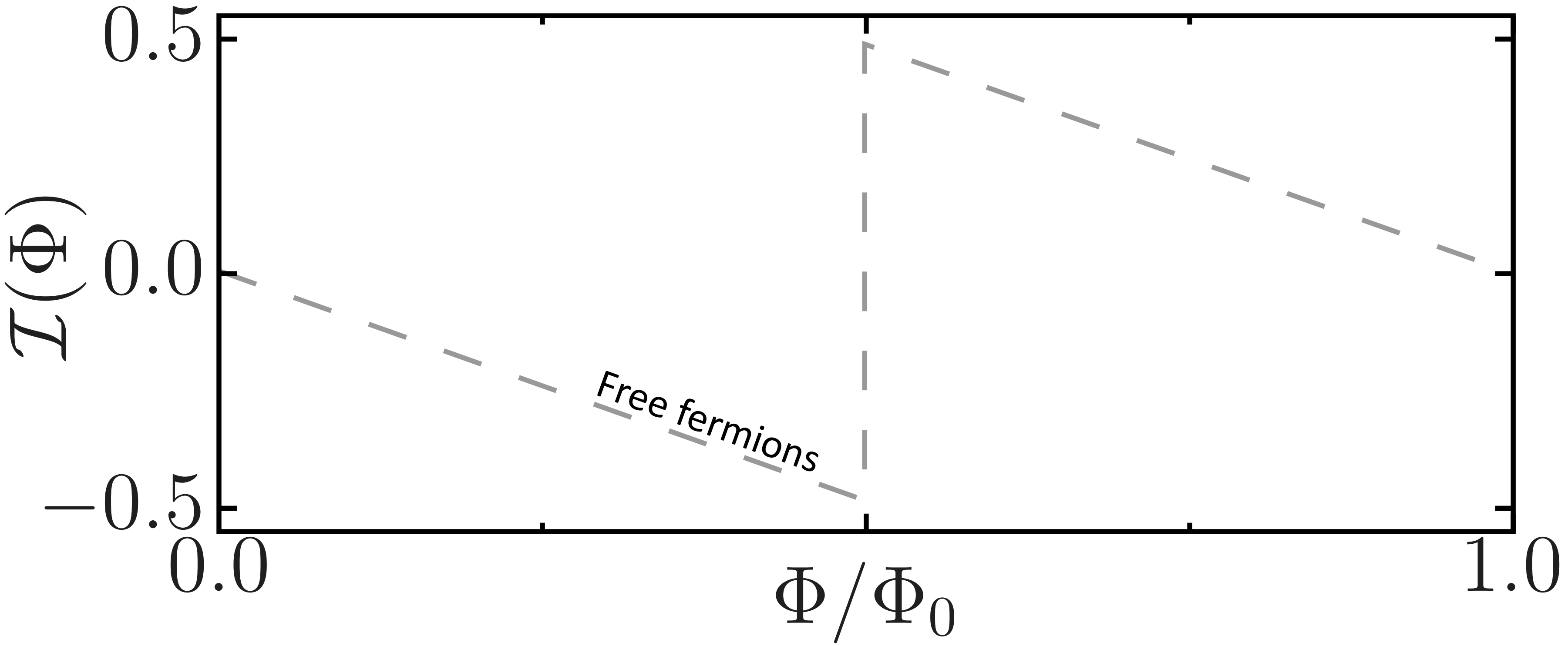
$$\mathcal{H}_{\text{eff}} = \sum_j \tilde{w} (e^{i(2\pi/L)(\Phi/\Phi_0)} c^\dagger_j c_{j+1} + h.c.)\, \sigma^x_{j+1/2} + (\tau/2)\, \sigma^z_{j+1/2}$$

- Motivation
  - Introduction to one dimensional $\mathbb{Z}_2$ lattice gauge theory
- Results
  - Implementation on a ring pierced by a synthetic magnetic flux
  - Ground state current
  - Single meson dynamics in the ring

