UNIVERSITY OF INNSBRUCK

IQOQI
AUSTRIAN ACADEMY OF SCIENCES

An AMO Toolbox for Majorana Fermions in Optical Lattices

Christina Kraus
University of Innsbruck/IQOQI

SFB Foundations and Applications of Quantum Science

EU AQUTE

Outline

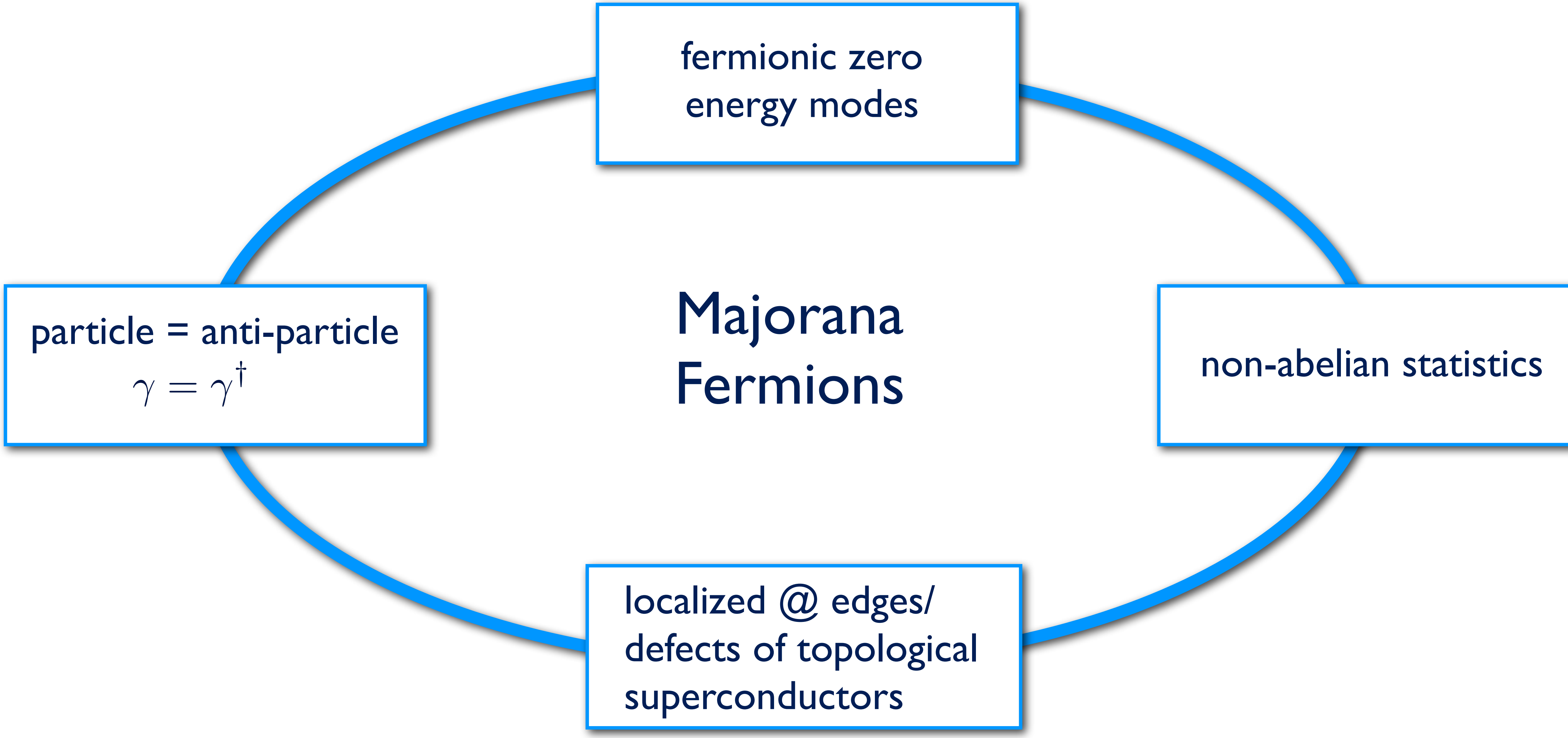
1. Introduction to Majorana Fermions

2. An AMO toolbox for Majorana fermions in the Kitaev wire

3. Majorana physics in the double wire system with pair hopping

4. Outlook

Majorana Fermions are/have...



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fermionic zero energy modes

particle = anti-particle
$\gamma = \gamma^\dagger$

Majorana Fermions

non-abelian statistics

localized @ edges/ defects of topological superconductors

Fundamental interest

Majorana ’37

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Quantum Information Theory

Majorana ’37

topological quantum computing/memory

Solid state physics

PRL **101**, 120403 (2008) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2008

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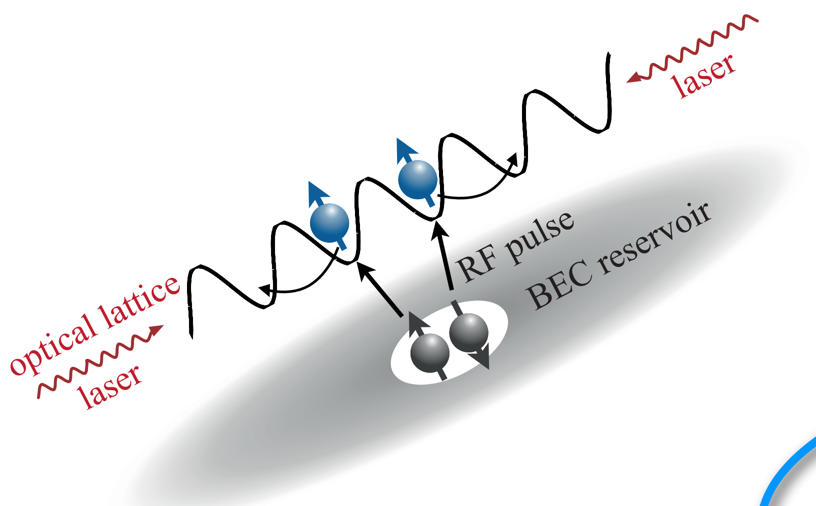

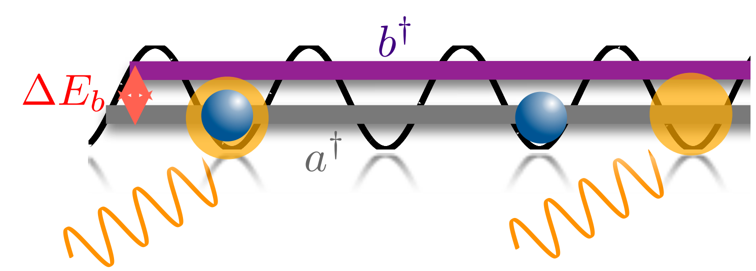

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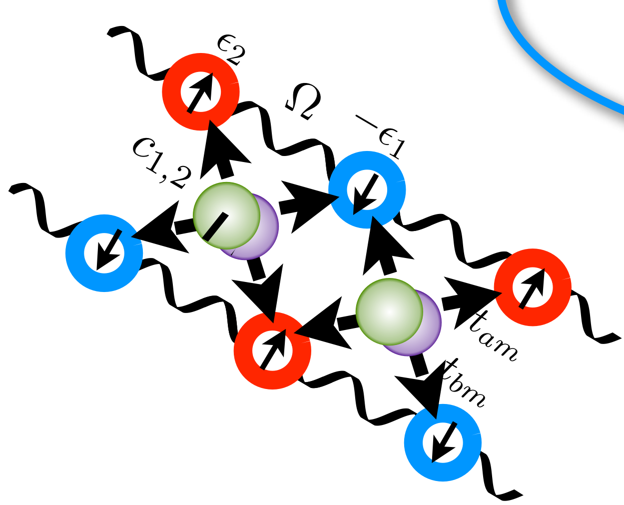
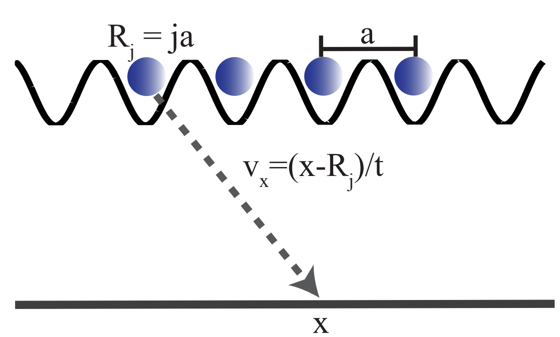
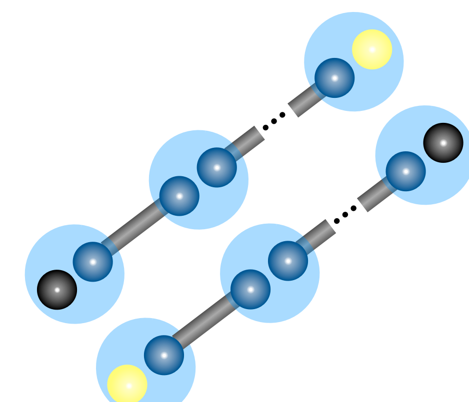
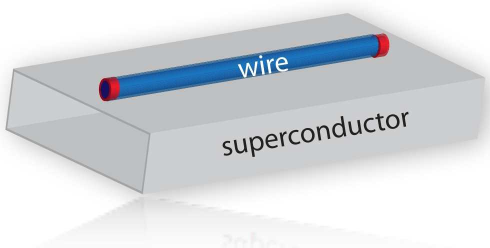






