SLOW DYNAMICS IN LATTICE GAUGE THEORIES: A QUANTUM SIMULATION WITH RYDBERG ATOMS

Federica Surace

TRIESTE JUNIOR QUANTUM DAYS - 26/07/2019

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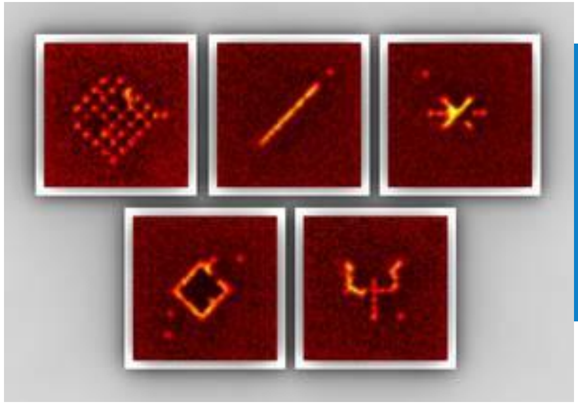
WHY GAUGE THEORIES AND QUANTUM SIMULATIONS?



High degree of **control** and **tunability** of quantum systems

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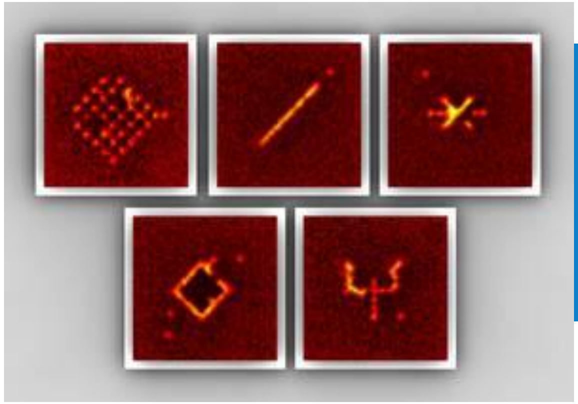

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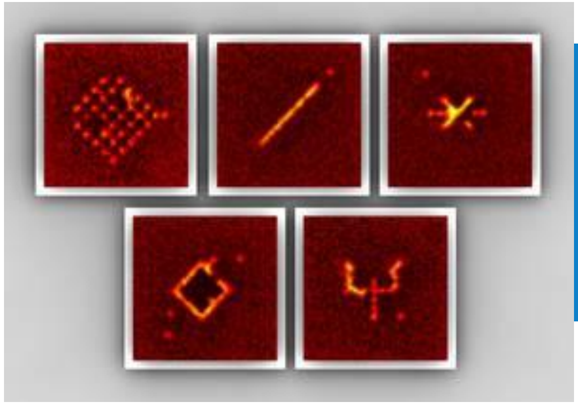
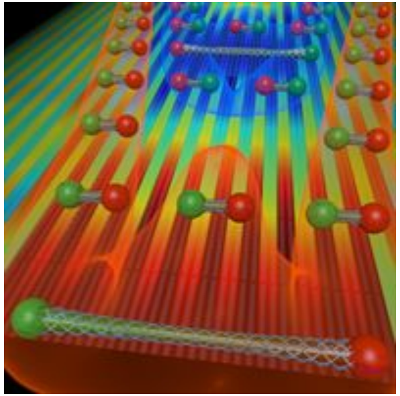


High degree of **control** and **tunability** of quantum systems

- Use of **quantum simulators** for **strongly correlated** matter
- **Time evolution** of many-particle quantum systems

WHY GAUGE THEORIES AND QUANTUM SIMULATIONS?

- Access to **real-time** dynamics: perspectives for **high energy** physics



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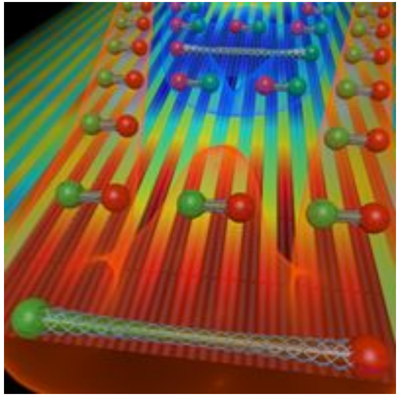
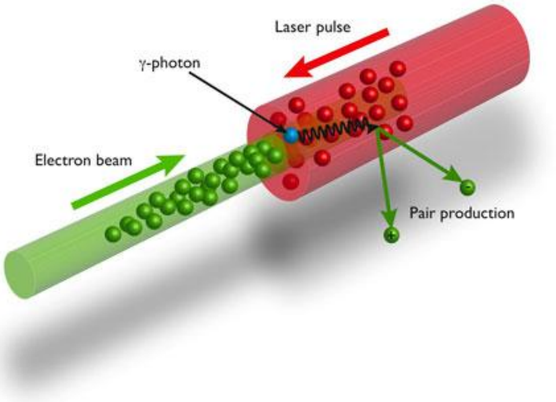


- Hope (long-term): overcome limitations of **experiments**, **classical computation**?



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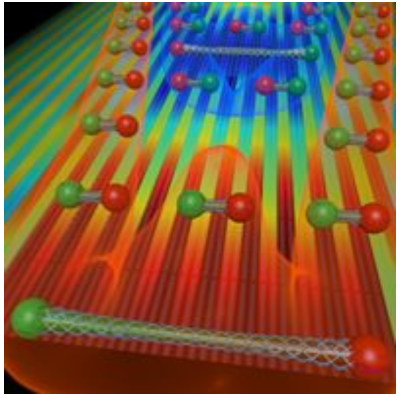
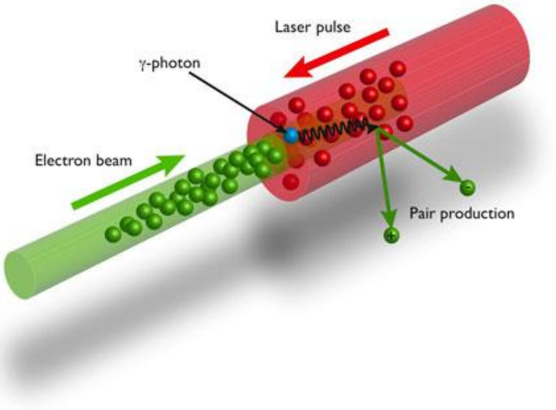
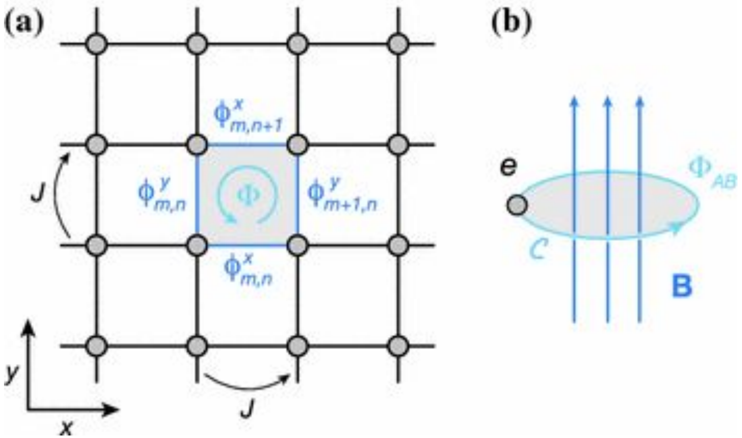


→ **LATTICE GAUGE THEORIES**



STATIC VS DYNAMICAL GAUGE FIELDS

Static gauge fields



Particles hopping around a plaquette acquire a phase

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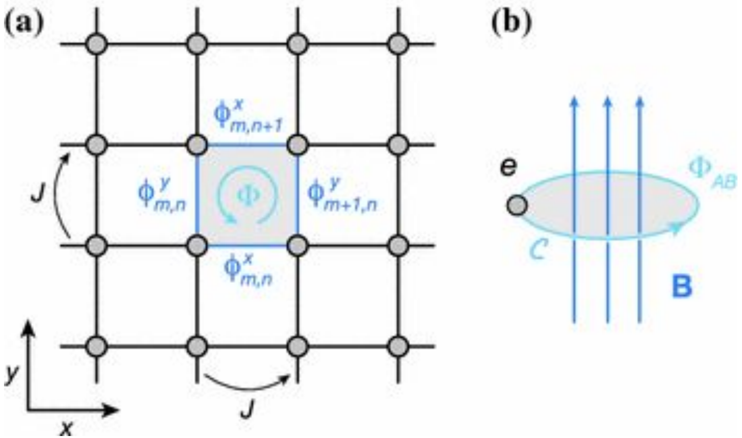

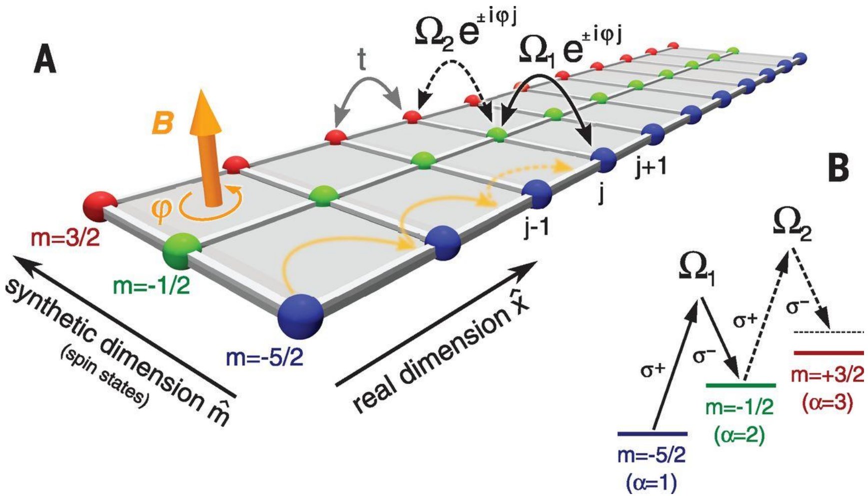

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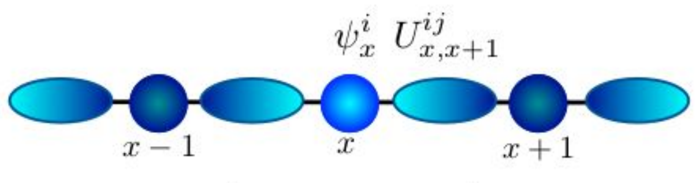
Mancini, M., Pagano, G., Cappellini, G., Livi, L., Rider, M., Catani, J., ... & Fallani, L., *Science*, **349**, 1510-1513 (2015).