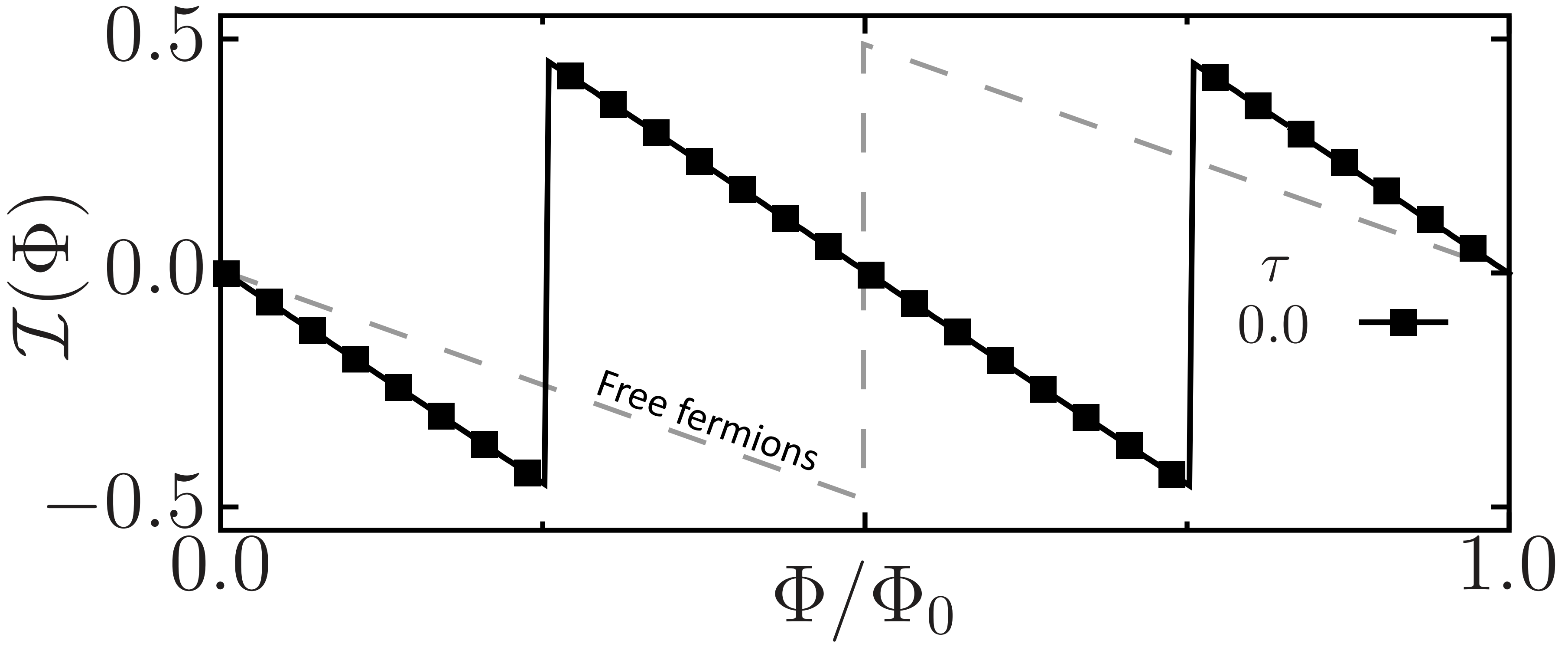
Ground state current



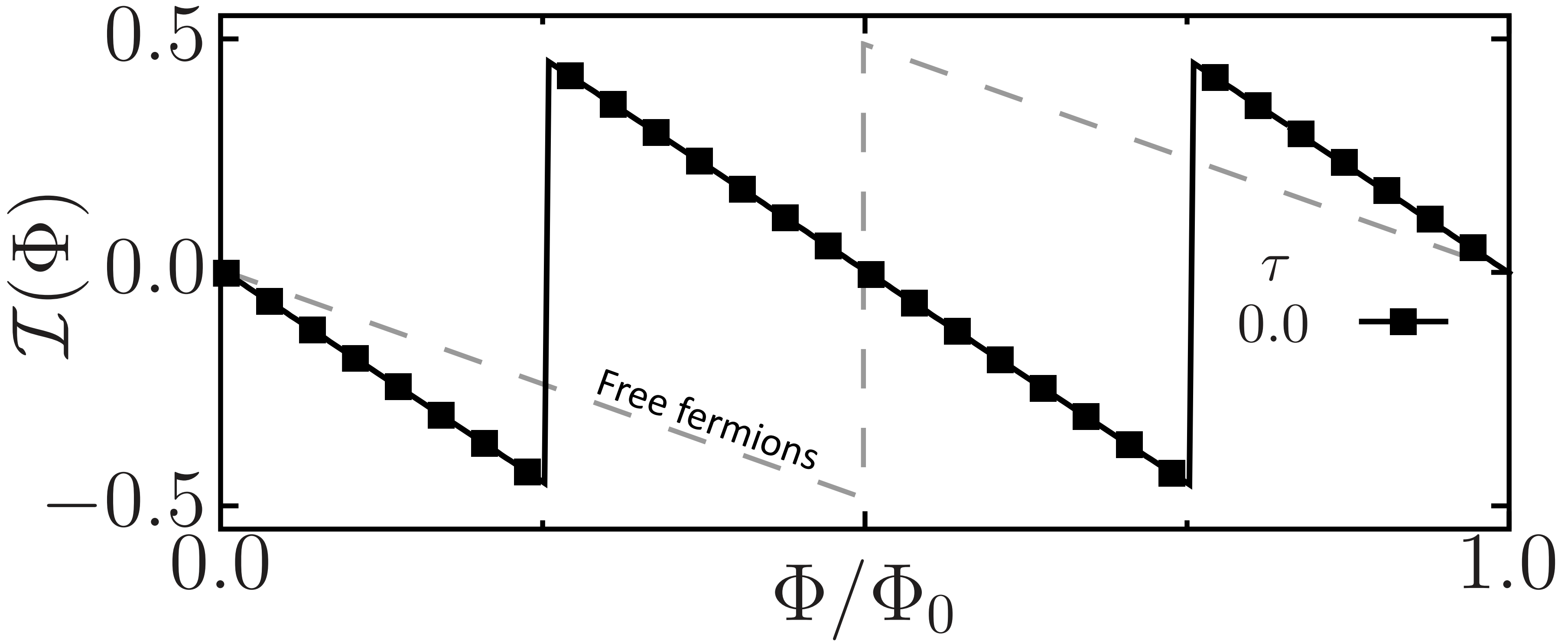
Ground state current



Ground state current



Ground state current



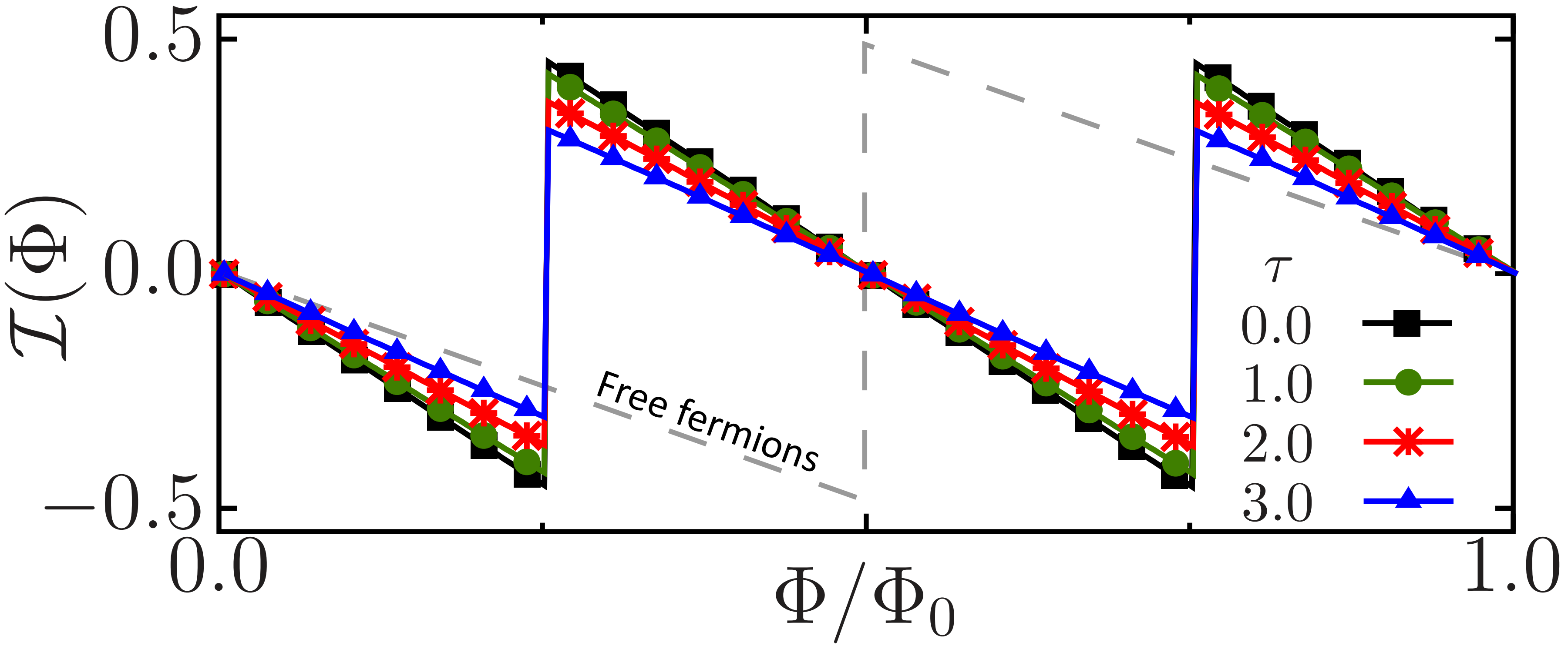
Symmetry at $\tau = 0$

$$W = \prod_{\text{ring}} \sigma^x_{j+\frac{1}{2}}$$

$\mathbb{Z}_2$ Flux – adds to the total phase acquired by particles circulating the ring

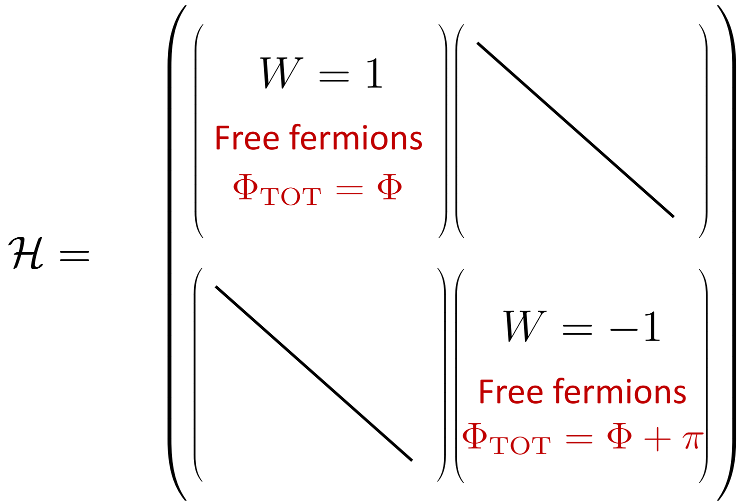
$$\mathcal{H} = \begin{pmatrix} \begin{pmatrix} W = 1 \\ \text{Free fermions} \\ \Phi_{\text{TOT}} = \Phi \end{pmatrix} & \\ & \begin{pmatrix} W = -1 \\ \text{Free fermions} \\ \Phi_{\text{TOT}} = \Phi + \pi \end{pmatrix} \end{pmatrix}$$

Ground state current



The symmetry is broken for $\tau \neq 0$

$$W = \prod_{\text{ring}} \sigma^x_{j+\frac{1}{2}}$$



- Motivation and introduction
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Exact solution of the two-particle problem on the ring with flux

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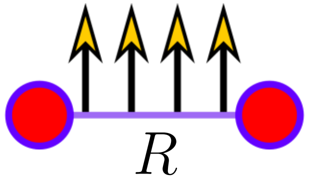

$$\Psi_E(s,R) = \mathcal{N}\, e^{i\,K s}\, \chi_E(K, R)$$

Center of mass momentum $K = \frac{2\pi}{L}\, n$

$$2w\cos\left(\frac{K}{2} + \frac{2\pi\Phi}{L\Phi_0}\right)\left[\chi(R+1) + \chi(R-1)\right] + \tau R\,\chi(R) = E\,\chi(R)$$

Wannier-Stark equation

G. H. Wannier – Rev. Mod. Phys. (1962)

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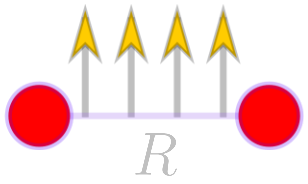