Majorana Fermions in the Kitaev Wire

$$H = -J \sum_{j=1}^{L-1} \boxed{a_j^\dagger a_{j+1} + h.c.} + \sum_{j=1}^{L-1} \boxed{\Delta a_j a_{j+1} + h.c.} - \mu \sum_{j=1}^{L} a_j^\dagger a_j$$



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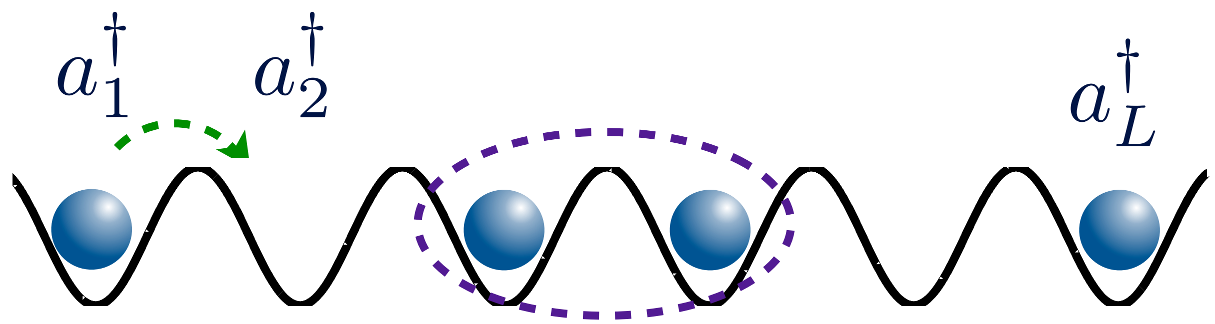

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$$J = |\Delta|, \mu = 0$$

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$\tilde{a}_L^\dagger$: zero energy mode

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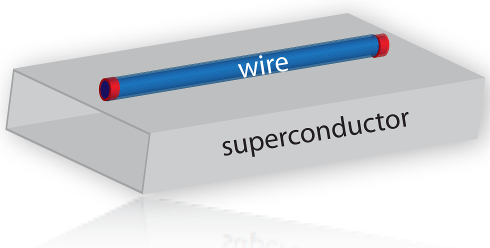

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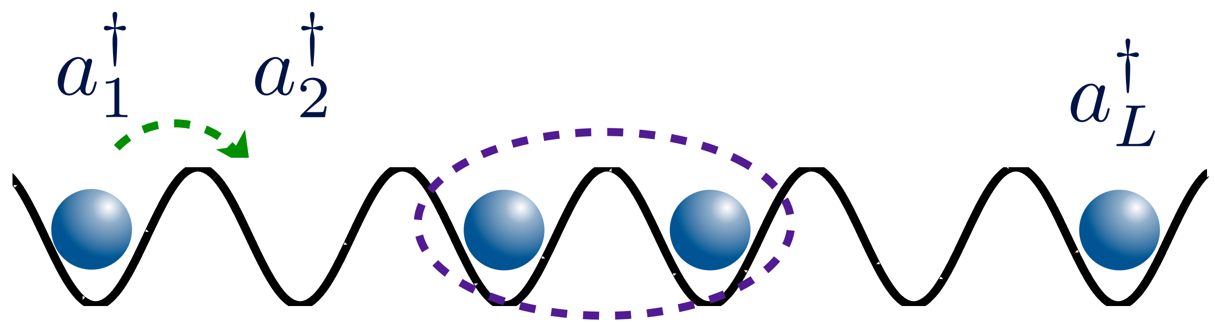

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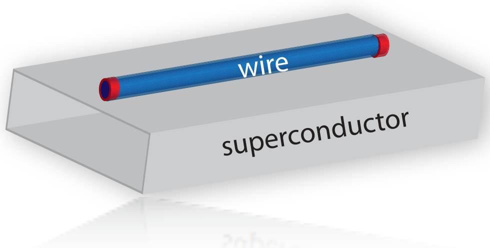

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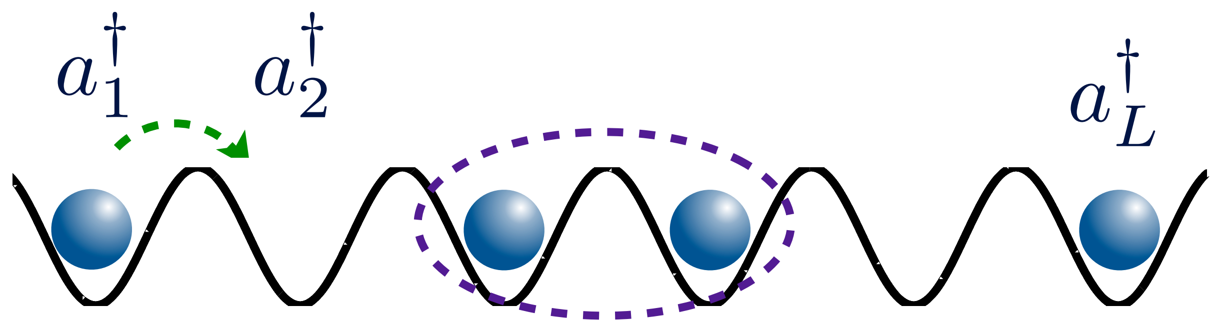

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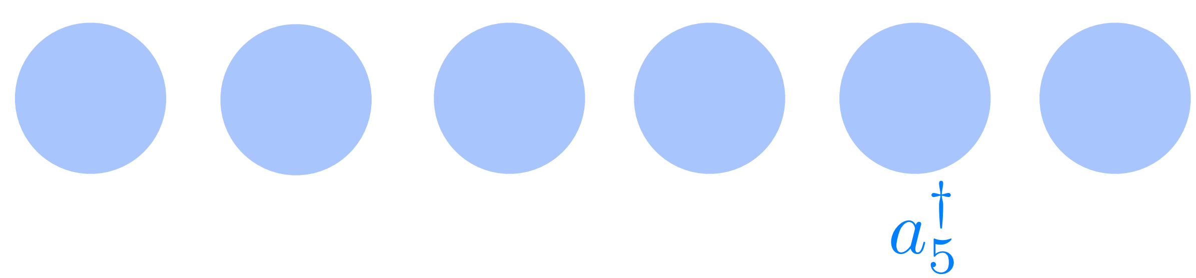

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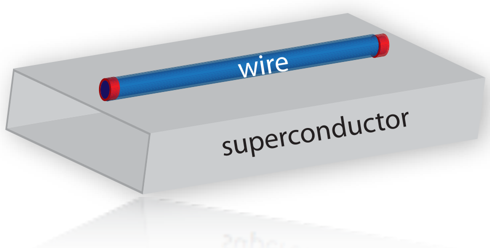

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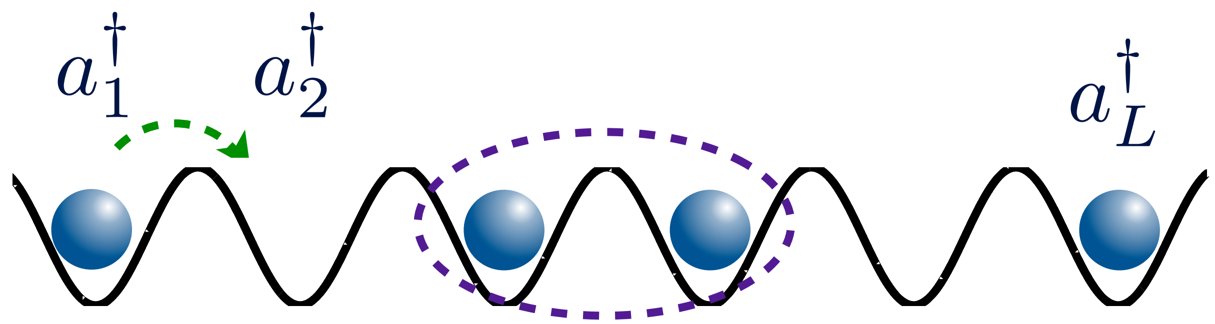