STATIC VS DYNAMICAL GAUGE FIELDS

Dynamical gauge fields

- additional “link” degrees of freedom



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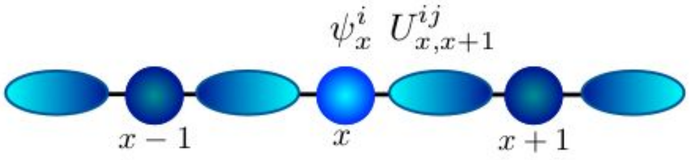

condensed matter
frustrated magnets

quantum computing
toric code

high energy physics
standard model

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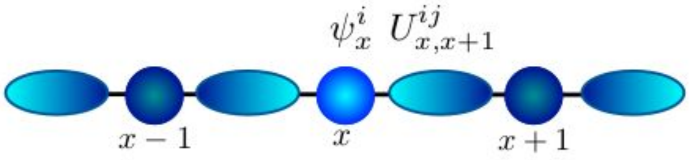
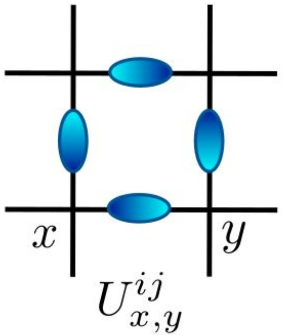


- Problem:
  - complex many-body interactions
  - local (gauge) symmetries



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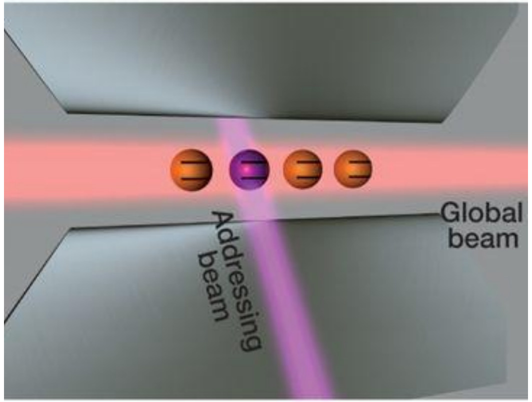
So far, no experimental evidence that atomic systems can simulate gauge theories at large scale



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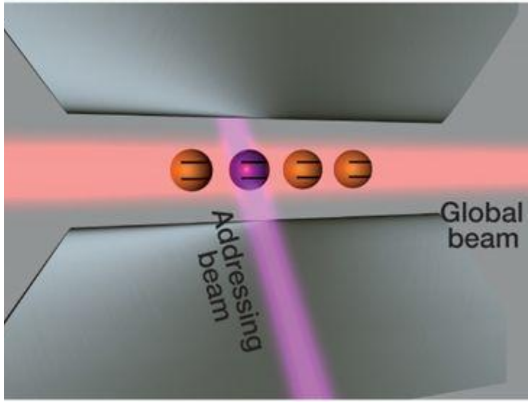

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We show that this has been done:

U(1) GAUGE THEORY in 1+1d

exploiting dynamics induced by **Rydberg** interactions

OUTLINE

The model

- Rydberg: FSS model
- U(1) gauge: quantum link model

OUTLINE

1 The model

- Rydberg: FSS model
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2 Slow dynamics

- Density oscillations
- String inversion

OUTLINE

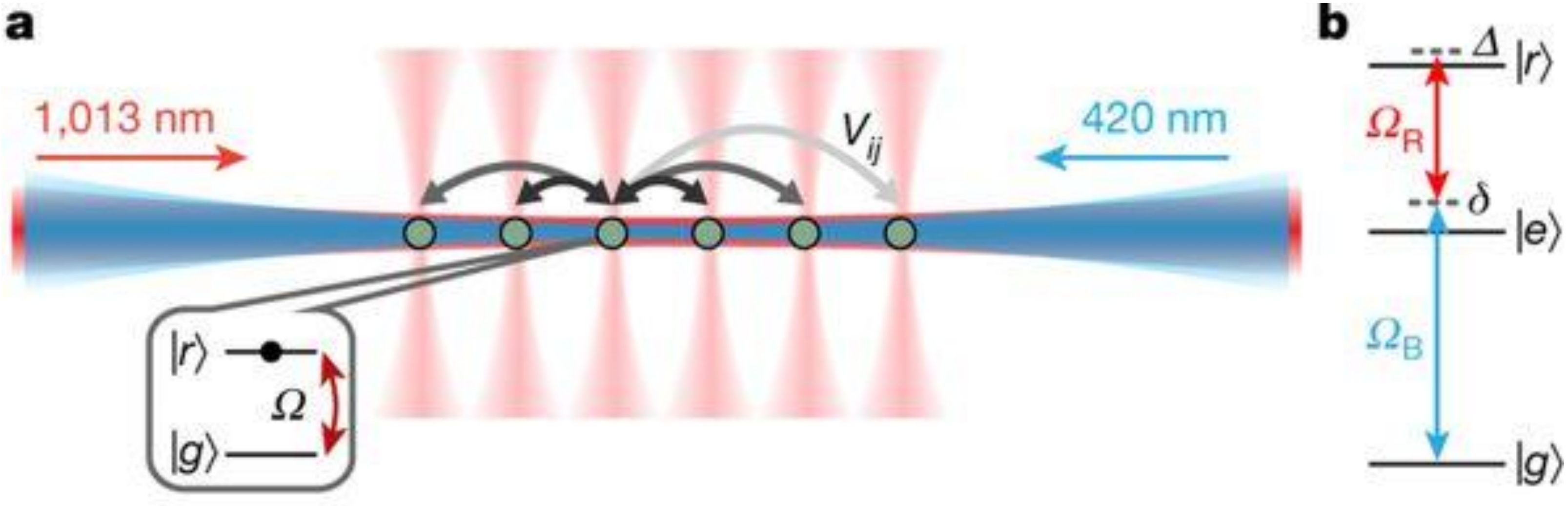
1 The model

- Rydberg: FSS model
- U(1) gauge: quantum link model

2 Slow dynamics

- Density oscillations
- String inversion
- No string breaking
- Particle-antiparticle pairs

RYDBERG ATOM EXPERIMENT



$$\hat{H}_{\mathrm{Ryd}} = \sum_{j=1}^{L} (\Omega\, \hat{\sigma}_j^x + \delta\, \hat{\sigma}_j^z) + \sum_{j \neq \ell = 1}^{L} V_{j,\ell} (\hat{\sigma}_j^z + 1)(\hat{\sigma}_\ell^z + 1)$$

H. Bernien, S. Schwartz, A. Keesling, H. Levine, A. Omran, H. Pichler, S. Choi, A. S. Zibrov, M. Endres, M. Greiner, et al., *Nature* **551**, 579 (2017)

FSS MODEL

$$\hat{H}_{\text{FSS}} = \sum_j \left(\Omega\, \hat{\sigma}_j^x + \delta\, \hat{n}_j + V\, \hat{n}_j \hat{n}_{j+2}\right) \qquad \hat{n}_j \hat{n}_{j+1} = 0$$

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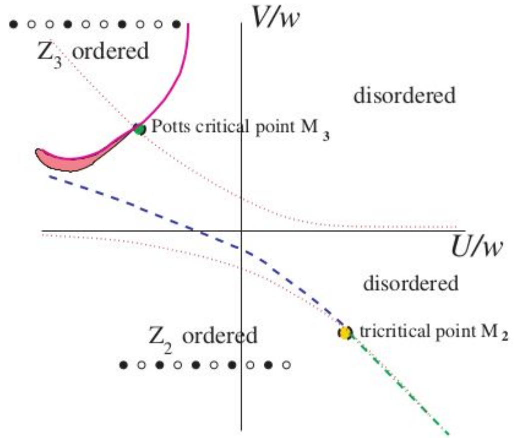
Phase diagram



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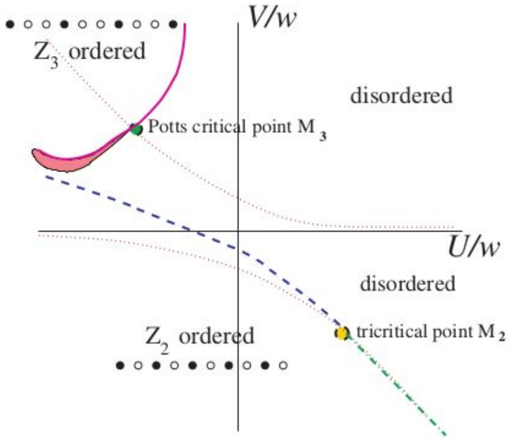

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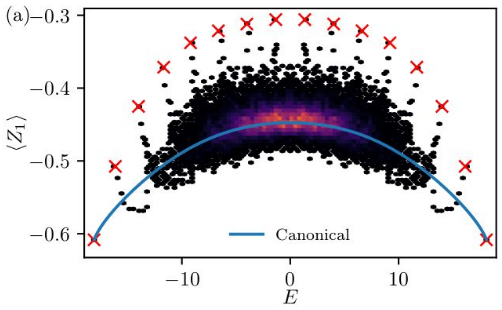
Non-equilibrium dynamics



- Quantum many-body scars
- Violation of ETH

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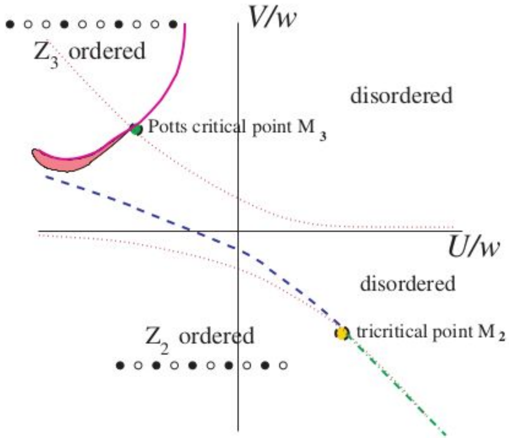

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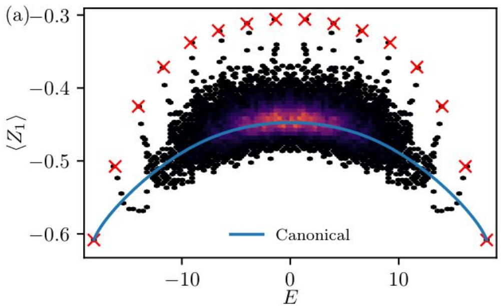

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Here: **Gauge theories**

U(1) LATTICE GAUGE THEORIES

Matter (sites)

Fermions $\{\hat{\Phi}_i^\dagger, \hat{\Phi}_j\} = \delta_{i,j}$

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Even sites		
	●	e^+
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Odd sites		
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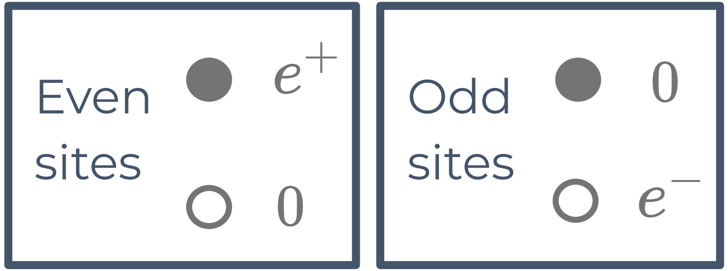

Bare vacuum

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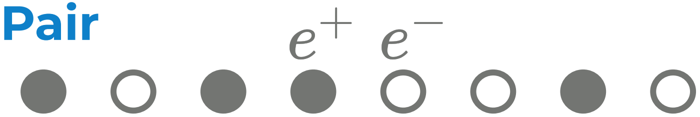

Gauge fields (links)

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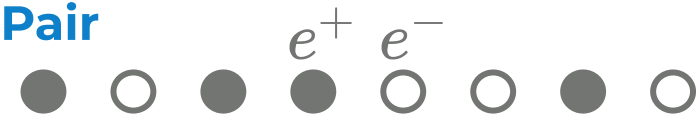

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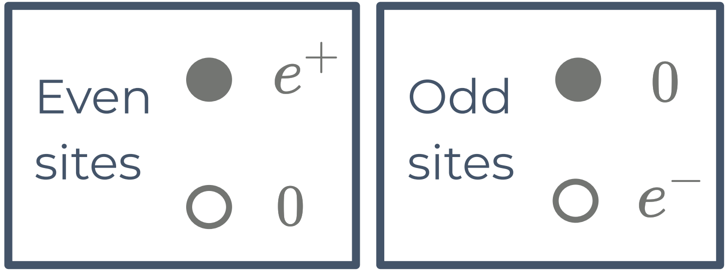

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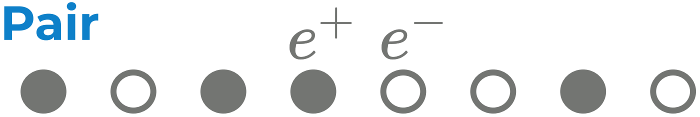

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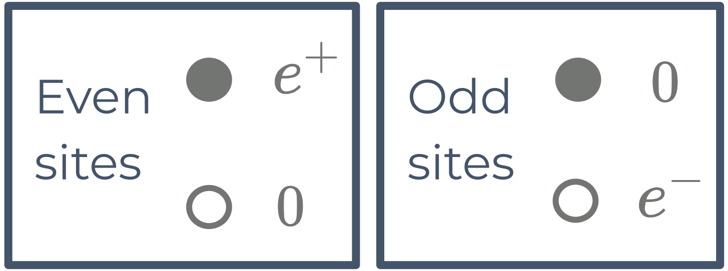