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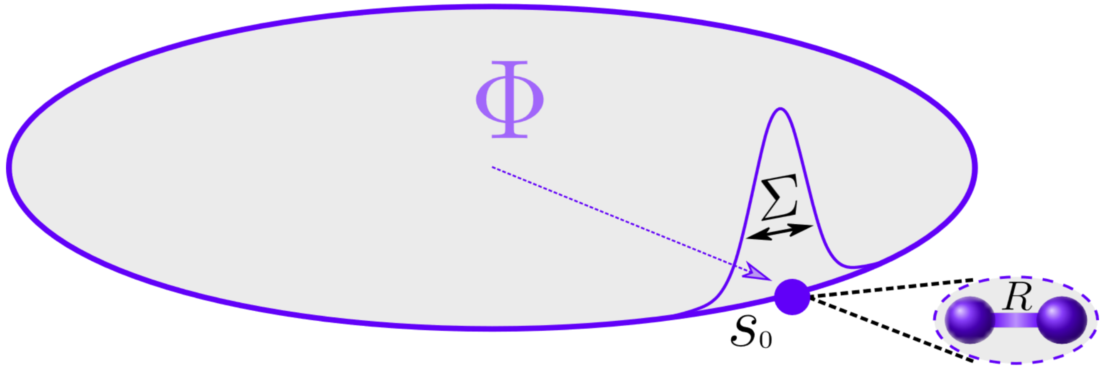
Wannier-Stark equation

G. H. Wannier – Rev. Mod. Phys. (1962)

Quench dynamics



$$\Phi = 0 \to \Phi \neq 0$$

$$\psi_0(s,R) = e^{-(s-s_0)^2/(2\,\Sigma^2)}\, \Psi_{E_0}(s,R)$$

Σ → gaussian width

$\Psi_{E_0}(s,R)$ → lowest energy eigenstate

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Quench dynamics

	CENTER OF MASS DYNAMICS $P(s,t)$	STRING DYNAMICS $P(R,t)$	CURRENT DYNAMICS $\langle\psi(t)\vert\mathcal{I}\vert\psi(t)\rangle$
$\Sigma = 2$			
$\Sigma \to 0$			

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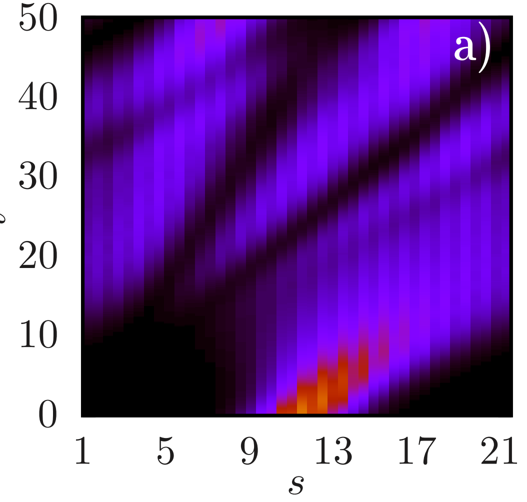
Quench dynamics

	CENTER OF MASS DYNAMICS $P(s,t)$	STRING DYNAMICS $P(R,t)$	CURRENT DYNAMICS $\langle\psi(t)\|\mathcal{I}\|\psi(t)\rangle$
$\Sigma = 2$			
$\Sigma \to 0$			

- Directional motion

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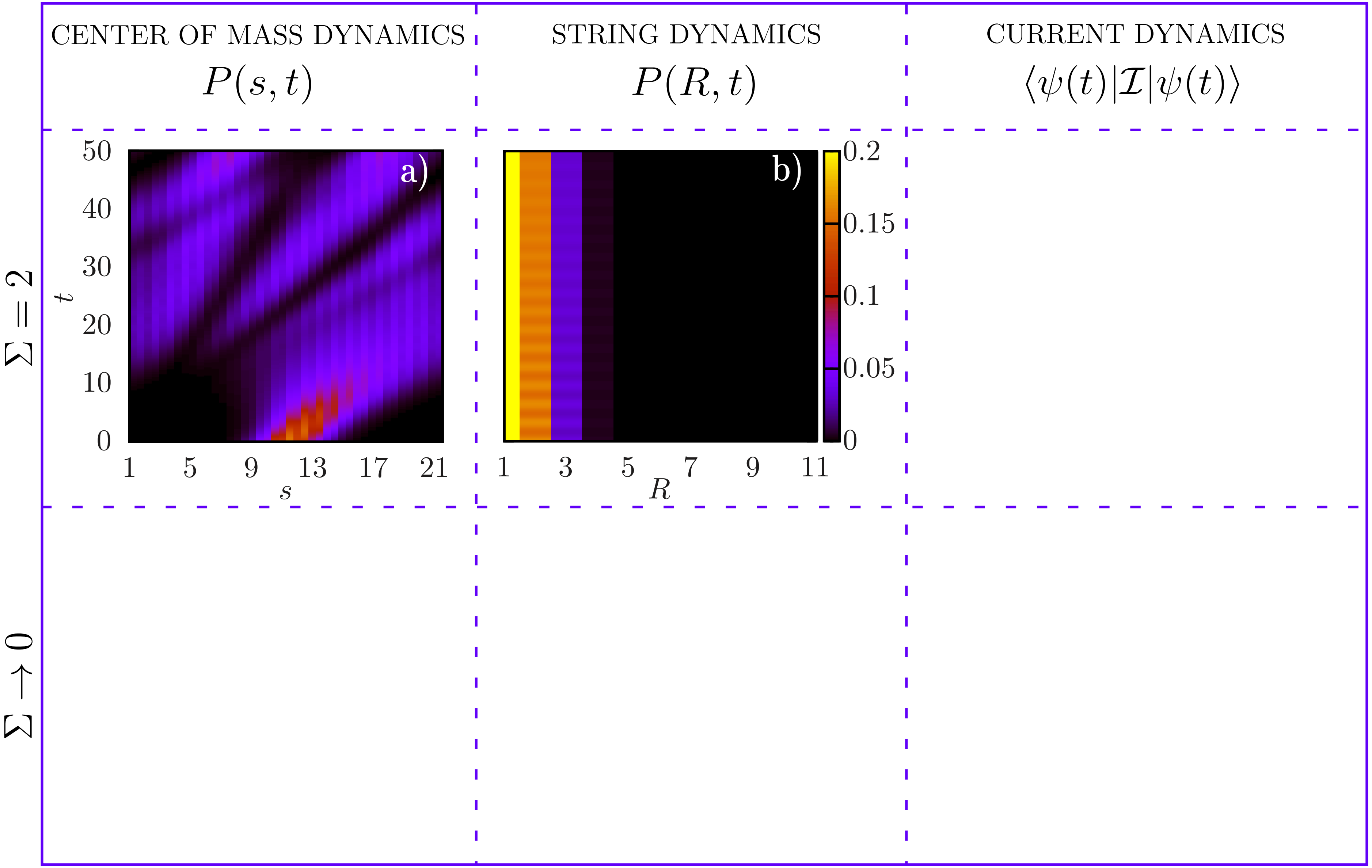
Quench dynamics