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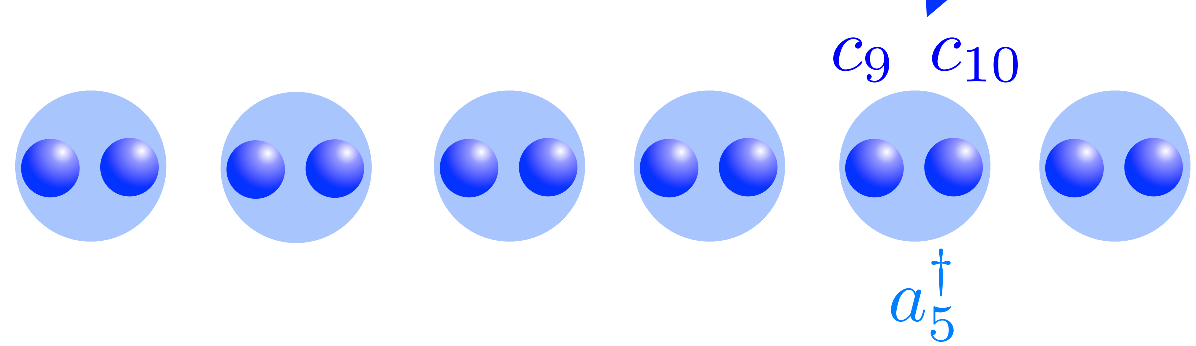

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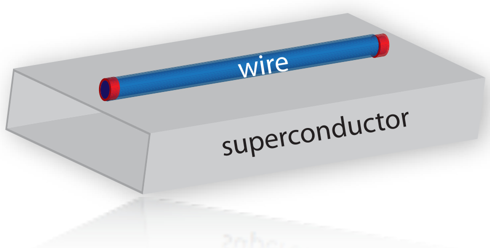

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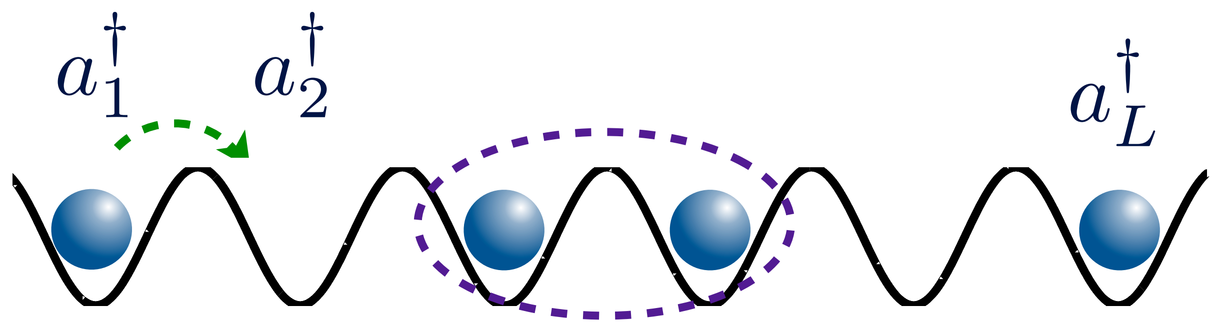

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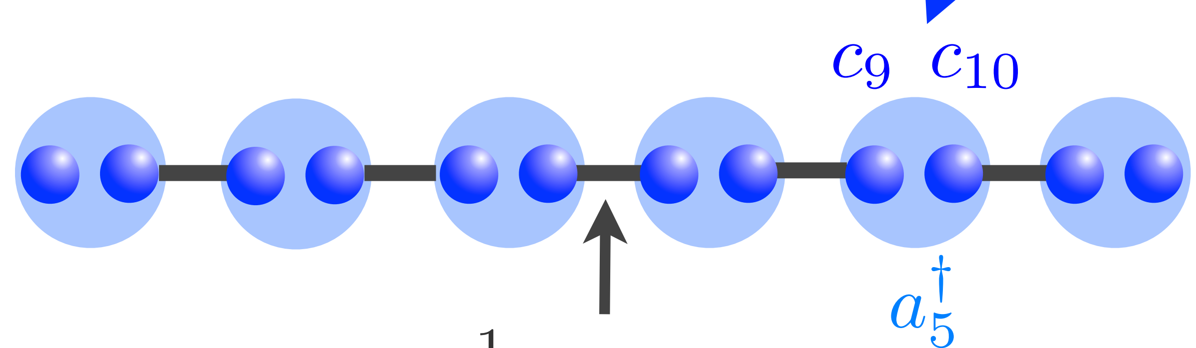

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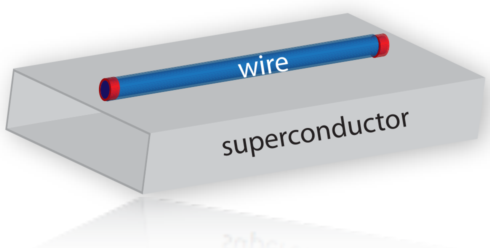

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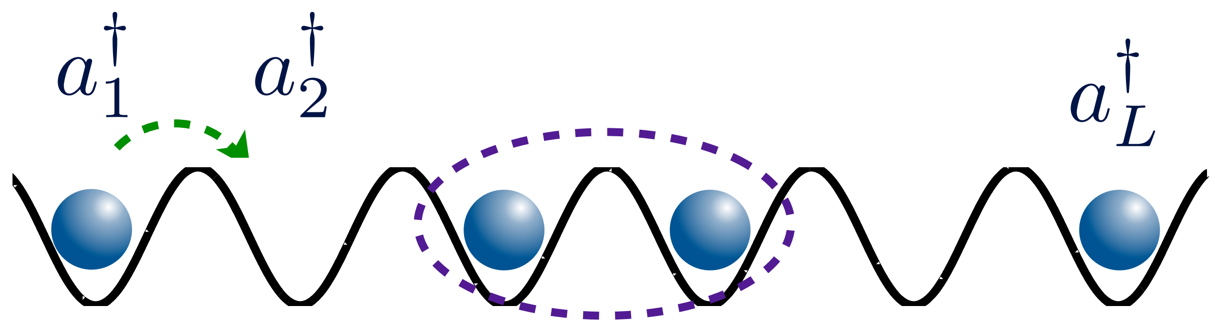

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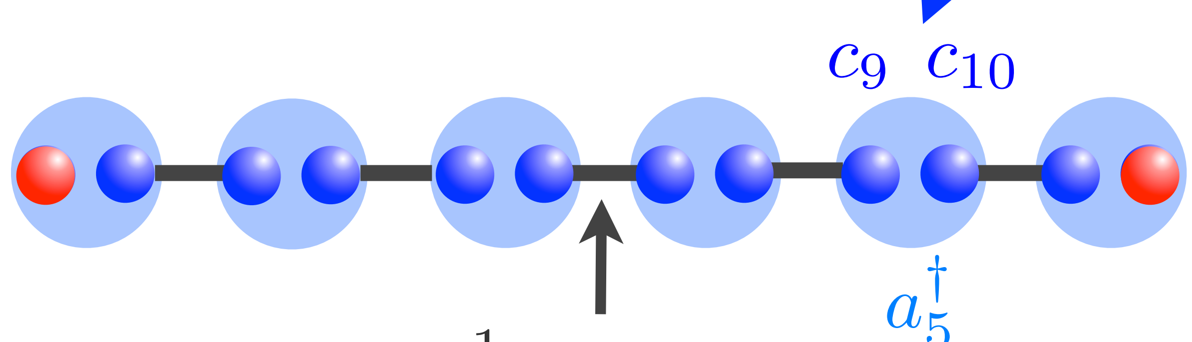

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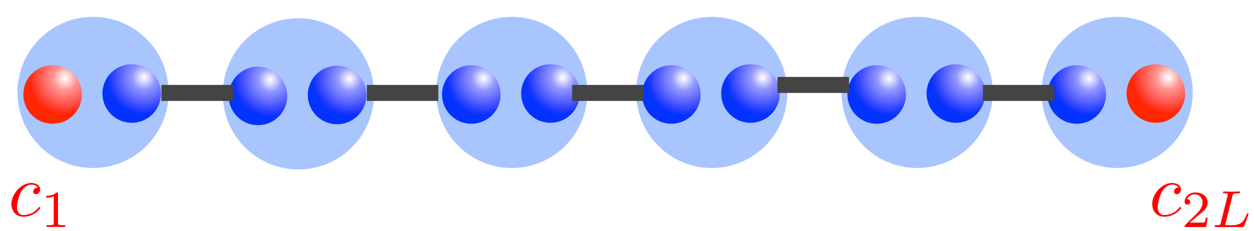