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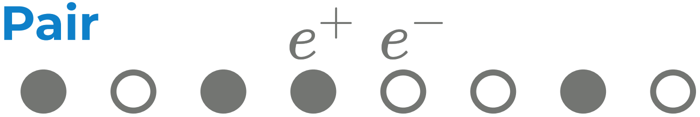

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Gauss law

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Pair e^+ e^-

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$$\hat{H} = -w \sum_{j=1}^{L-1} (\hat{\Phi}_j^\dagger \hat{U}_{j,j+1} \hat{\Phi}_{j+1} + \mathrm{h.c})$$

Matter-field interaction

Hopping of fermions

mediated by gauge fields

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Mass term

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Quantum link S=1/2

$$\hat{E}|\blacktriangleright\rangle = +\frac{1}{2}|\blacktriangleright\rangle$$

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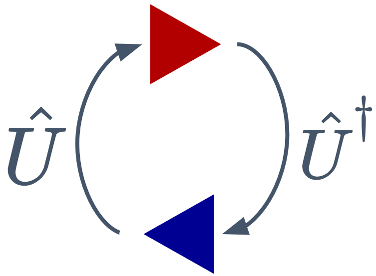

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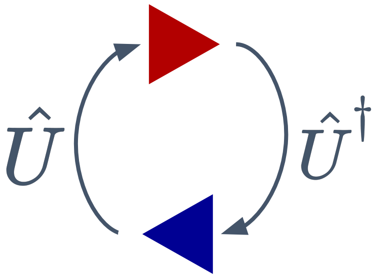

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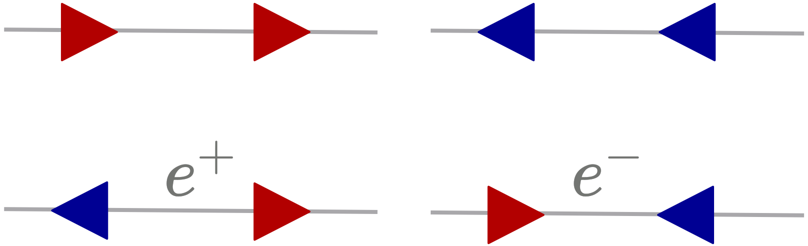
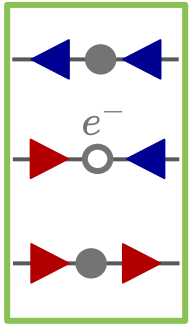


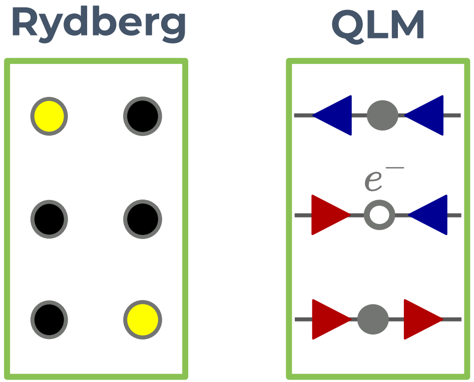
MAPPING - STATES

QLM



MAPPING - STATES

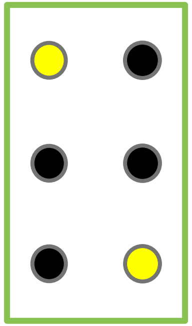
odd sites



MAPPING - STATES

odd sites

Rydberg



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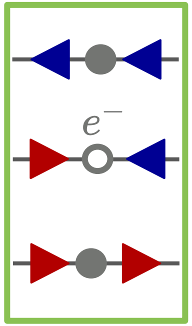
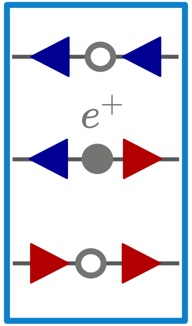


even sites

QLM



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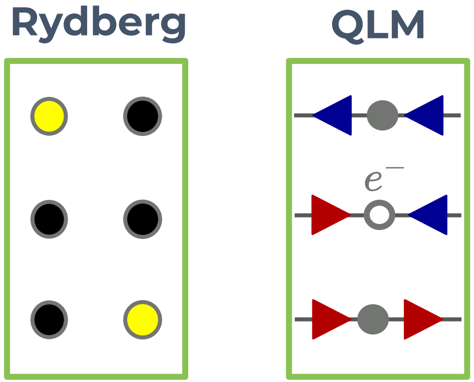
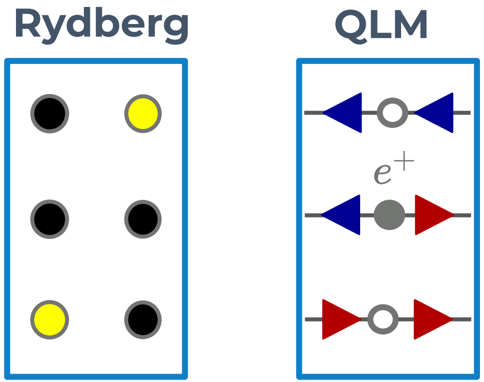
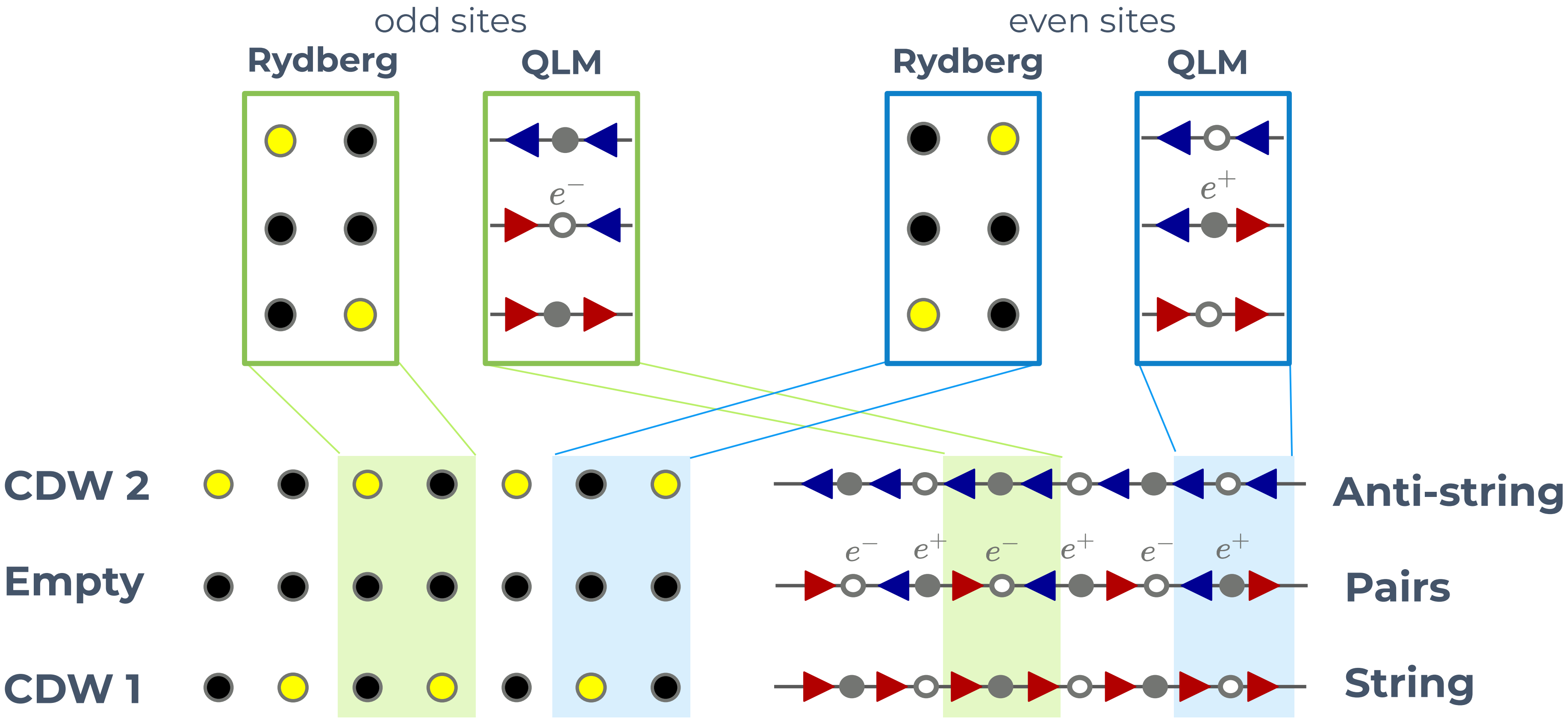


even sites



MAPPING - STATES



MAPPING - HAMILTONIAN

$$\hat{H}_{\text{FSS}} = \sum_j \left(\Omega \, \hat{\sigma}_j^x + \delta \, \hat{n}_j \right)$$

↕

$$\hat{H}_{QLM} = -w \sum_j (\hat{\Phi}_j^\dagger \hat{S}^+_{j,j+1} \hat{\Phi}_{j+1} + \text{h.c})$$

$$+m \sum_j (-1)^j \hat{\Phi}_j^\dagger \hat{\Phi}_j$$

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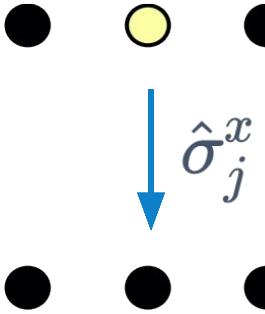

$$\Omega = -w$$

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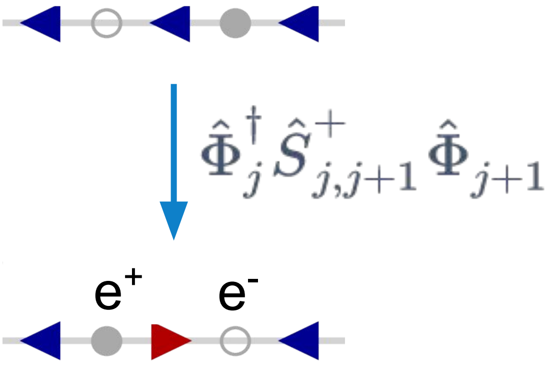

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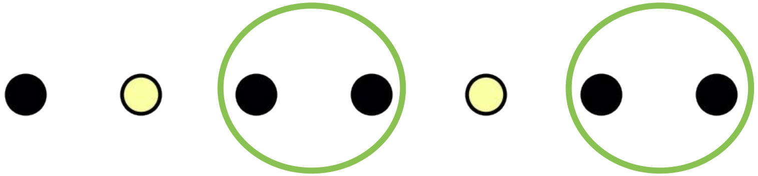