- Directional motion
- Suppressed string oscillations

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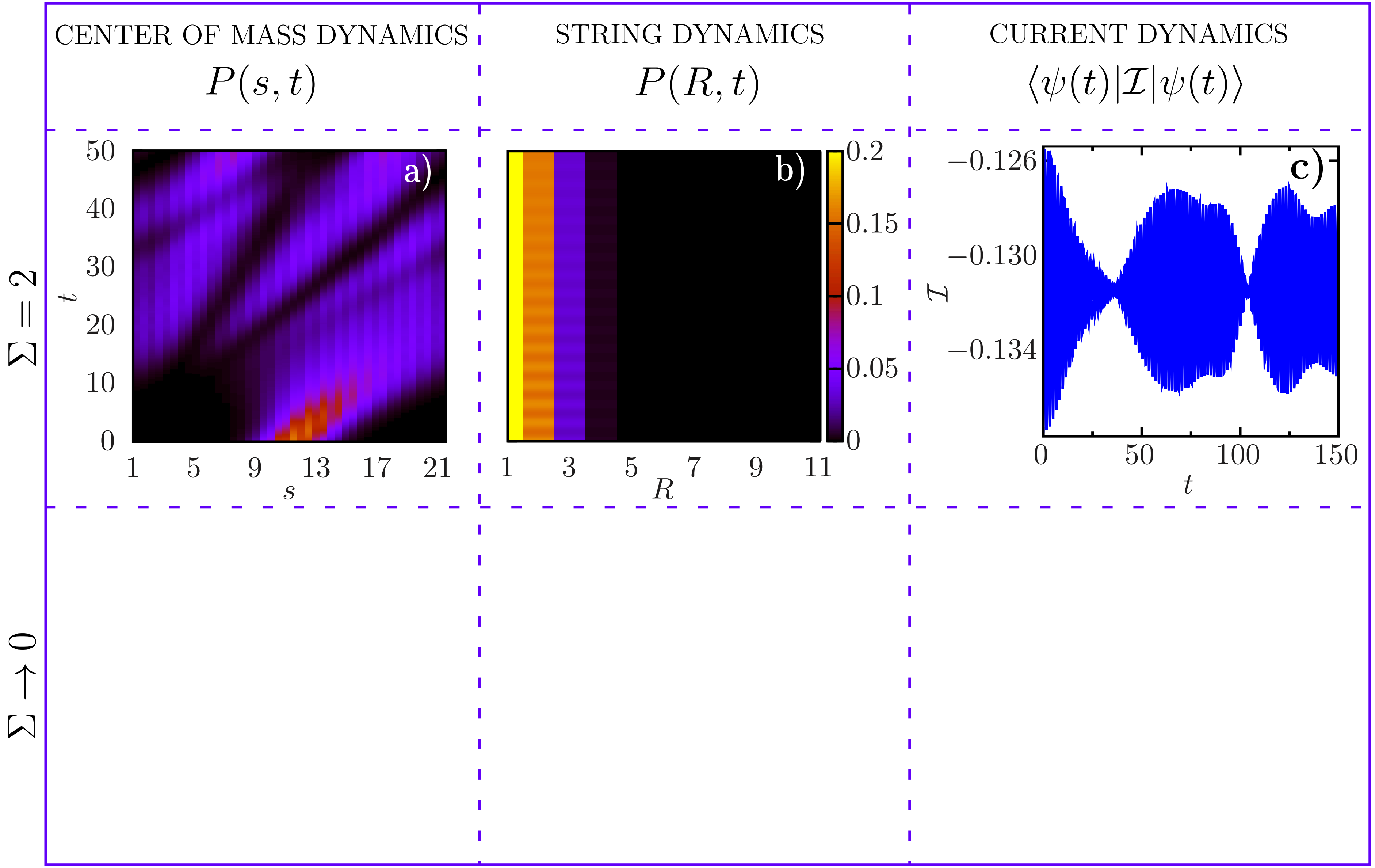
Quench dynamics



- Directional motion
- Suppressed string oscillations
- $\mathcal{I}$ oscillates around a finite value $\mathcal{I}_0$

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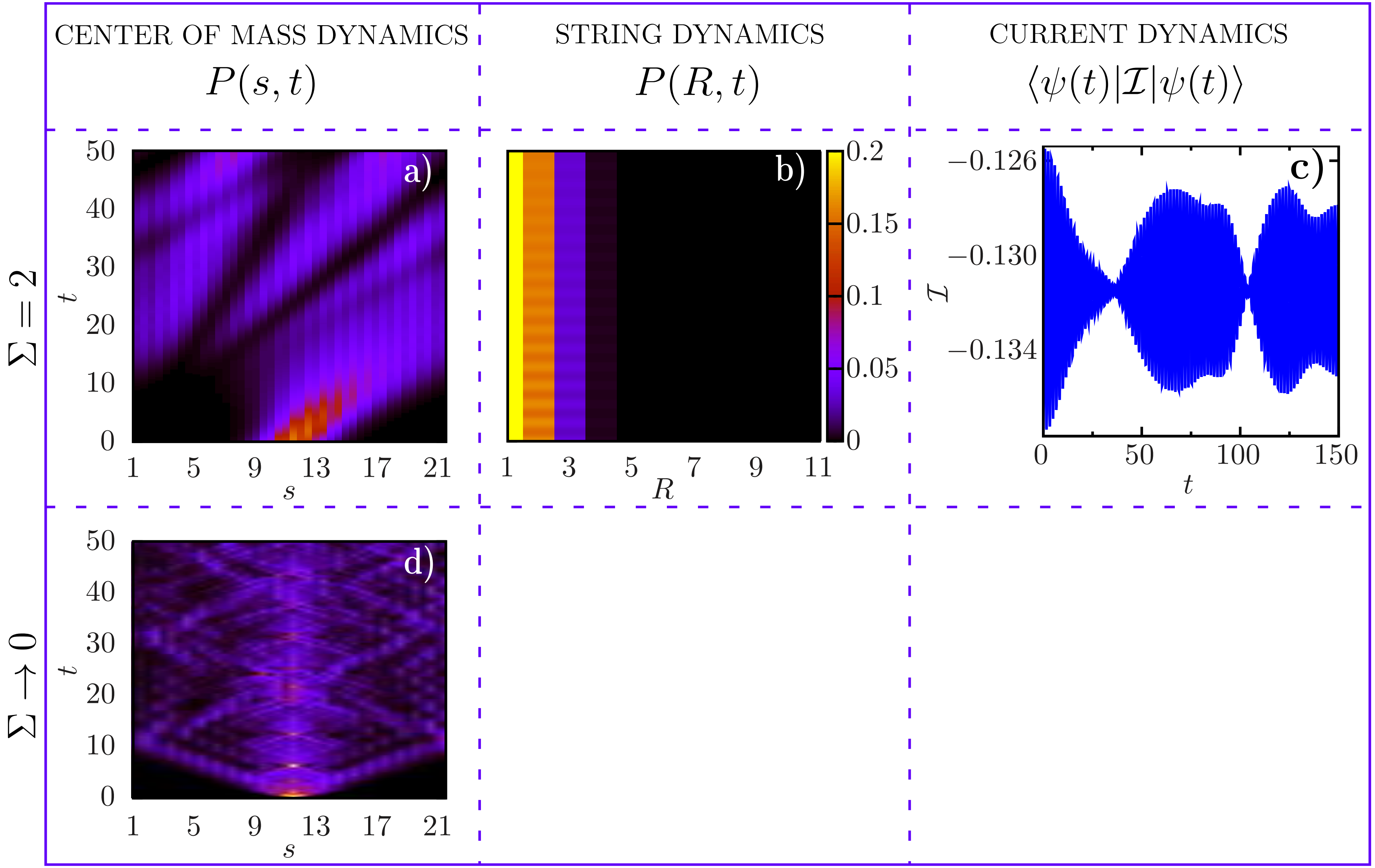
Quench dynamics



- Directional motion
- Suppressed string oscillations
- $\mathcal{I}$ oscillates around a finite value $\mathcal{I}_0$