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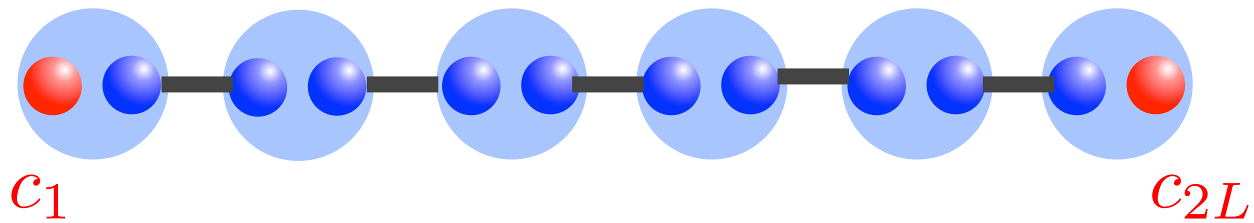

Properties of Majorana Fermions

Non-local zero Energy Mode

$$\tilde{a}_L^\dagger = \frac{1}{2}(c_{2L} + i c_1)$$

Two unpaired Majorana fermions

$$c = c^\dagger$$
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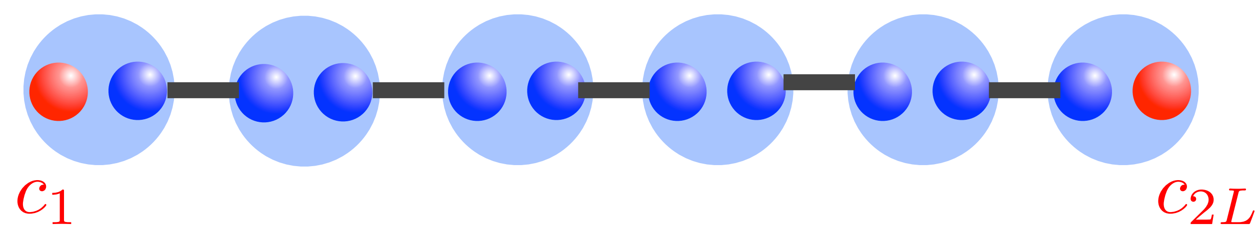

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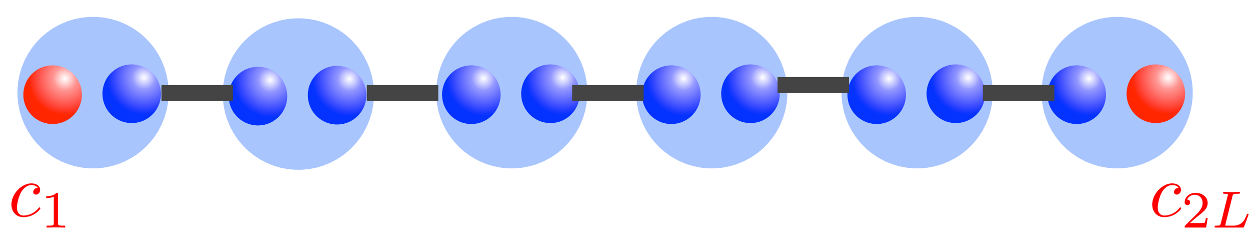

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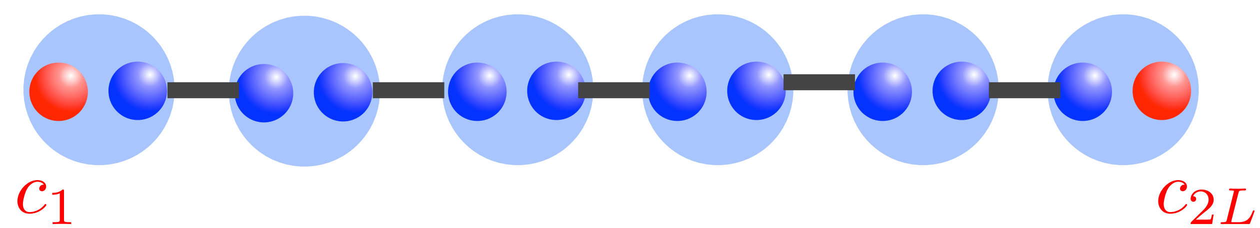

2-dim zero Energy Subspace; Different Parities

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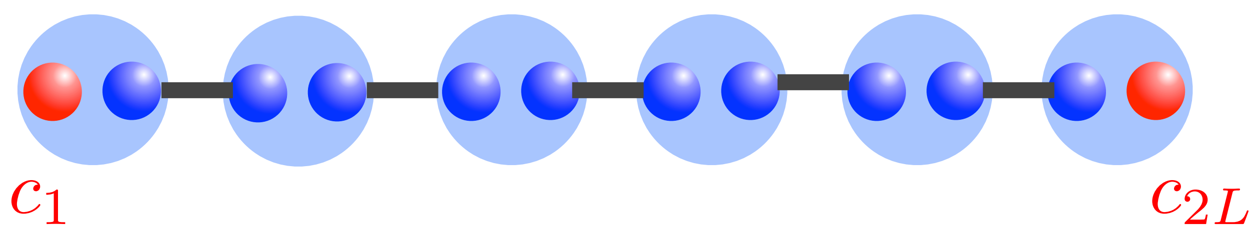

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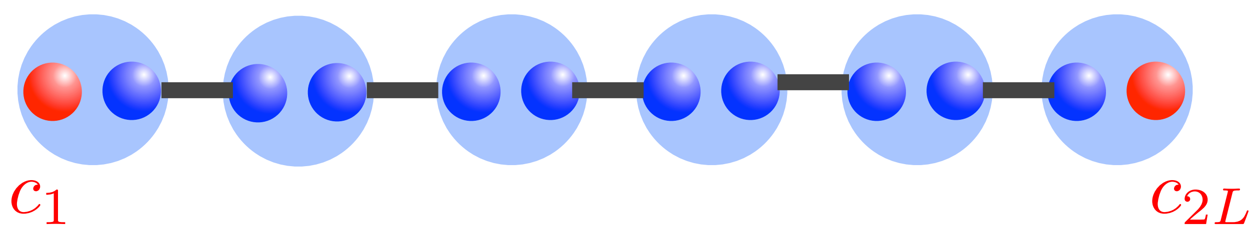


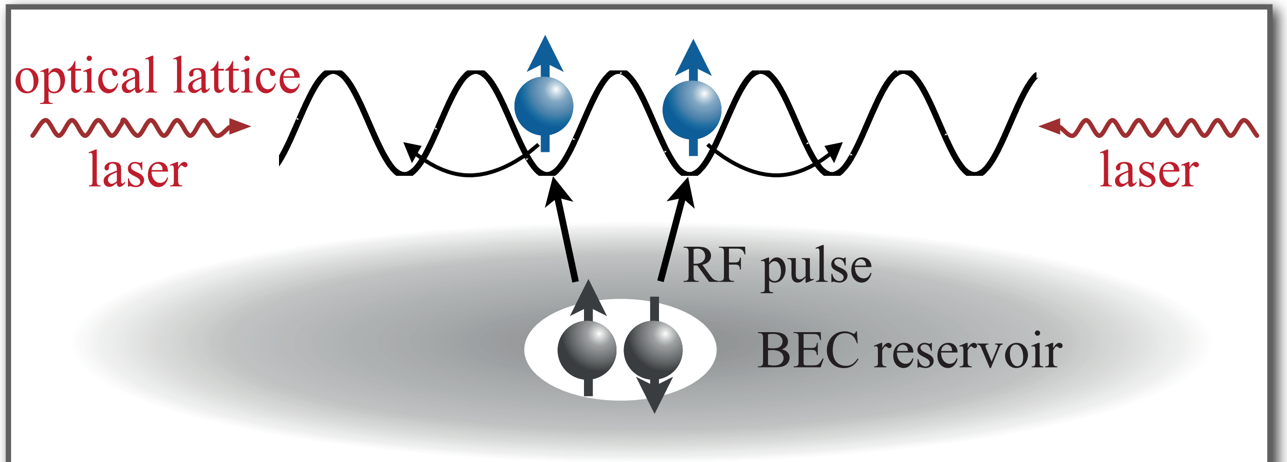
Topological Protection

2-dim zero Energy Subspace; Different Parities

Non-abelian Statistics

Exploring Majorana Physics in the Kitaev Wire using AMO Tools

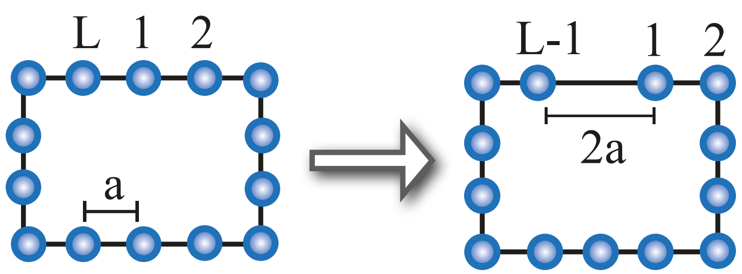
Majorana Physics in an AMO Realization of the Kitaev Wire