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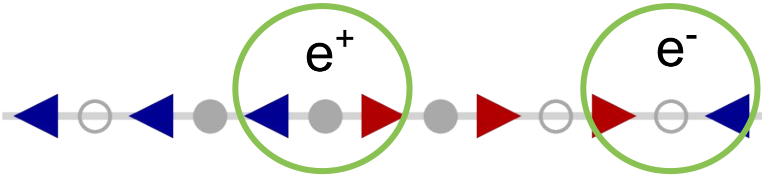
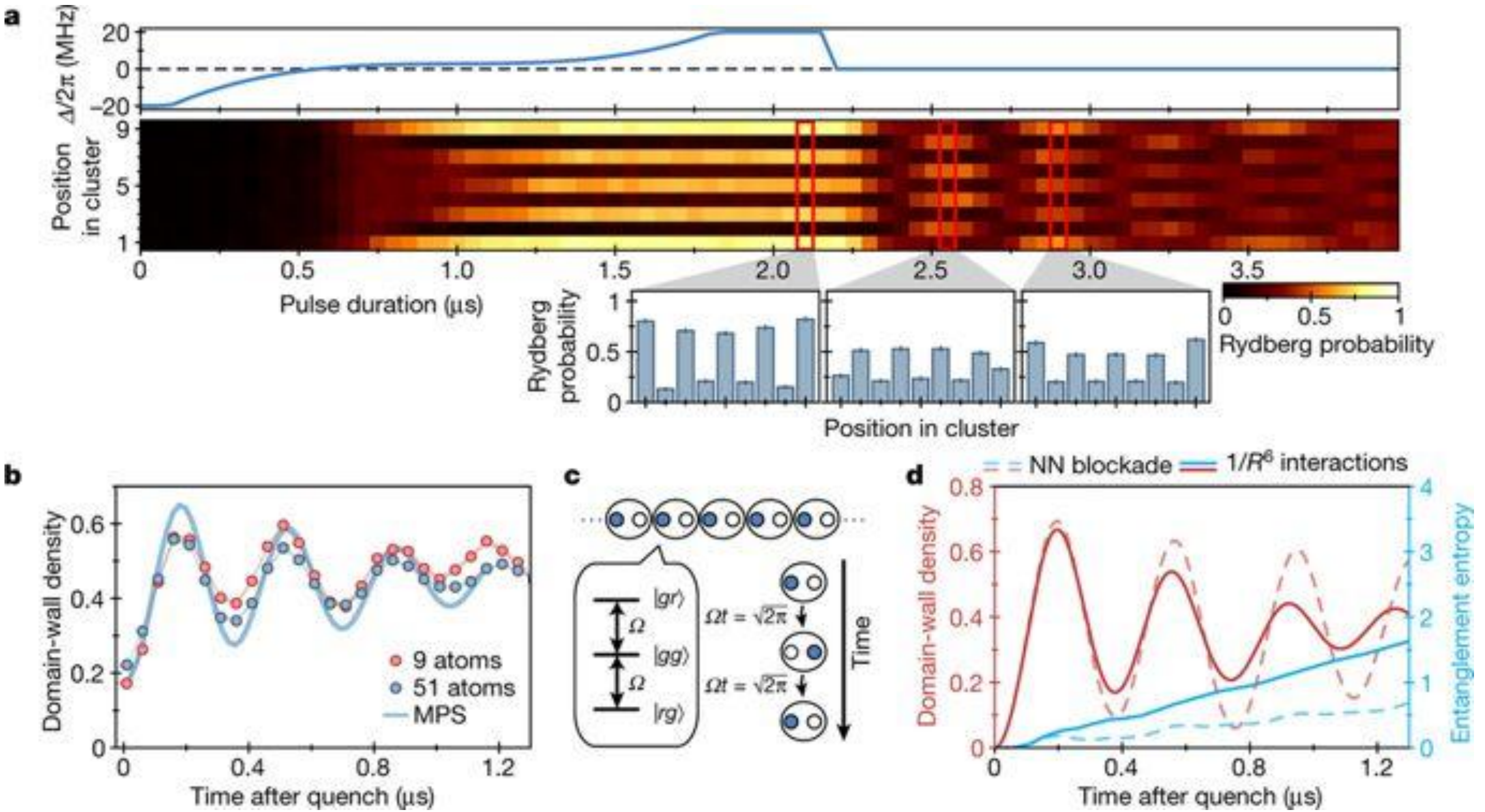
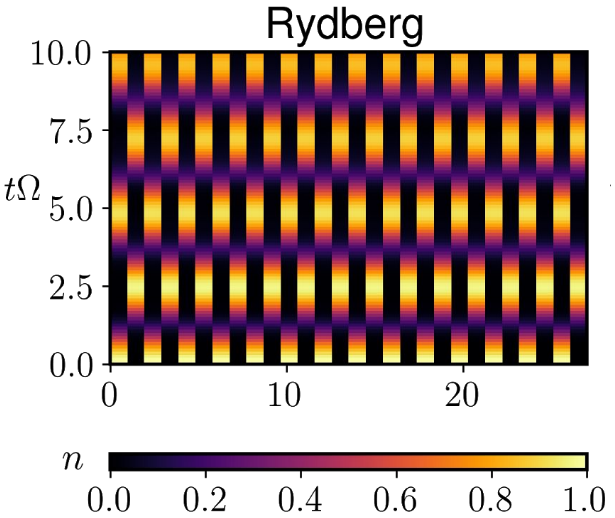


EXPERIMENT: SLOW DYNAMICS



H. Bernien, S. Schwartz, A. Keesling, H. Levine, A. Omran, H. Pichler, S. Choi, A. S. Zibrov, M. Endres, M. Greiner, et al., *Nature* **551**, 579 (2017)

INTERPRETATION AS STRING INVERSION



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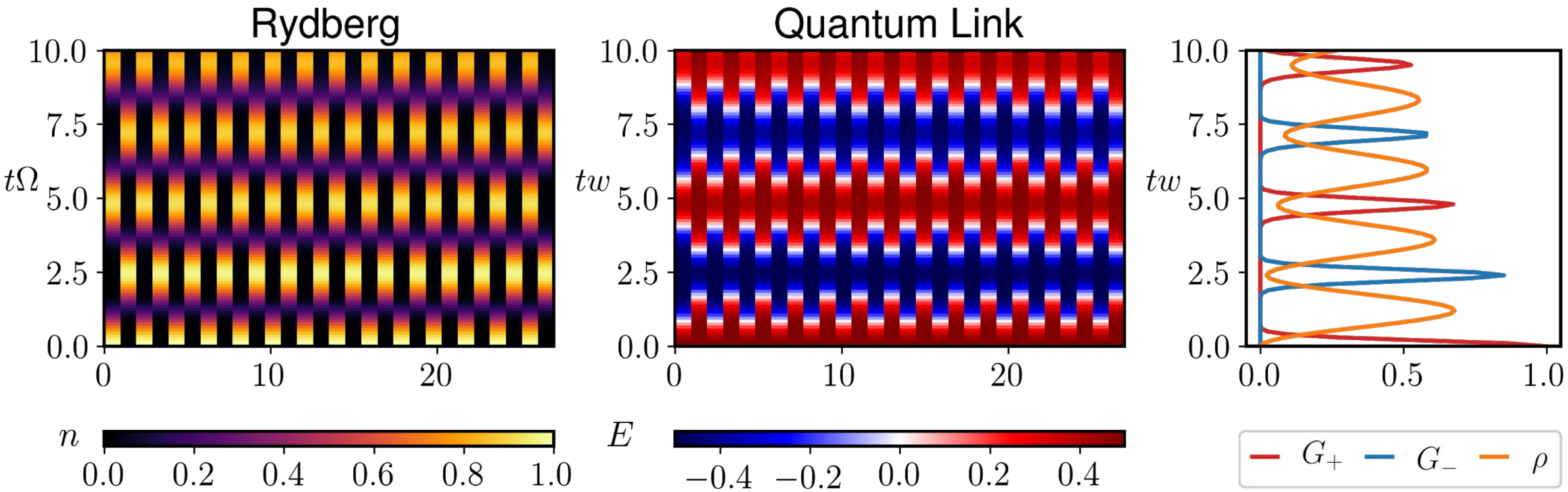

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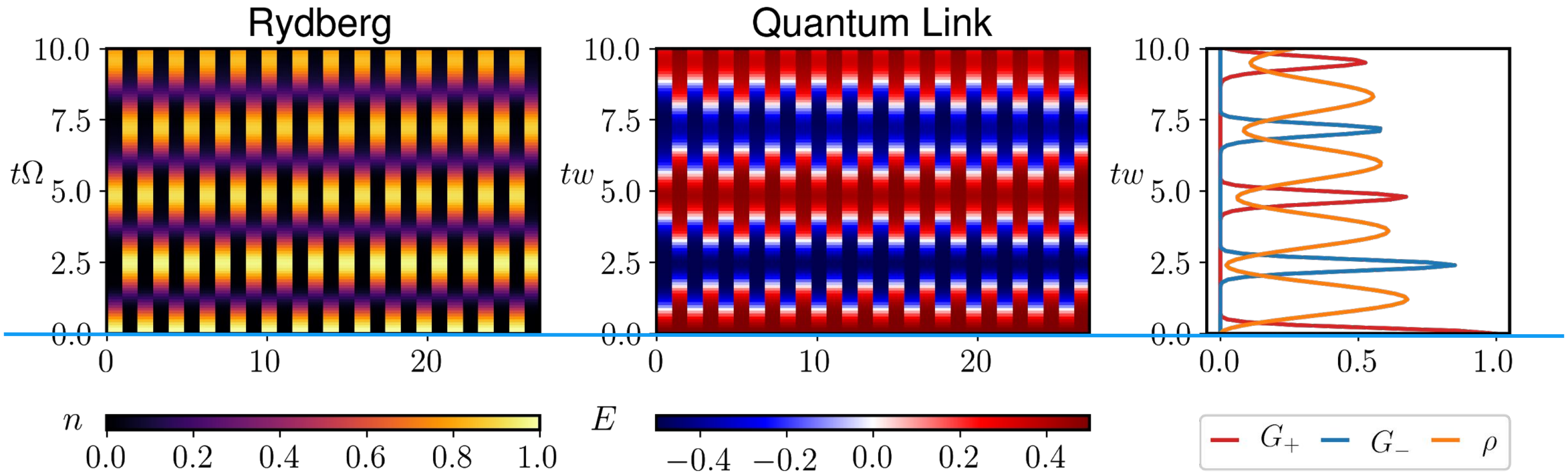
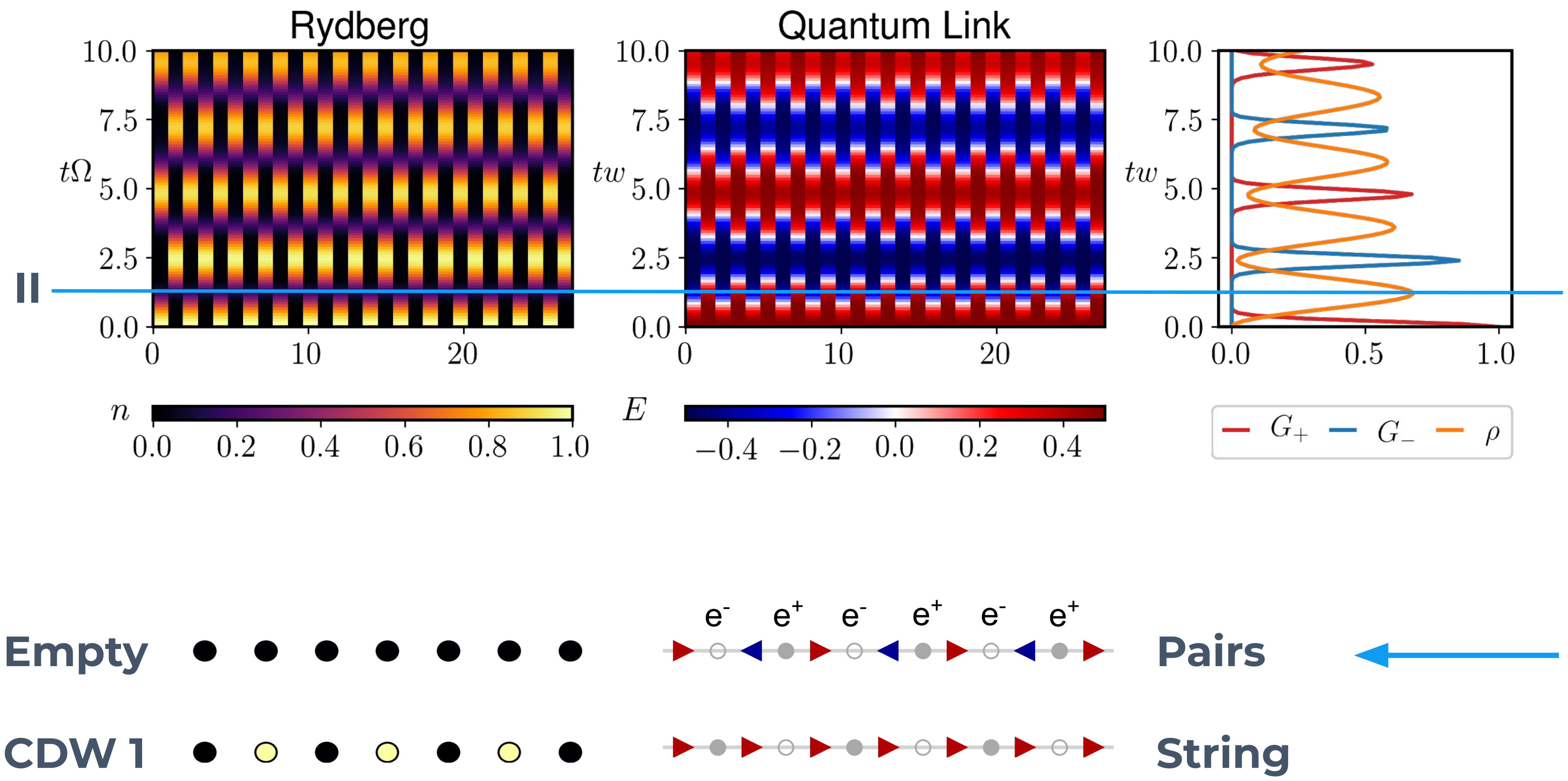