- Non-directional motion

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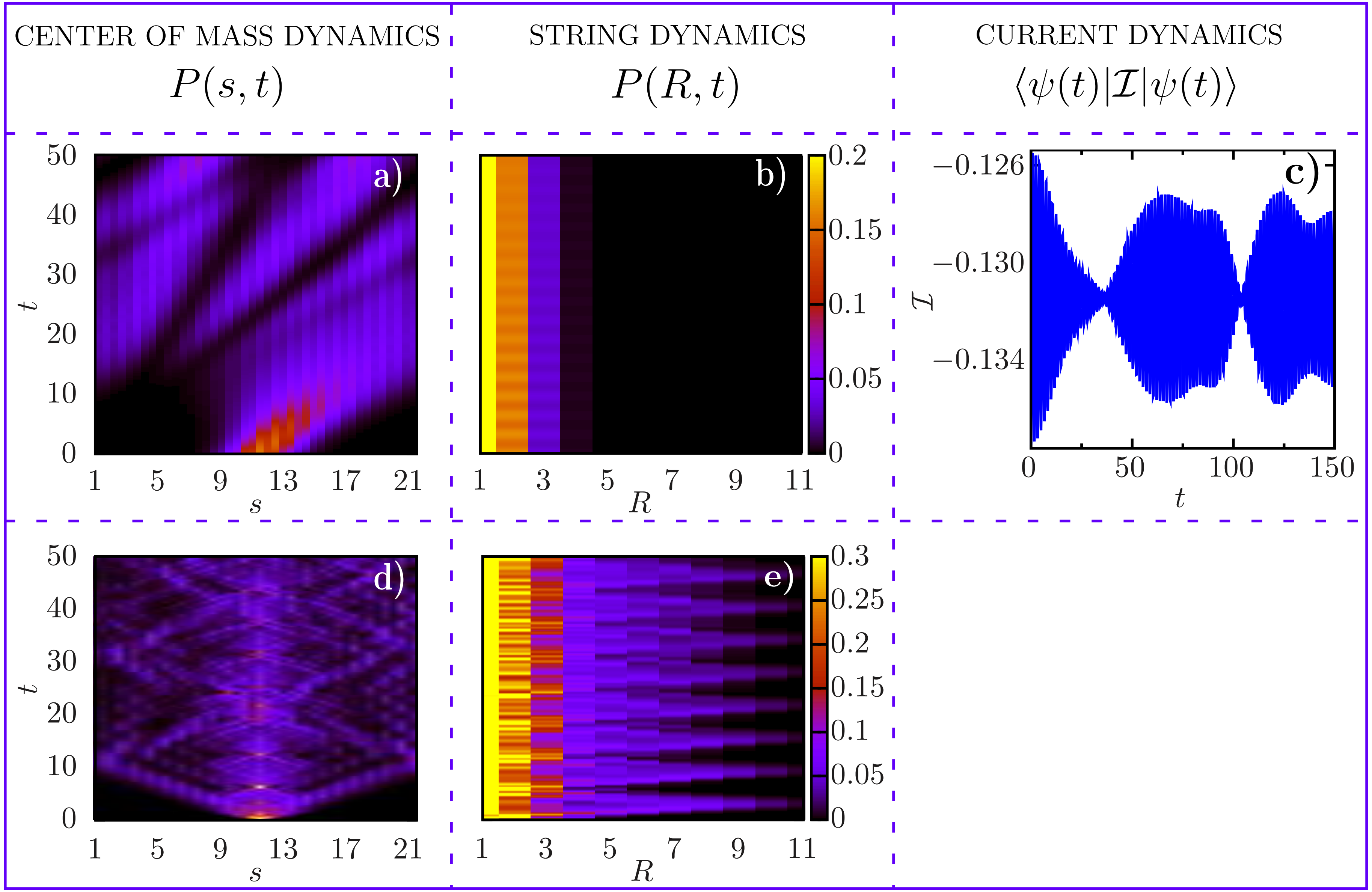
Quench dynamics



- Directional motion
- Suppressed string oscillations
- $\mathcal{I}$ oscillates around a finite value $\mathcal{I}_0$

- Non-directional motion
- Broad string oscillations

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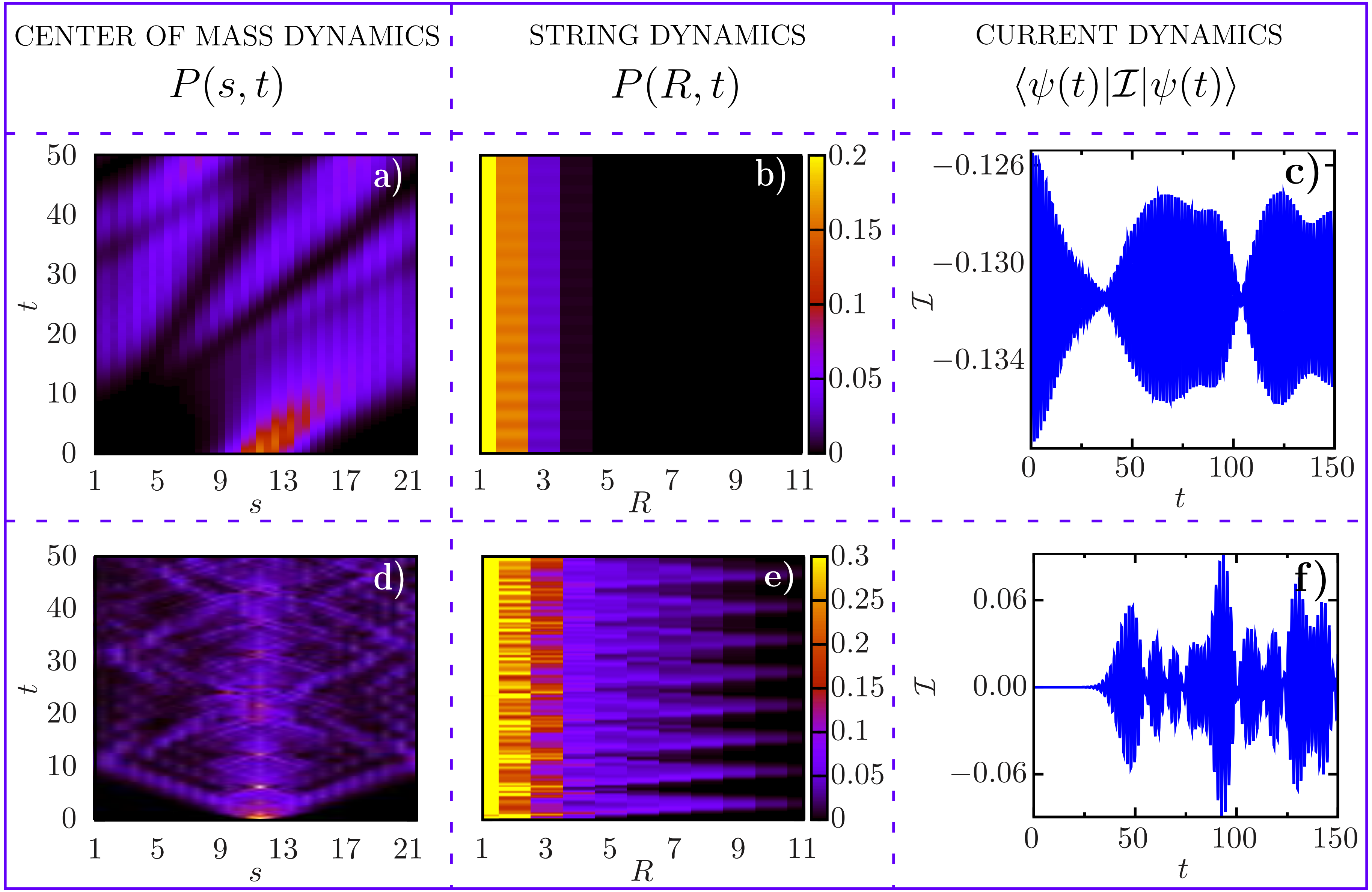
Quench dynamics



- Directional motion
- Suppressed string oscillations
- $\mathcal{I}$ oscillates around a finite value $\mathcal{I}_0$

- Non-directional motion
- Broad string oscillations
- $\mathcal{I}$ is zero on average

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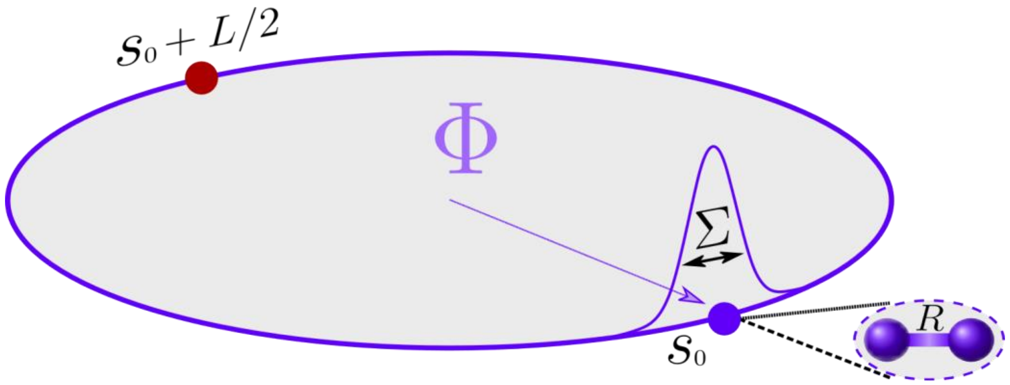
Aharonov-Bohm effect



	$P_{mid}(t)$	$\tilde{P}_{mid}(w) = 1/T \int_0^T dt\, e^{iwt} P_{mid}(t)$
$\tau = 10$		
$\tau = 0.1$		