L. Jiang et al. PRL 106 (2011)

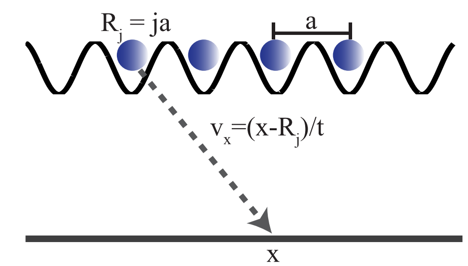
Majorana Physics in an AMO Realization of the Kitaev Wire

Preparation of ground state with a definite parity

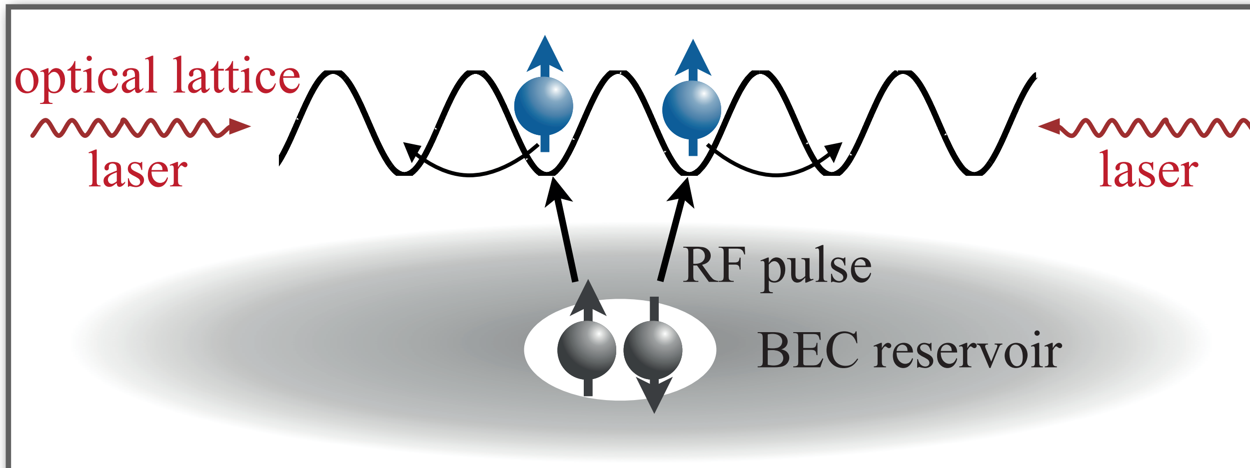


Detection with AMO tools

- Time-of-flight imaging
- Spectroscopy



C.K, S. Diehl, P. Zoller, M. Baranov, NJP 2012



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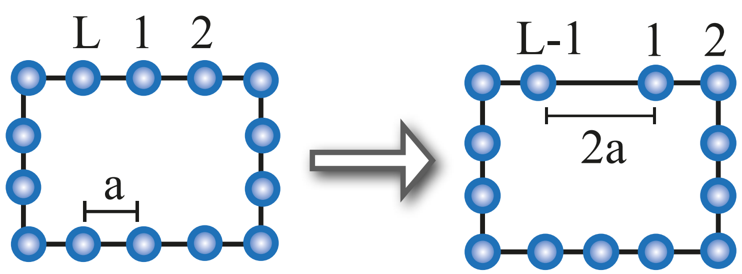

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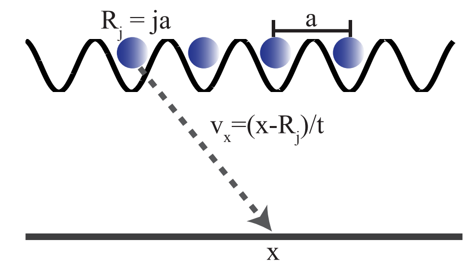

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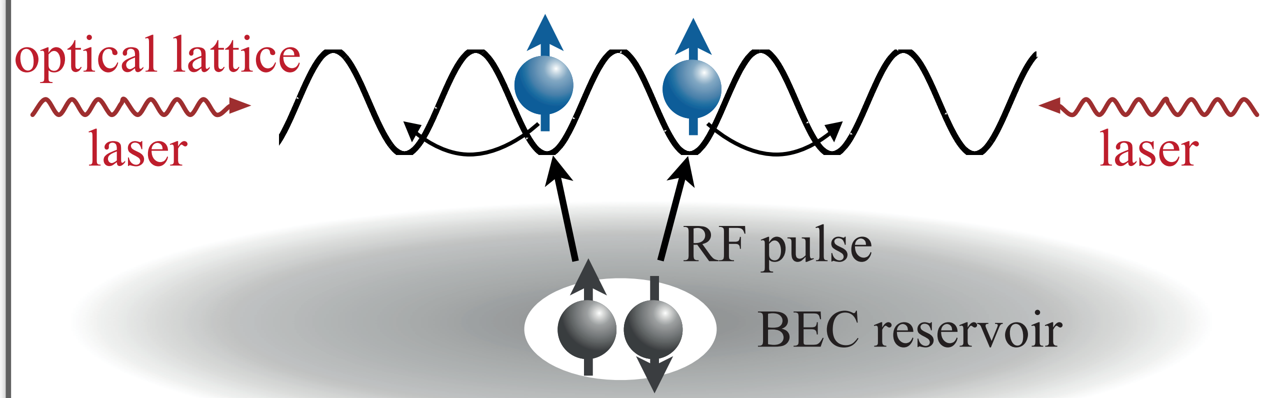
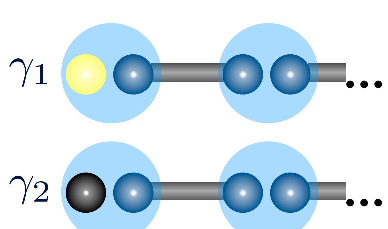


L. Jiang et al. PRL 106 (2011)

Efficient braiding of MFs

- local site addressing
- 4 sites, 4 time steps

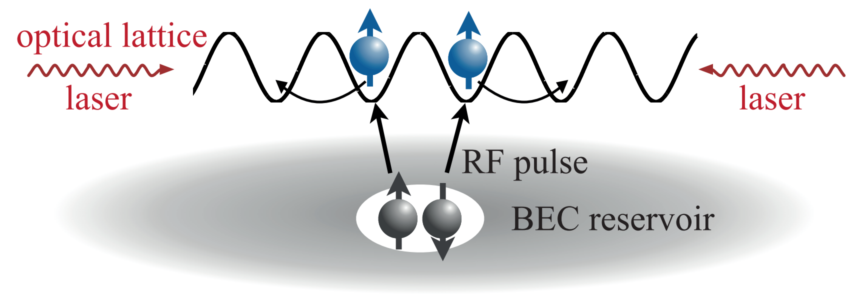


Implementation of Deutsch-Jozsa algorithm for 2 qubits via braiding only

(Braiding of MFs not universal!)

C.K, P. Zoller, M. Baranov, arvix: 1302.1824

Realization of the Kitaev wire...



...need a RESERVOIR!

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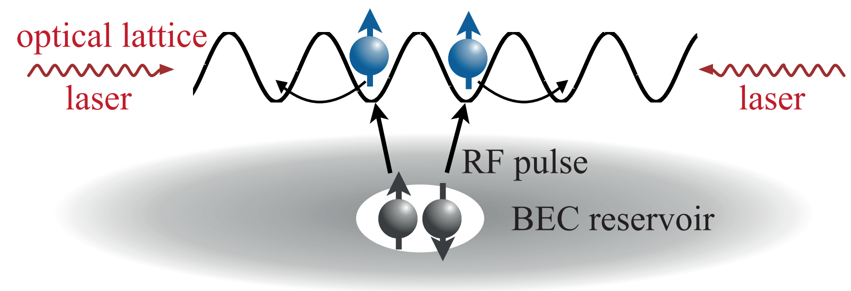

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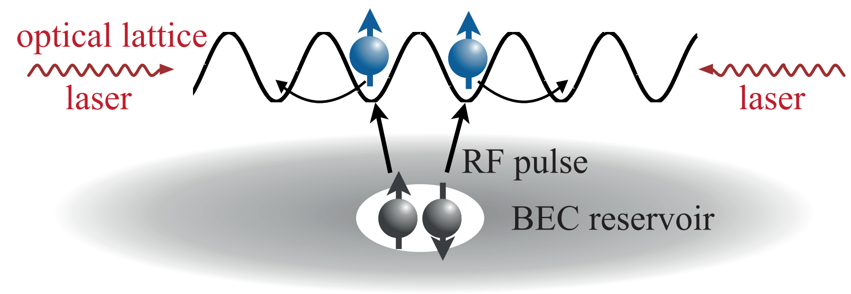
Reservoir

Majorana

Physics

Without

Realization of the Kitaev wire...