CDW 1

String

INTERPRETATION AS STRING INVERSION



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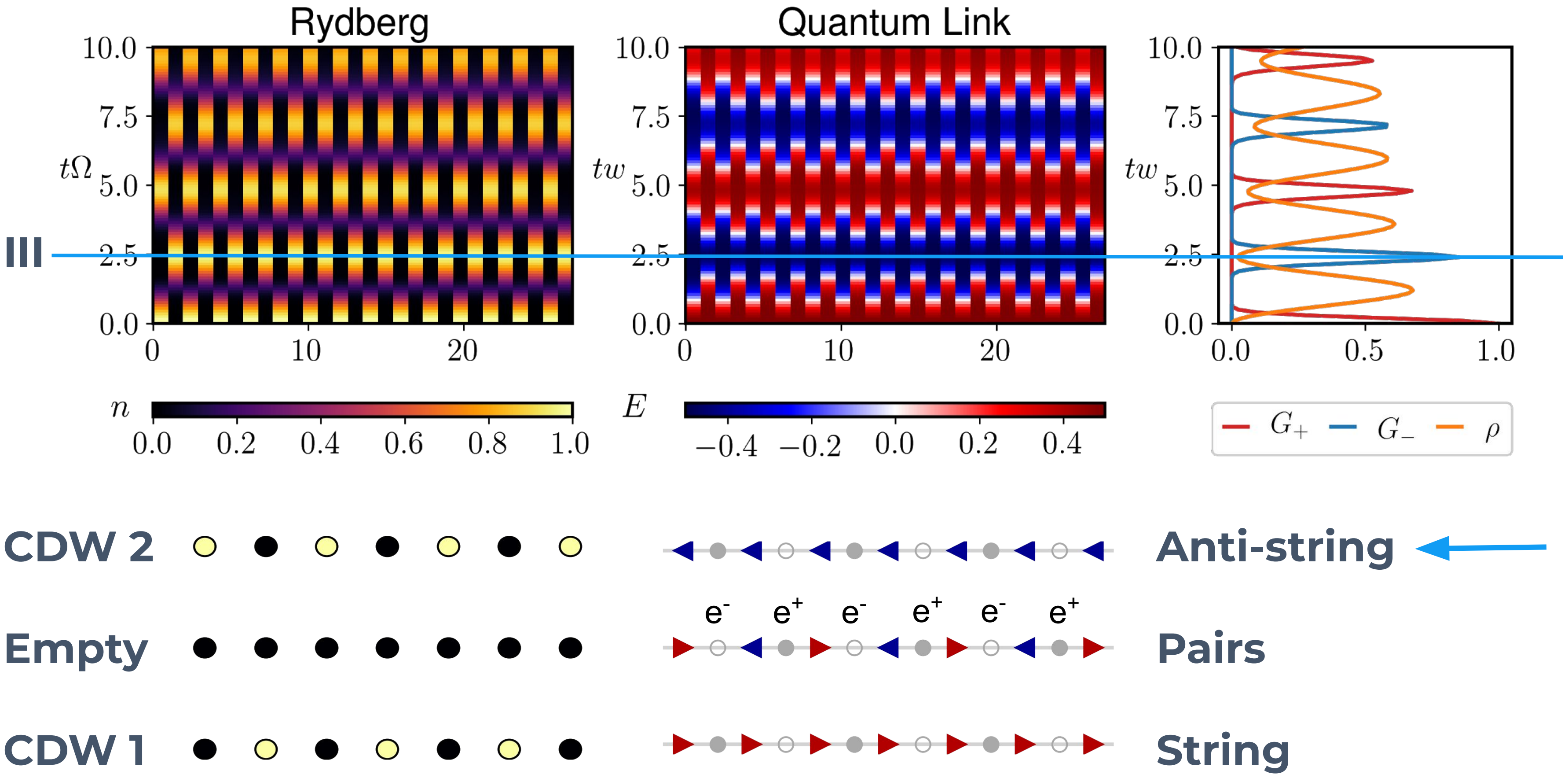

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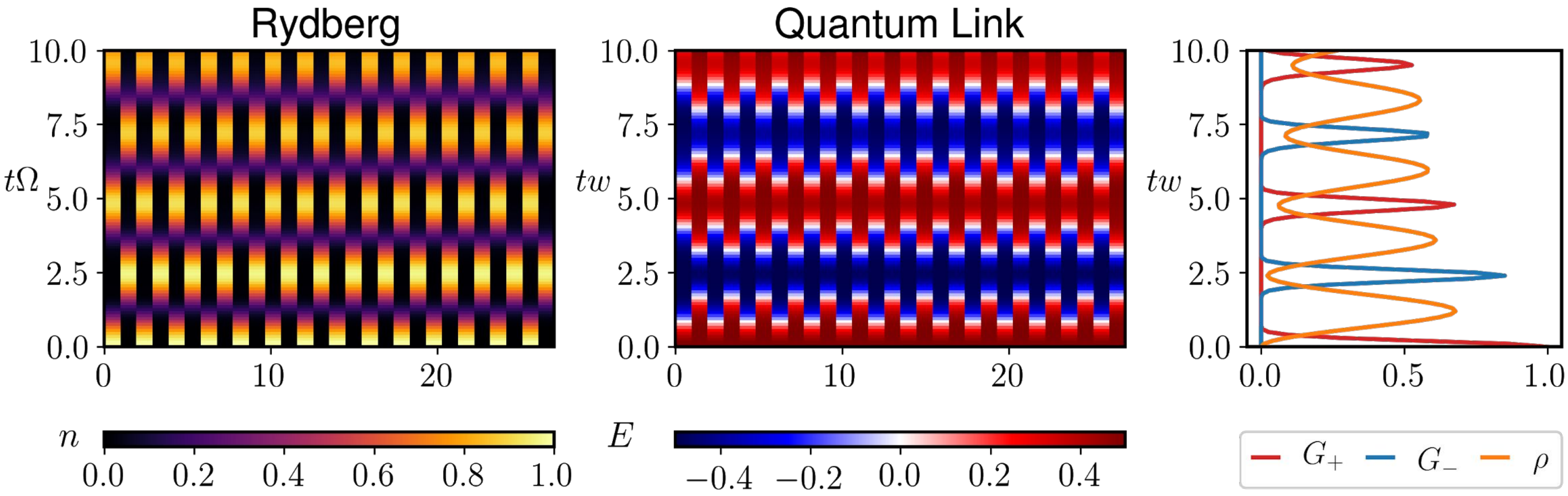

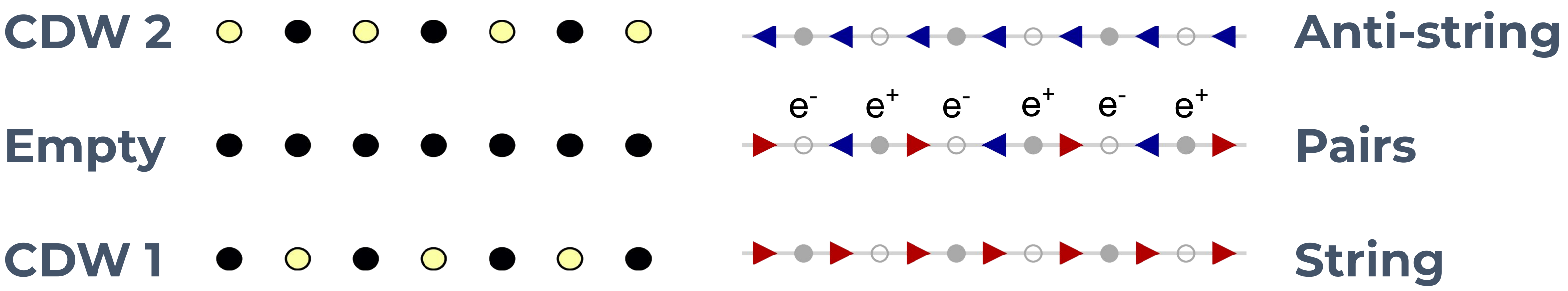

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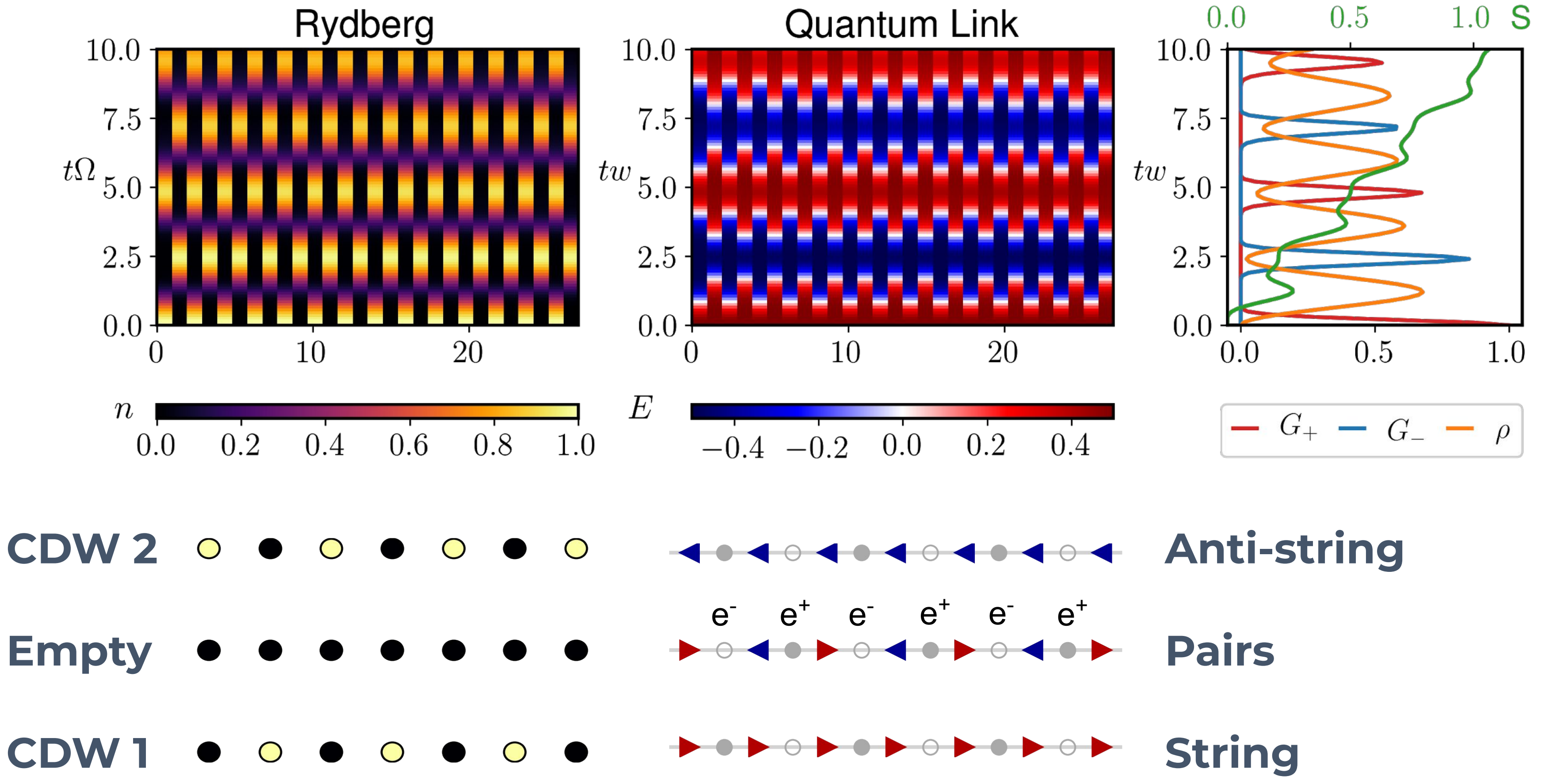