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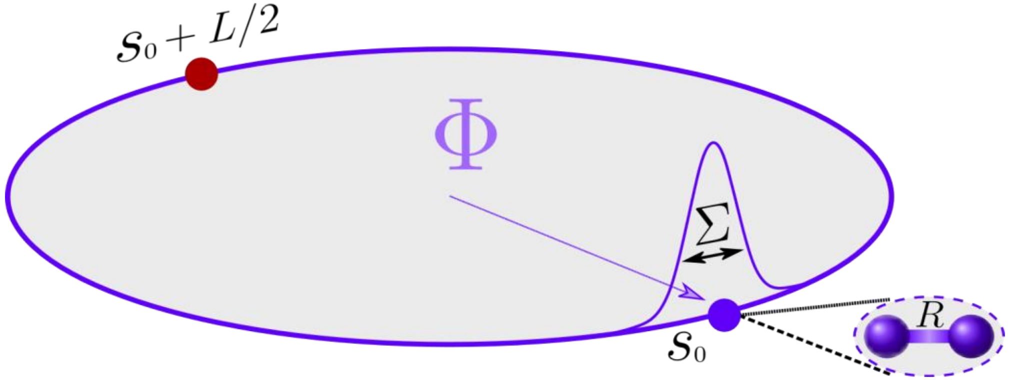
Aharonov-Bohm effect



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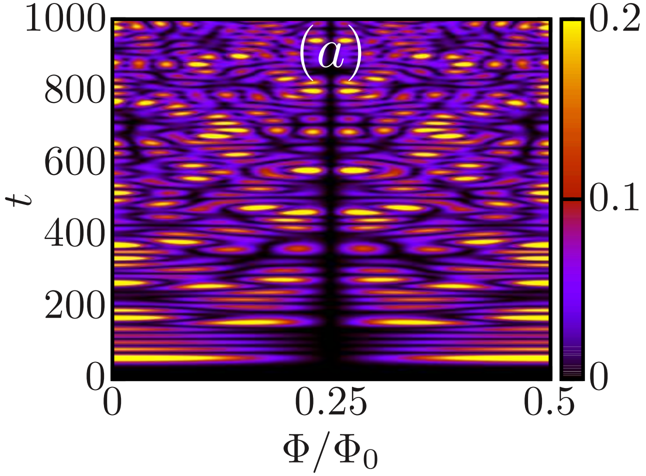
$\tau = 10$		
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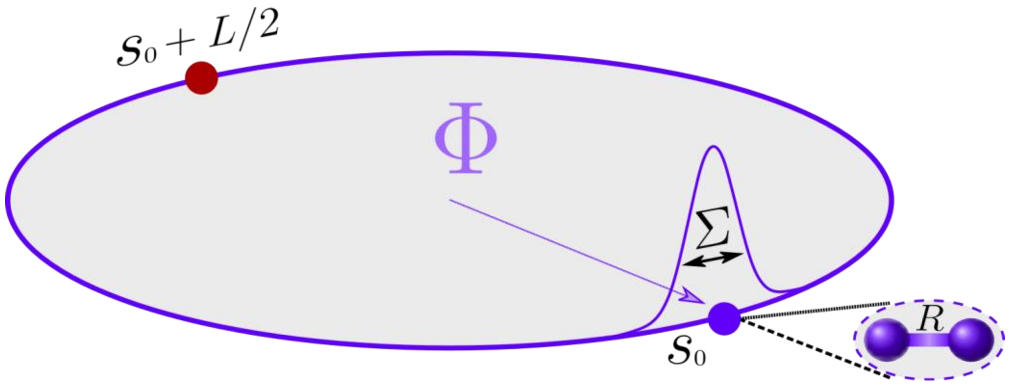

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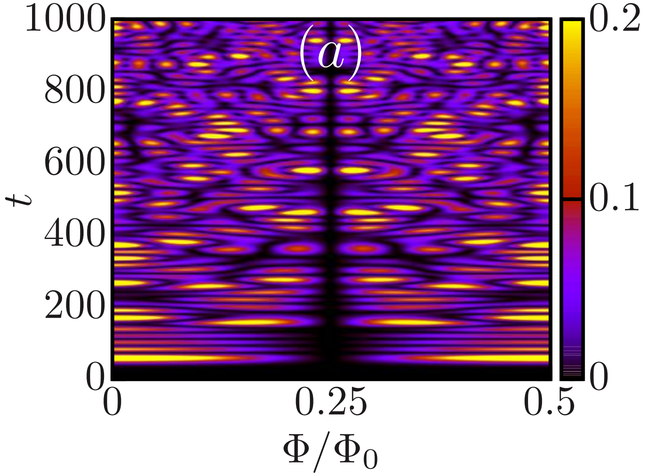
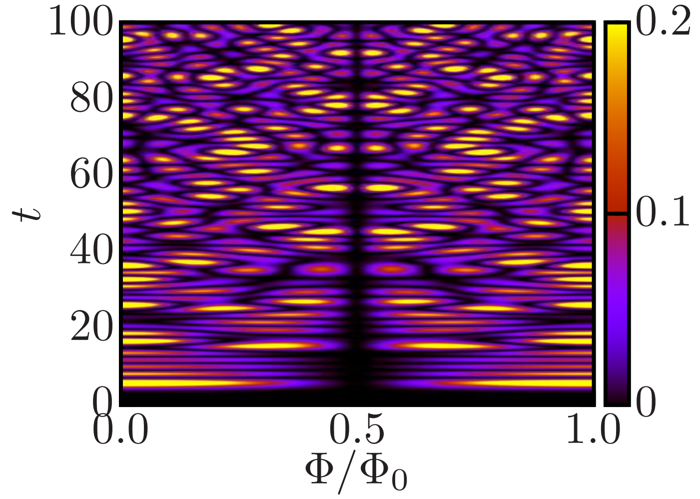


$\tau = 0.1$

- Effectively single particle Aharonov – Bohm effect
- Slow dynamics



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Aharonov-Bohm effect

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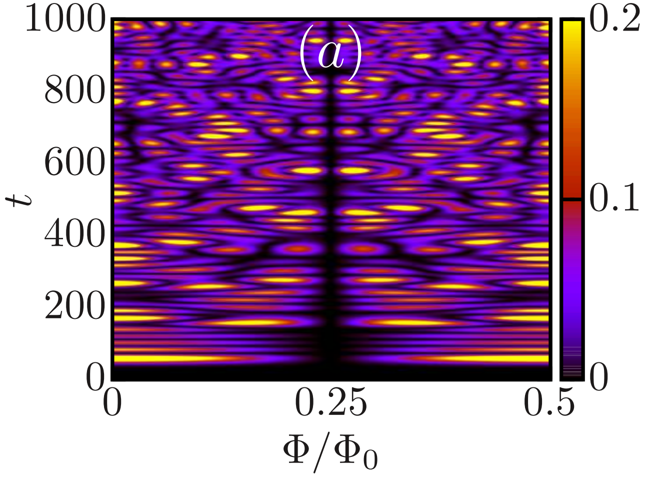
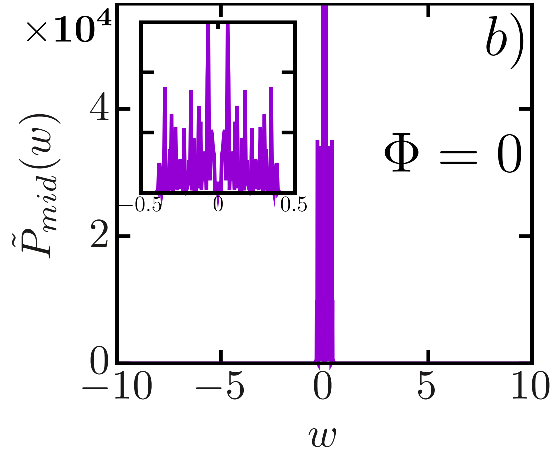
$\tau = 10$		
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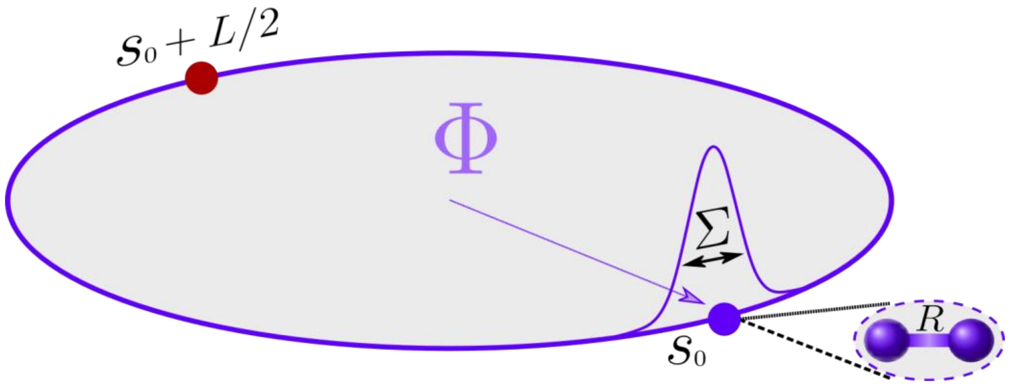
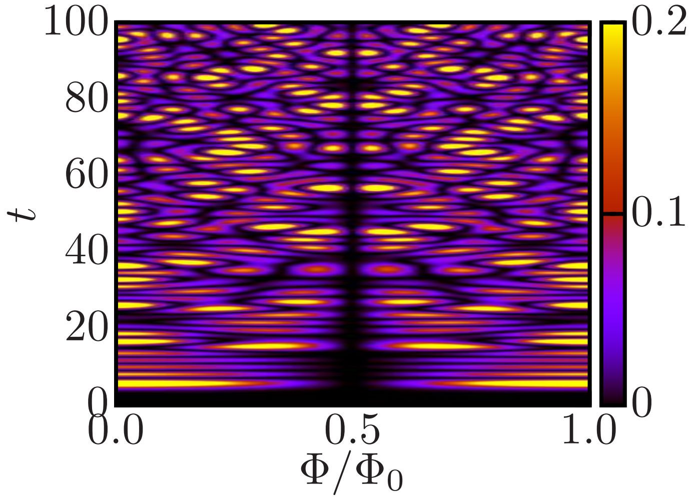