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Majorana Physics without Reservoir

Reservoir

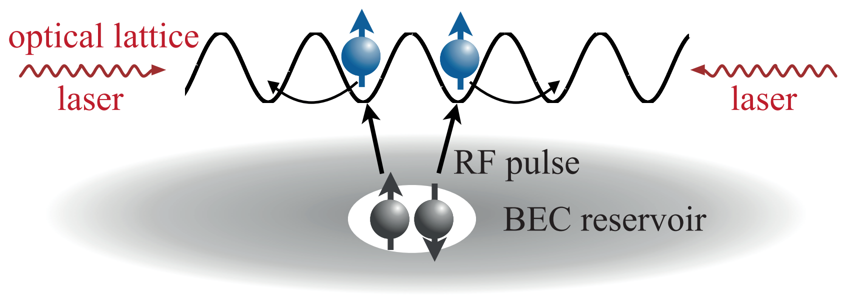
Without

Majorana

Physics

An alternative Route towards Majorana Physics

Realization of the Kitaev wire...



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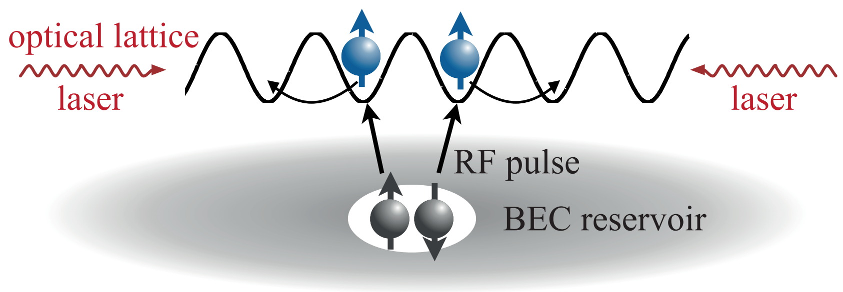

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Signatures that MFs can emerge in a purely number conserving setting!

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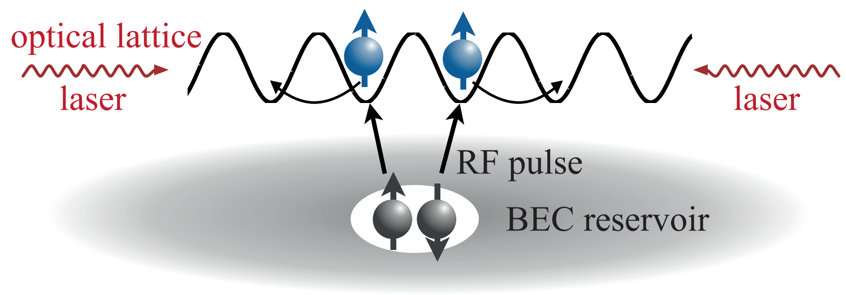

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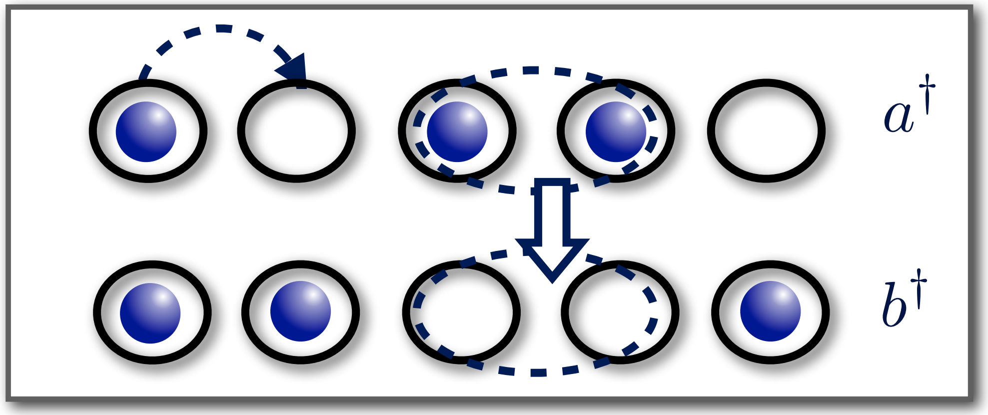
AMO realization of an INTERACTING system without RESERVOIR supporting Majoranas!

Majorana Fermions in a Double Wire with Pair Hopping

Role of the reservoir

- creates $\Delta a_j^\dagger a_{j+1}^\dagger + h.c.$
- $U(1) \to \mathbb{Z}_2$

"minimal reservoir?"



SYSTEM

BATH

Majorana Fermions in a Double Wire with Pair Hopping

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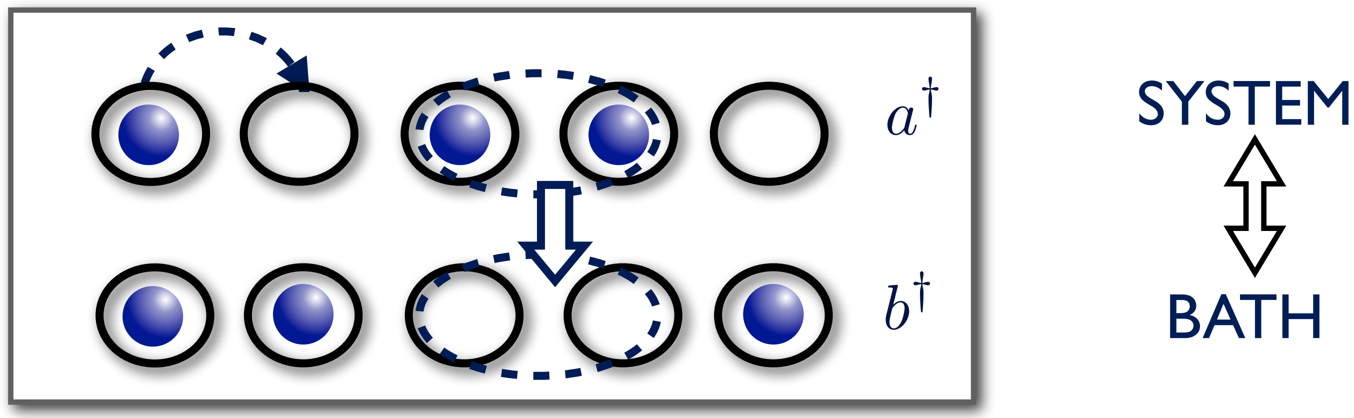

"One wires constitutes the reservoir for the other wire."

Majorana Fermions in a Double Wire with Pair Hopping

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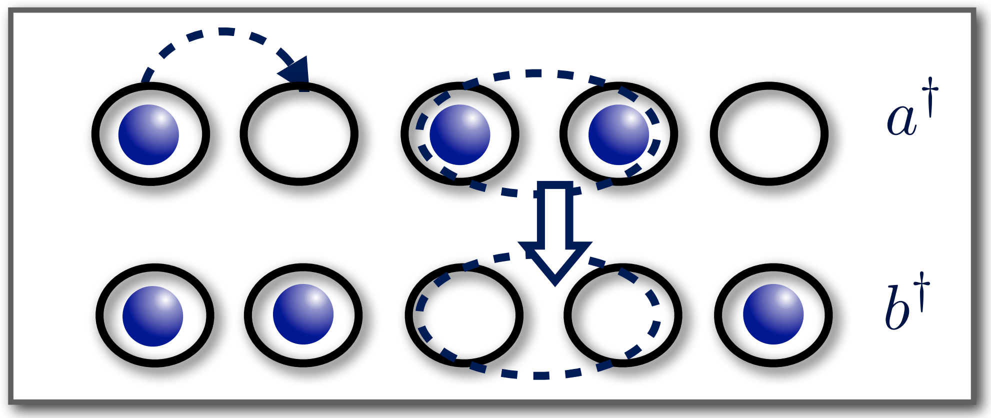

SYSTEM

$\Updownarrow$

BATH

"One wires constitutes the reservoir for the other wire."