GENERALITY - OTHER U(1) LGTs

$$\hat{H} = -w \sum_{j=1}^{L-1} (\hat{\Phi}_j^\dagger \hat{U}_{j,j+1} \hat{\Phi}_{j+1} + \mathrm{h.c}) + m \sum_{j=1}^{L} (-1)^j \hat{\Phi}_j^\dagger \hat{\Phi}_j + J \sum_{j=1}^{L-1} \hat{E}_{j,j+1}^2$$

$$\hat{G}_j = \hat{E}_{j,j+1} - \hat{E}_{j-1,j} - \hat{\Phi}_j^\dagger \hat{\Phi}_j + \tfrac{1-(-1)^j}{2}$$

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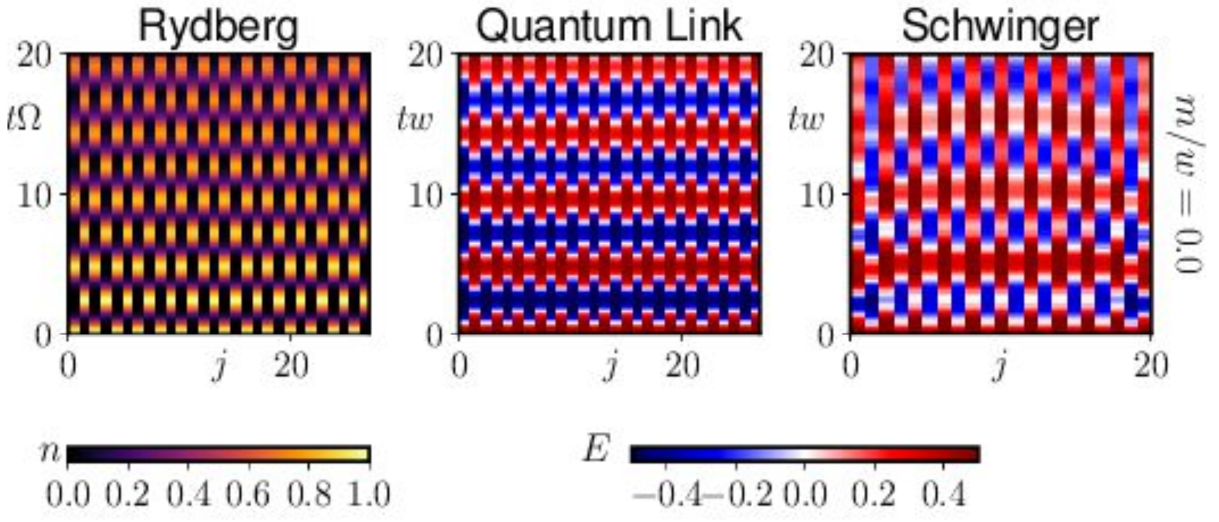

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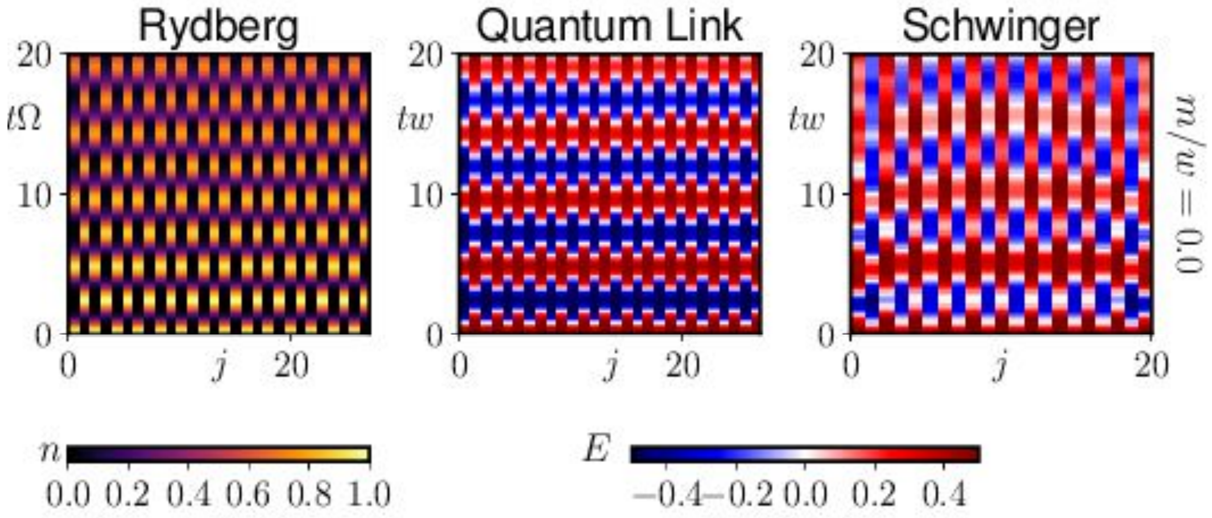
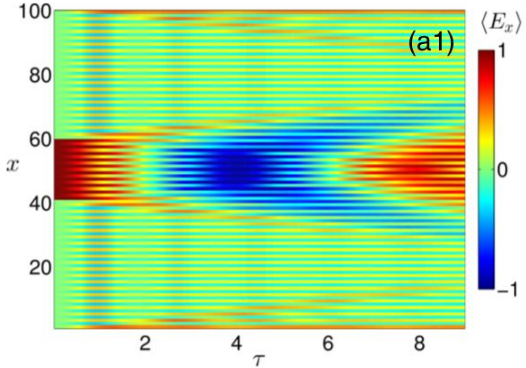
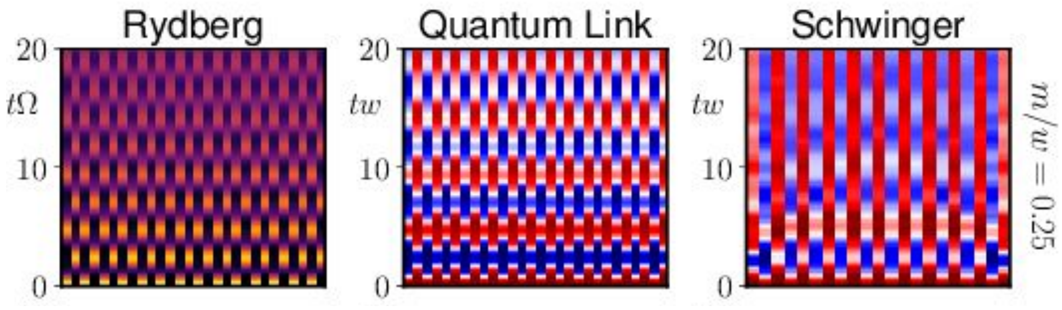


QLM S=1



T. Pichler, M. Dalmonte, E. RIco, P. Zoller, and S. Montangero *Phys. Rev. X* **6**, 011023 (2016)

WITH MASS - PHASE TRANSITION



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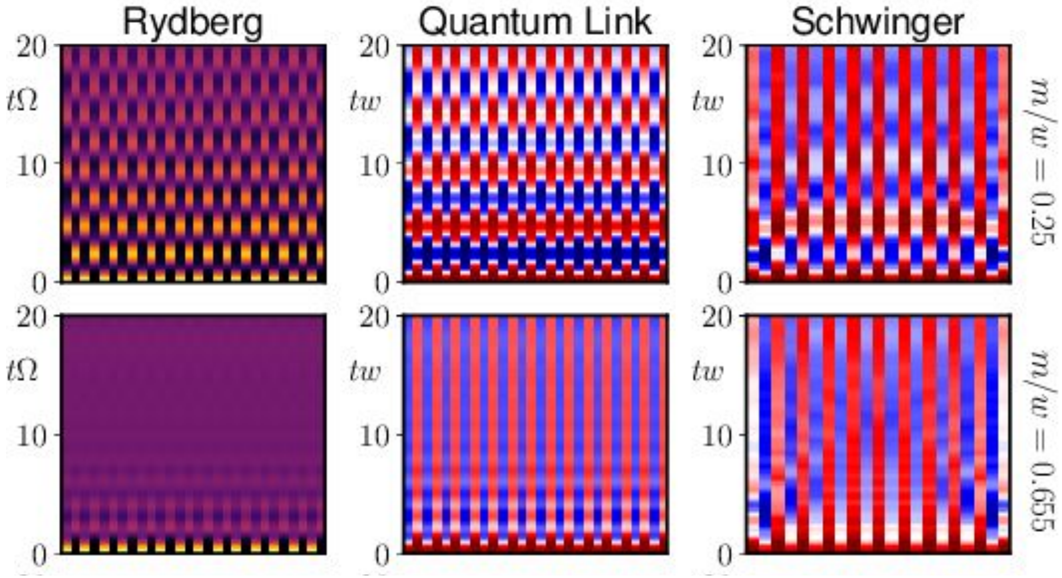

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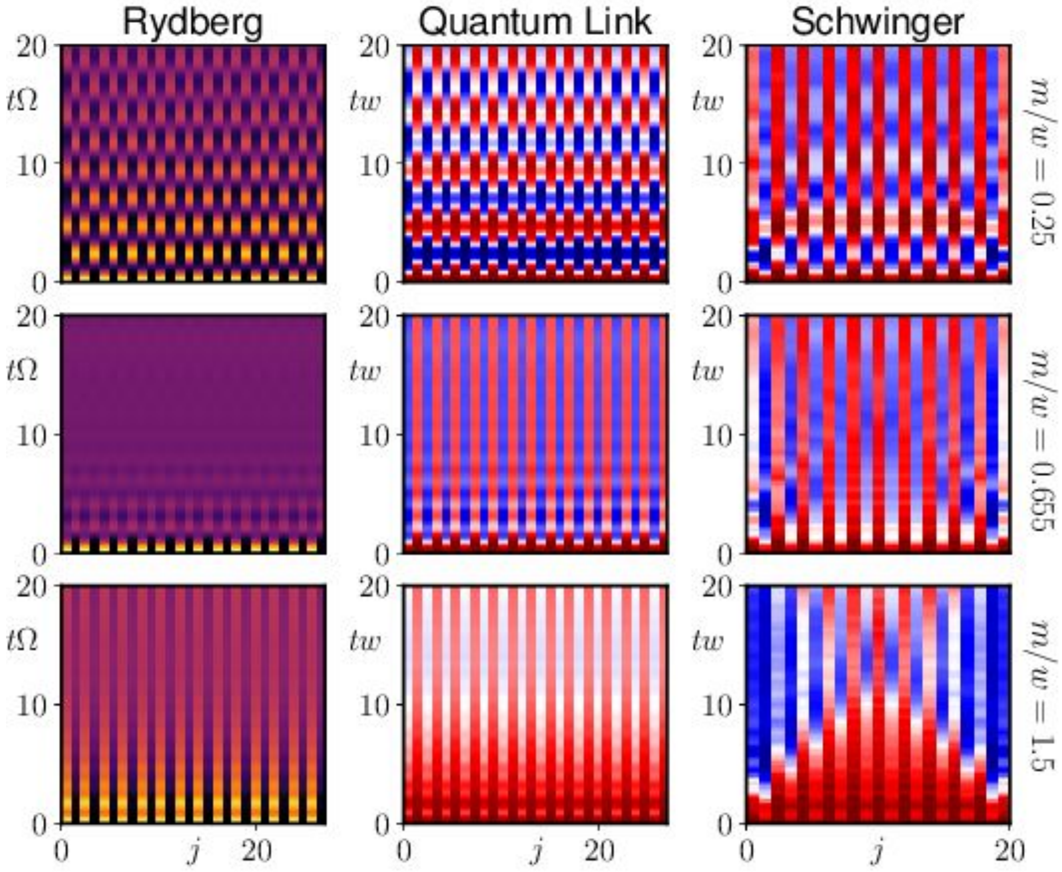