- Effectively single particle Aharonov – Bohm effect
- Slow dynamics
- Narrow frequency distribution



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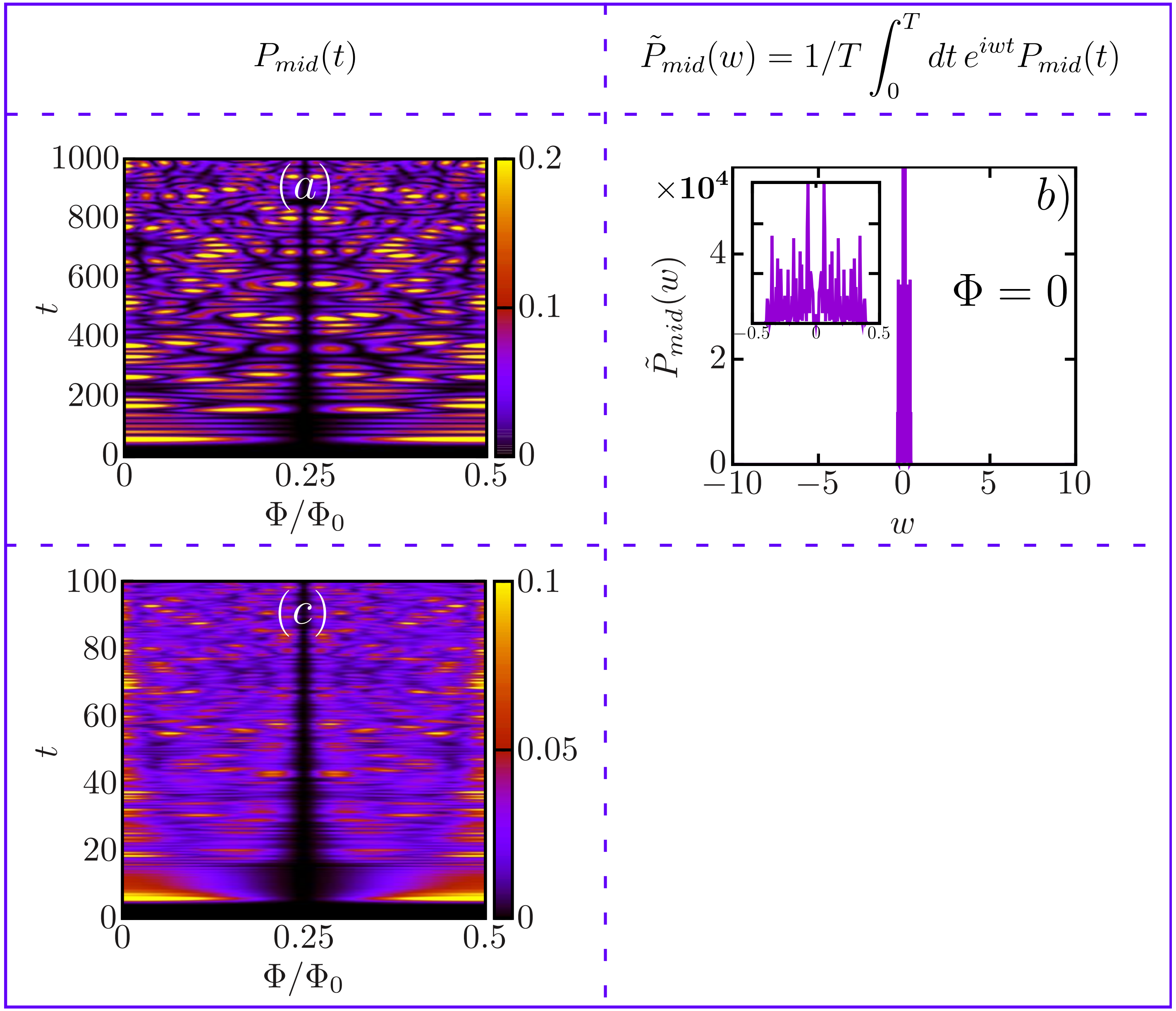
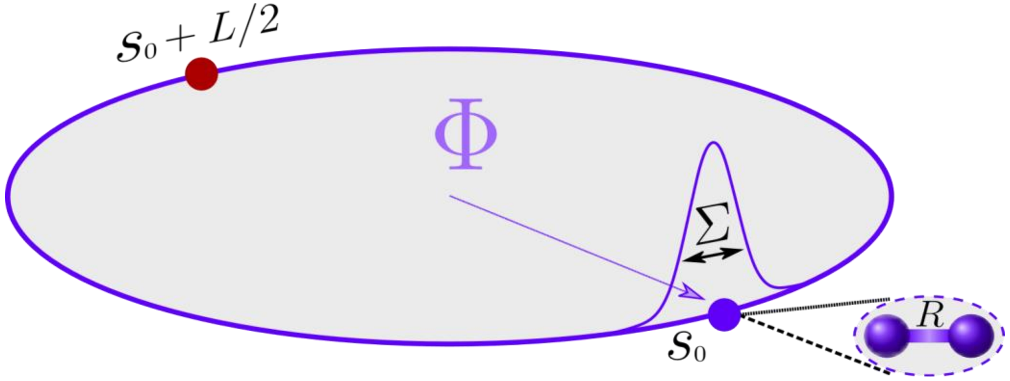
Aharonov-Bohm effect





- Effectively single particle Aharonov – Bohm effect
- Slow dynamics
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- Aharonov – Bohm oscillations combine with the string dynamics