$$H = \sum_{i=1}^{L-1} -t\left(a_i^\dagger a_{i+1i} + b_i^\dagger b_{i+1} + h.c.\right) + W\left(a_i^\dagger a_{i+1}^\dagger b_{i+1} b_i + h.c.\right)$$

hopping — pair hopping

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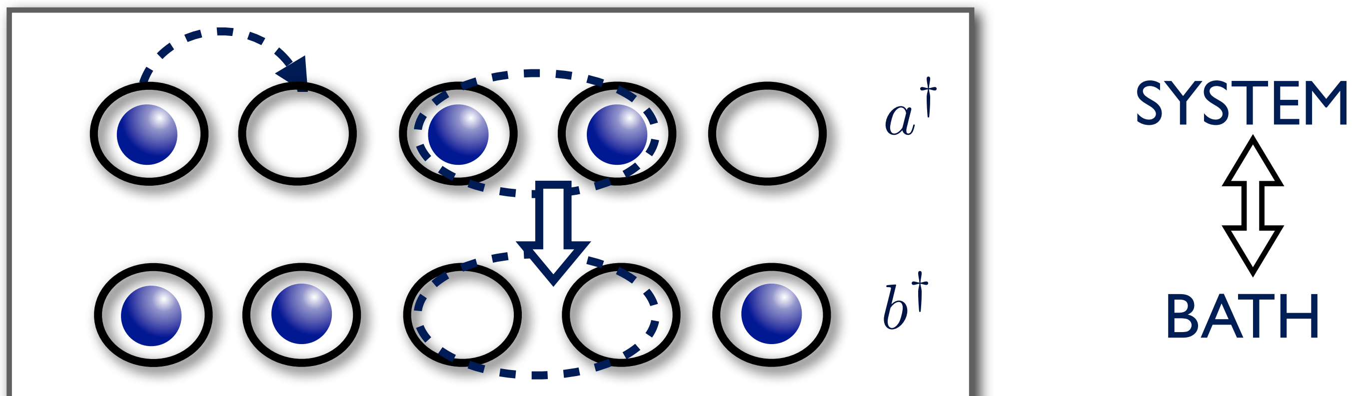

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hopping   pair hopping

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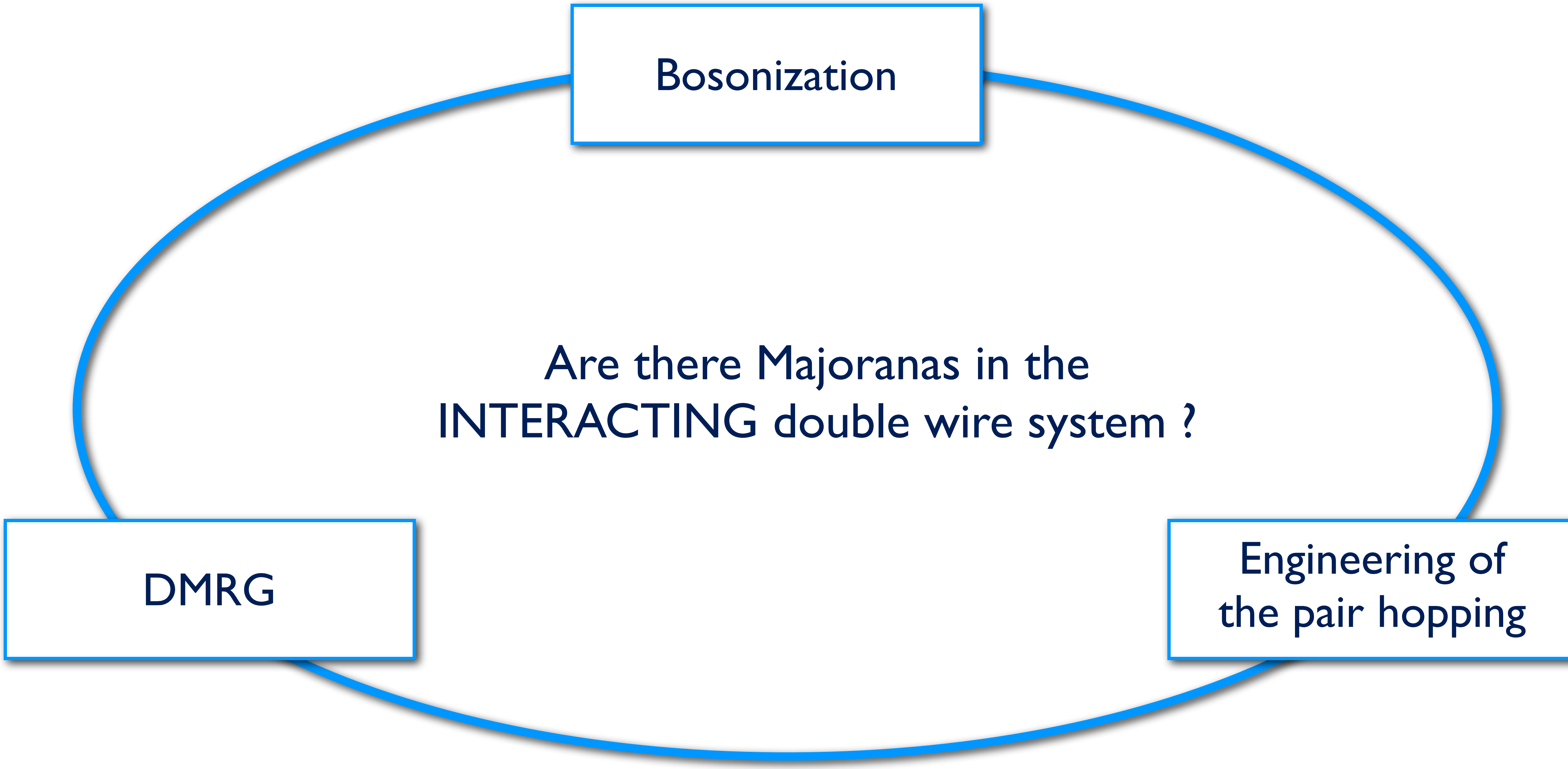

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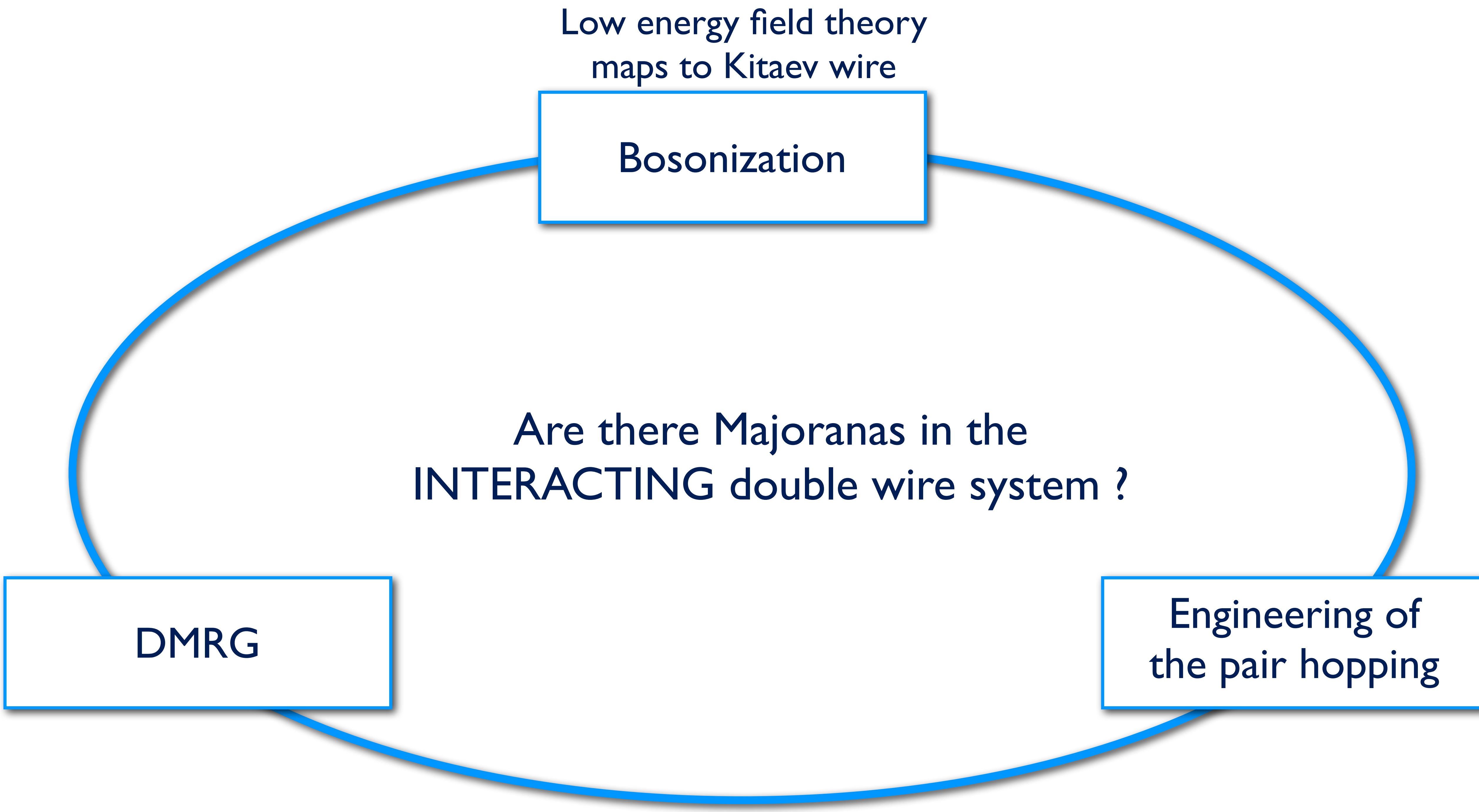