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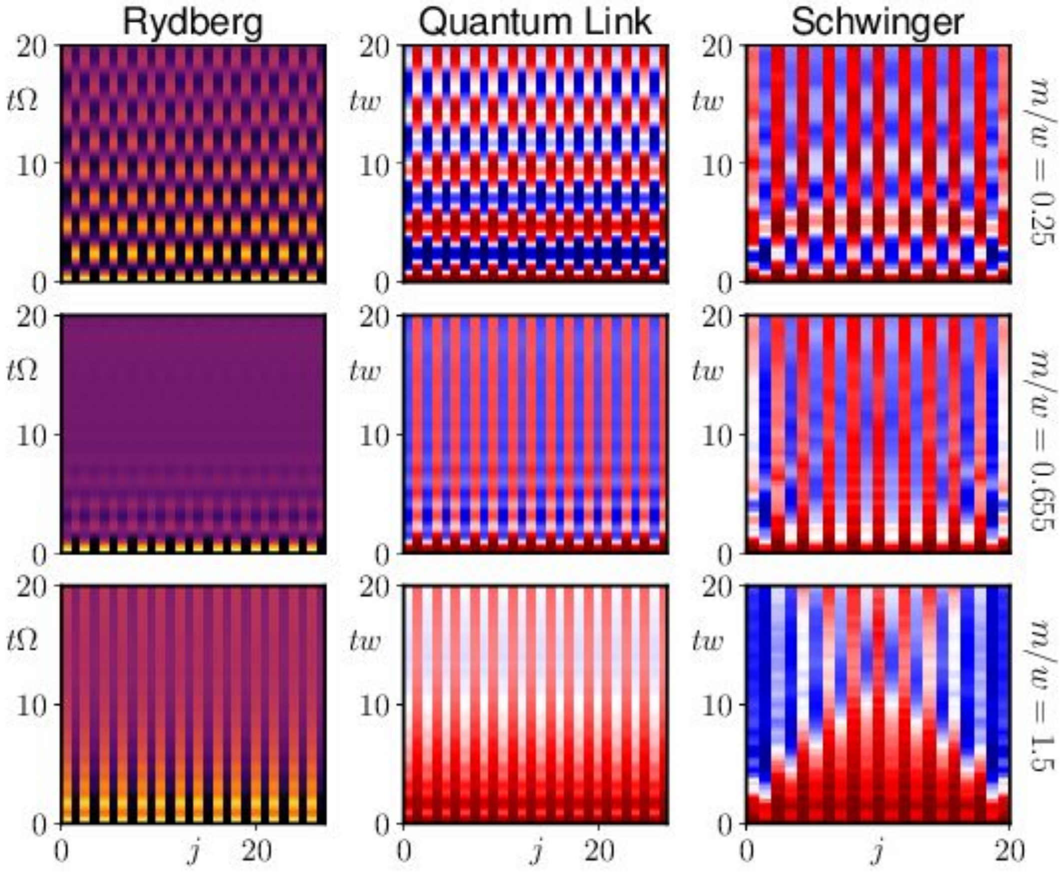
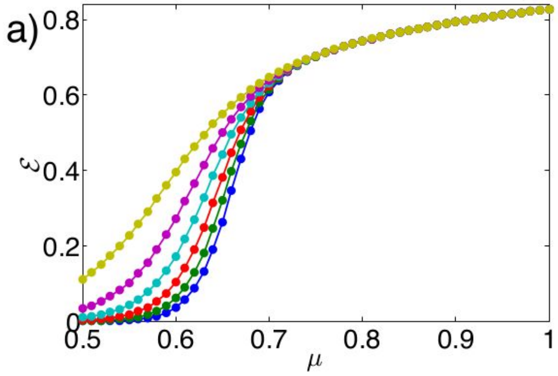
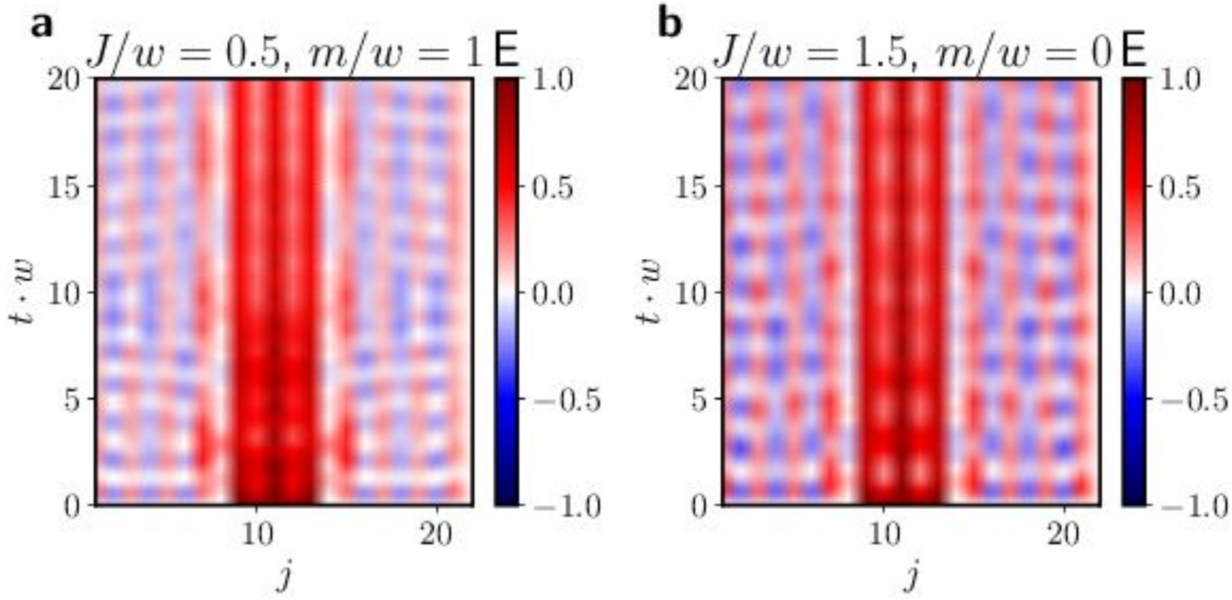


Phase transition



E. Rico, T. Pichler, M. Dalmonte, P. Zoller, and S. Montangero, *Phys. Rev. Lett.* **112**, 201601 (2014)

OTHER "SLOW DYNAMICS"- NO STRING BREAKING IN LATTICE SCHWINGER MODEL



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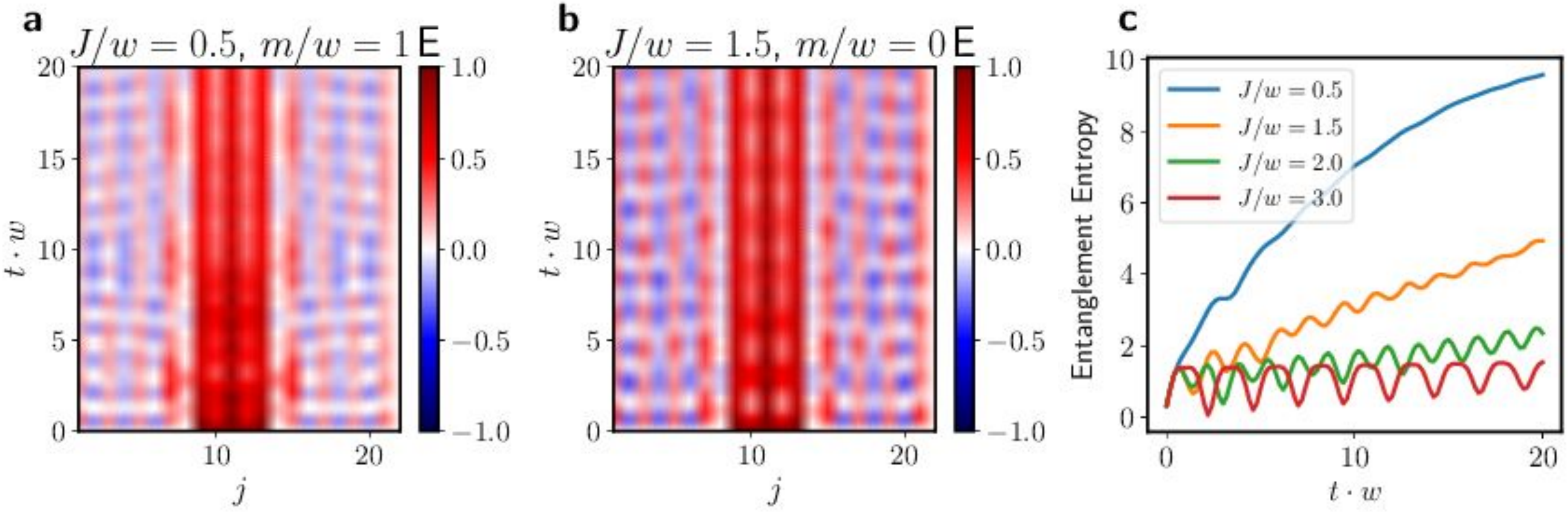

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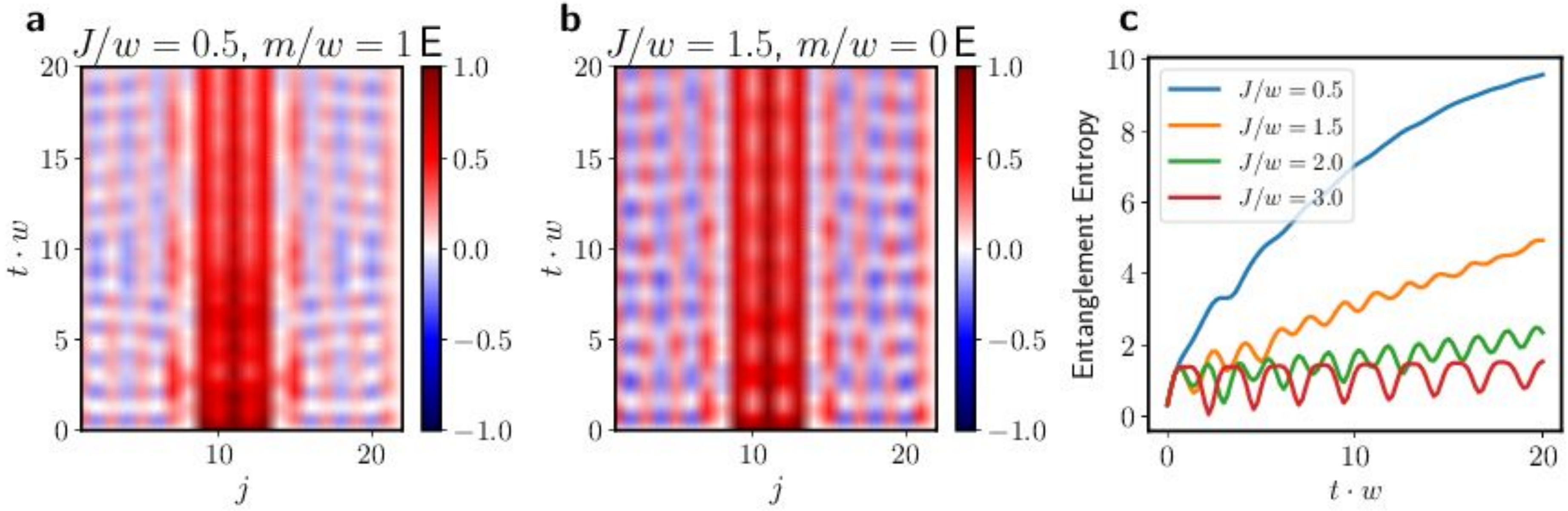
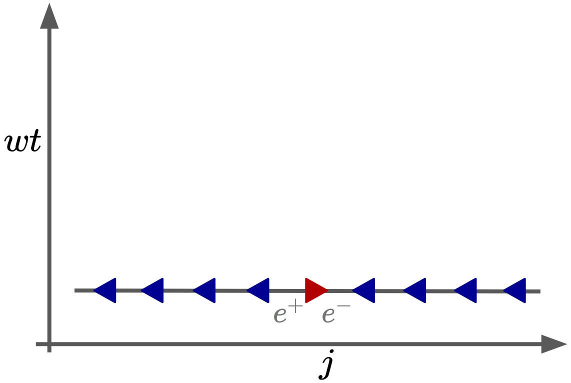