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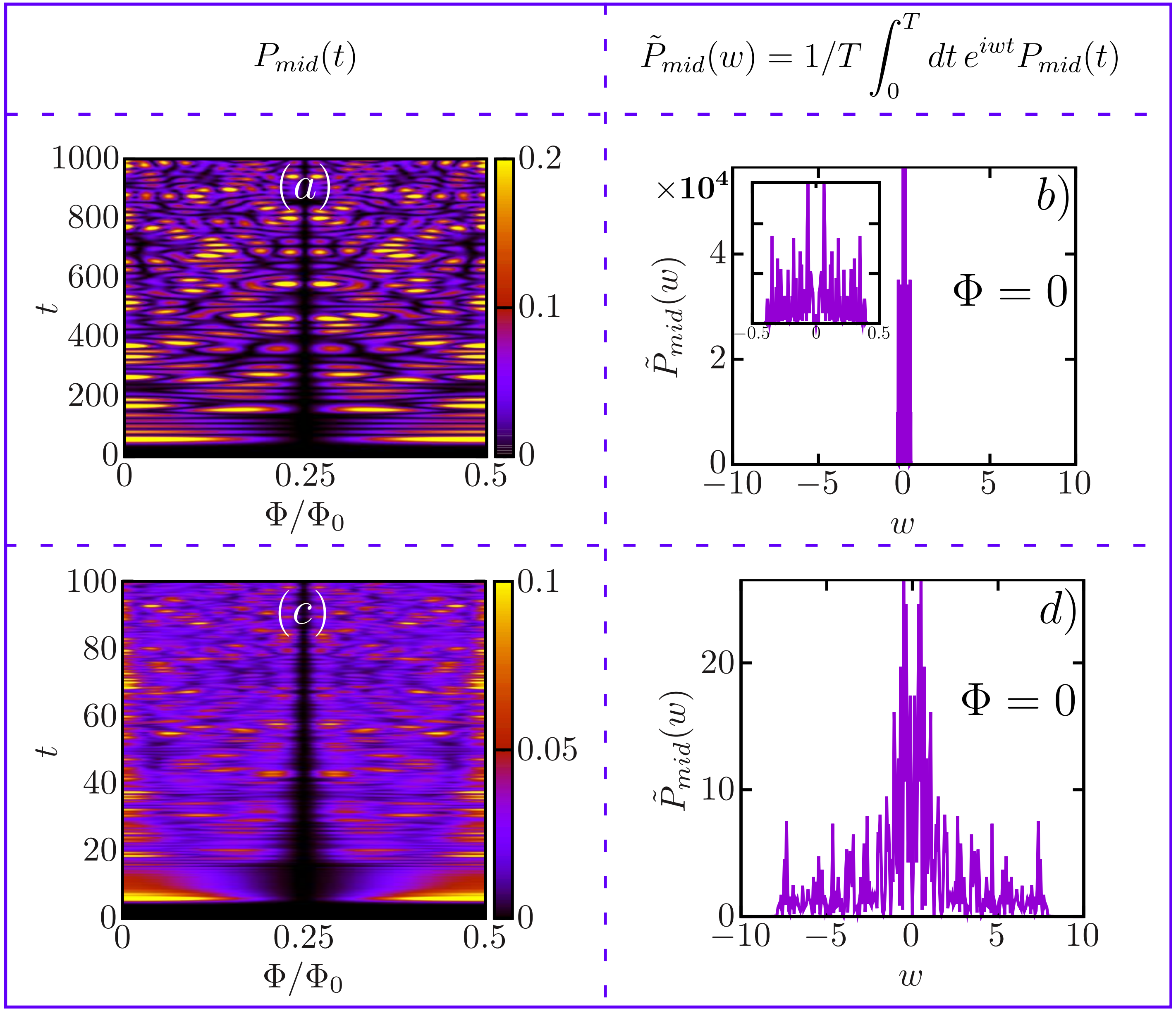

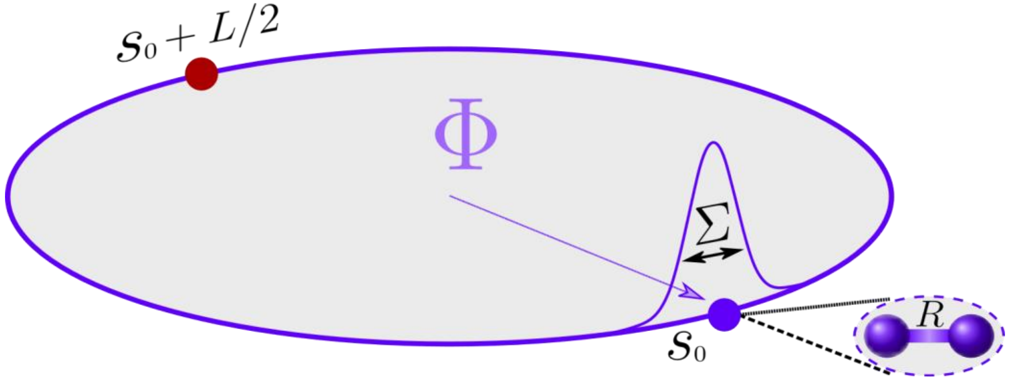

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Summary

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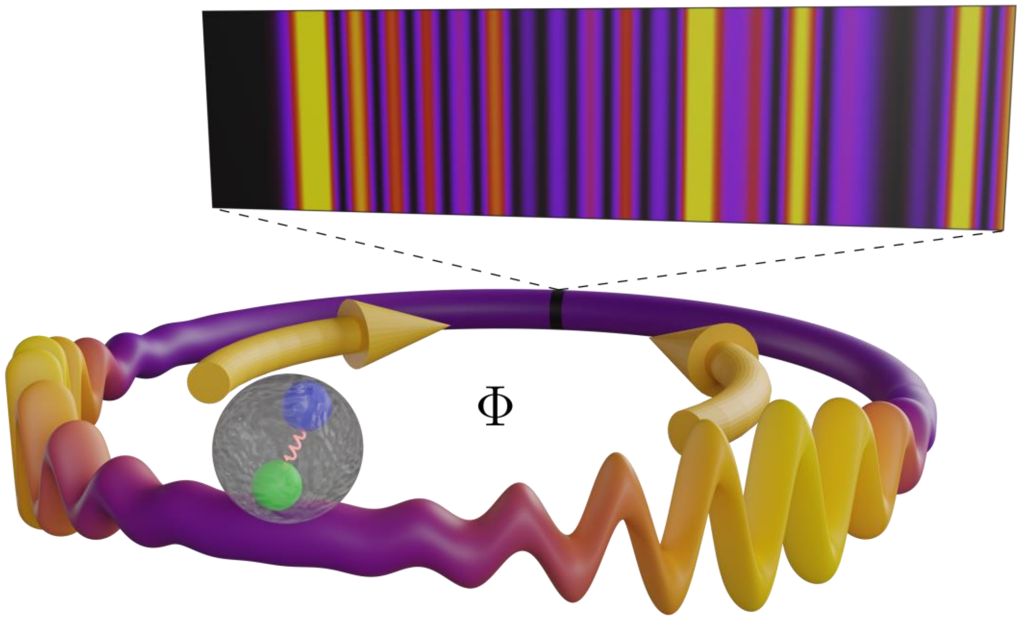
- We studied coherence properties of the theory
  - Fractionalization of the ground state current
  - Flux driven dynamics of a single meson
  - Aharonov-Bohm effect
- Future directions
  - Extension to other LGTs
  - Scattering with localized potential barriers in the ring



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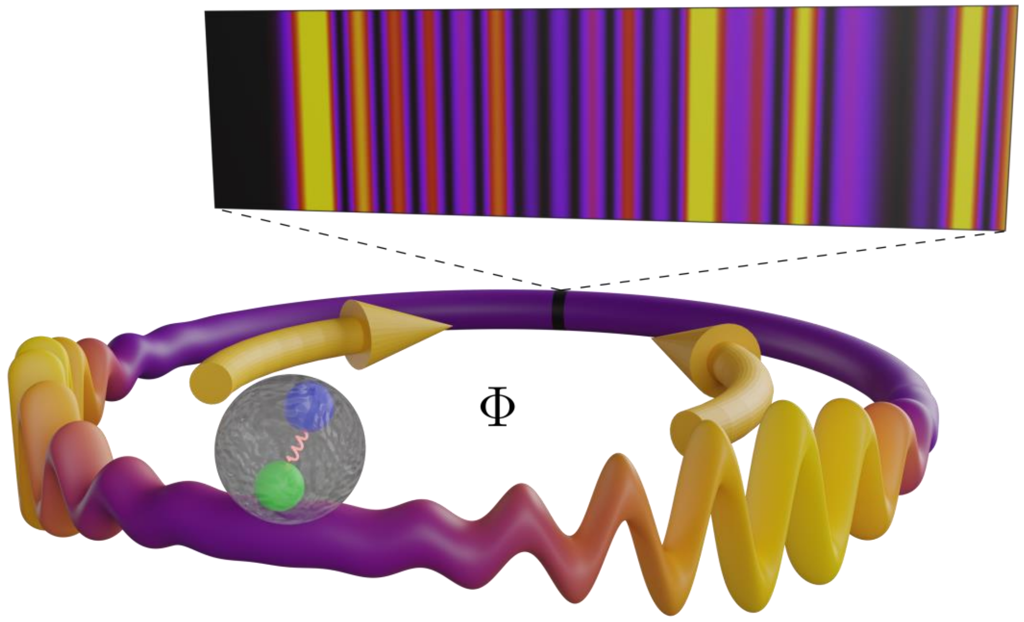

Thank you for your attention!