String breaking strongly suppressed

OTHER "SLOW DYNAMICS" - PARTICLE-ANTIPARTICLE PAIRS



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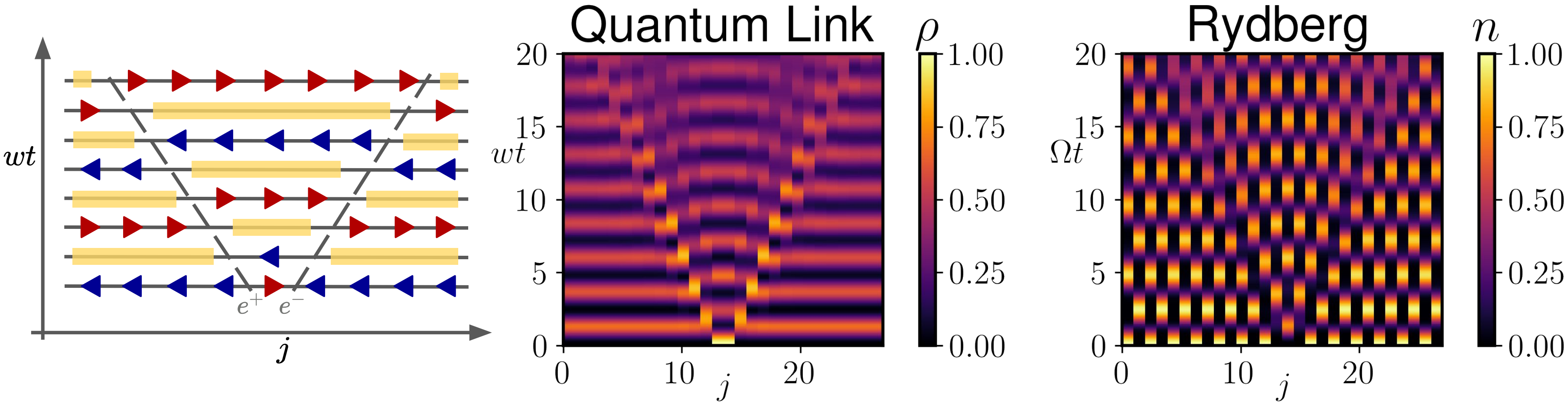

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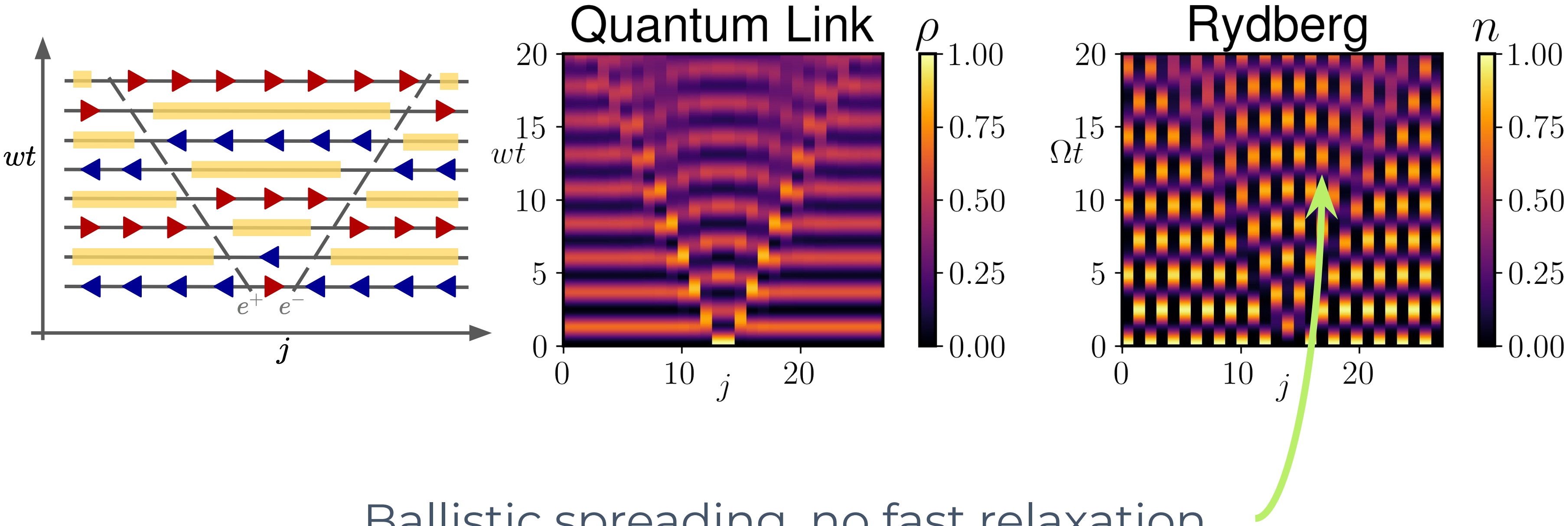
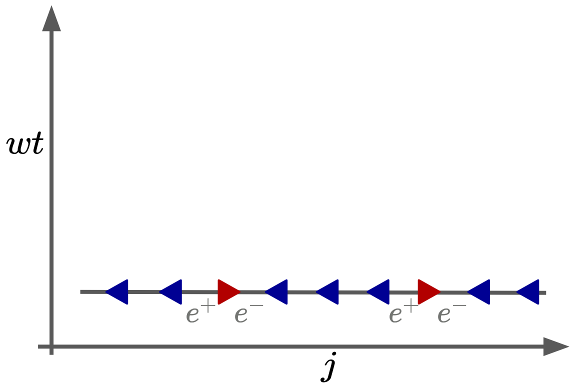


Ballistic spreading, no fast relaxation

OTHER "SLOW DYNAMICS" - PARTICLE-ANTIPARTICLE PAIRS



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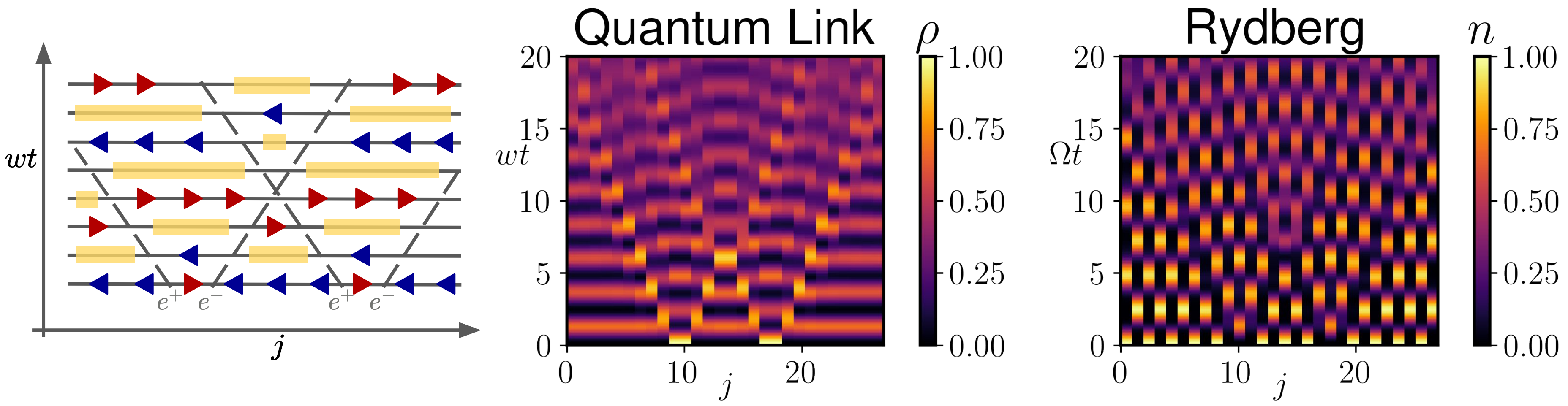

Two pairs: interference pattern

SUMMARY AND CONCLUSIONS

1 U(1) lattice gauge theory naturally realized in **Rydberg atom** arrays

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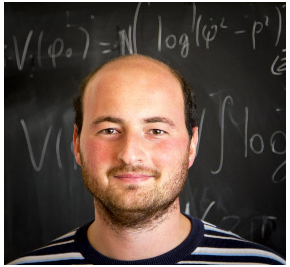
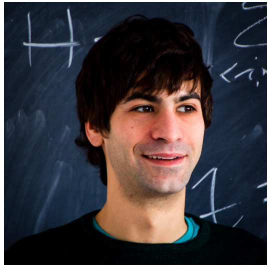
4 Perspective: experiments with **particle-antiparticle pairs**

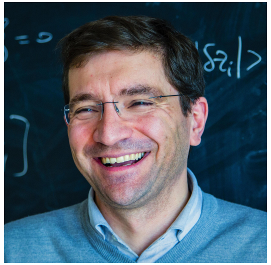


Paolo P.
Mazza

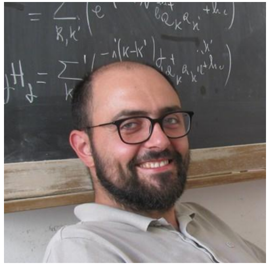


Giuliano
Giudici

Alessio
Lerose



Andrea
Gambassi



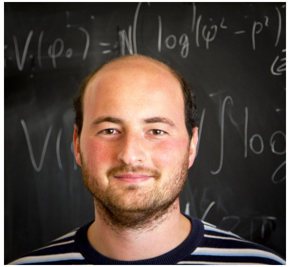
Marcello
Dalmonte

MA PER SEGUIR VIRTUTE E CANOSCENZA

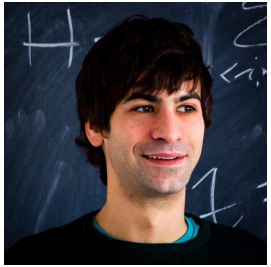
SISSA

40!

ICTP

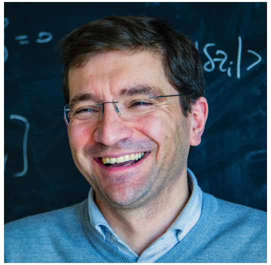


Paolo P. Mazza

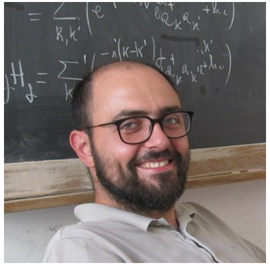


Giuliano Giudici

Alessio Lerose



Andrea Gambassi



Marcello Dalmonte

SISSA 40!

ICTP

THANK YOU FOR YOUR ATTENTION!