DMRG Study

Z_2 Symmetry

Two-fold degenerate Ground State with Different Parities

DMRG

⇩

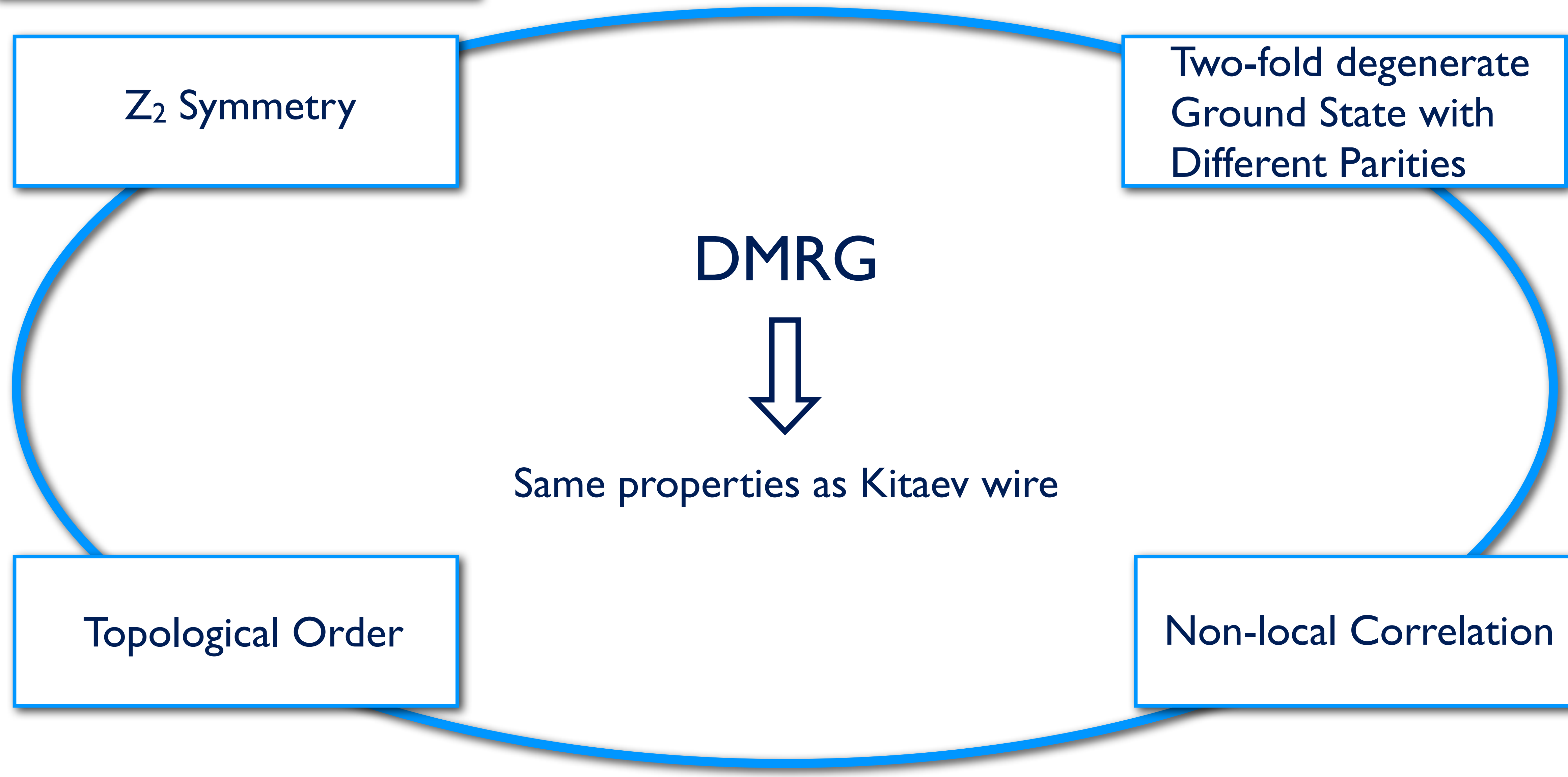
Same properties as Kitaev wire

Topological Order

Non-local Correlation

DMRG Study

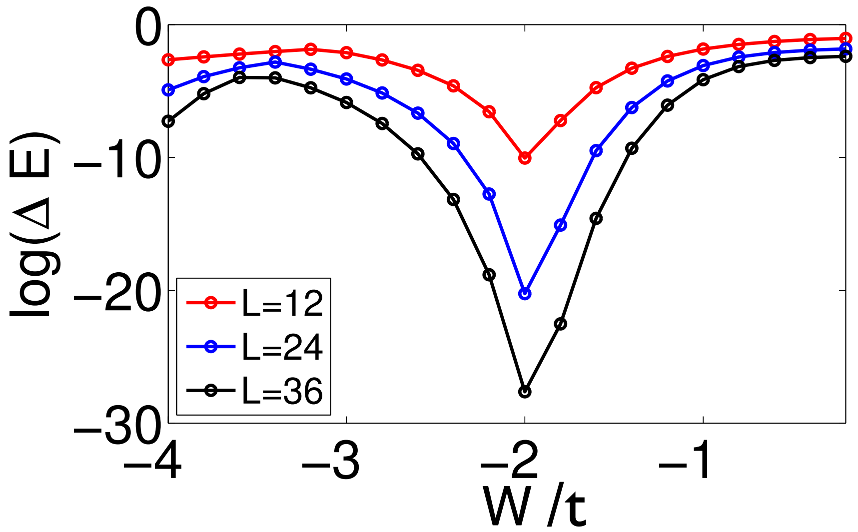
pair hopping: $U(1) \to \mathbb{Z}_2$

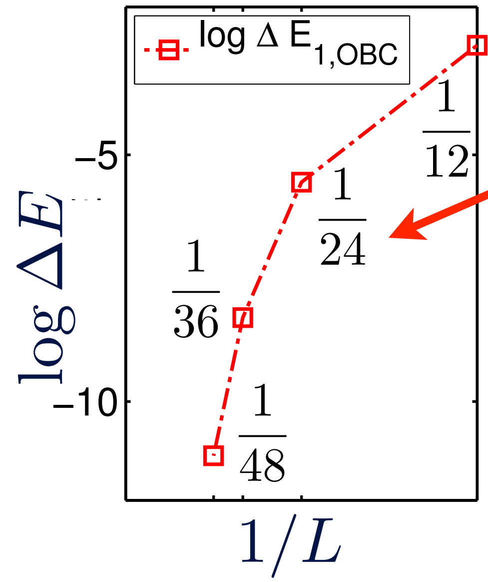


Gaps and non-local Correlations

Energy gap $\Delta E_1 = E_1 - E_0$ for open (OPB) and periodic (PBC) boundary conditions

$\Delta E_{1,\mathrm{OBC}}(W)$





$\Delta E_{1,\mathrm{OBC}} \simeq e^{-\alpha L}$

$\Delta E_{1,\mathrm{PBC}} \simeq 1/L^{\beta}$

parities: $|e,e\rangle, |o,o\rangle$

W/t = -1.8, n = 1/3

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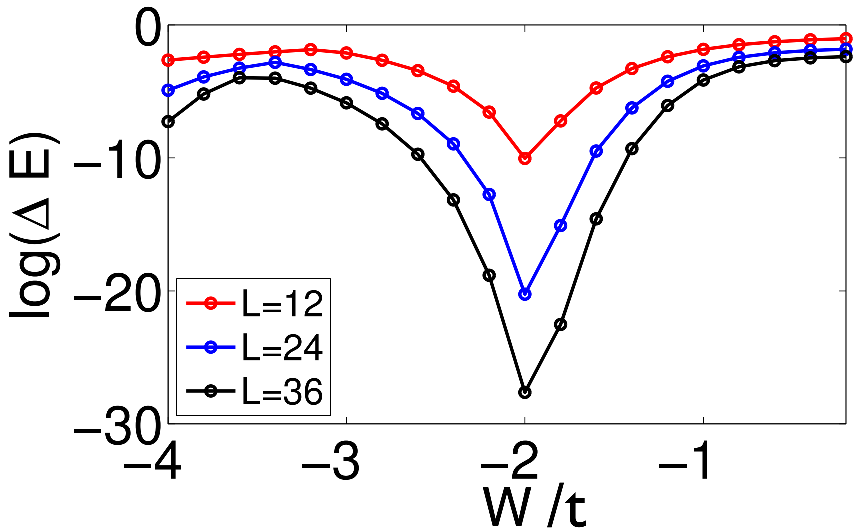

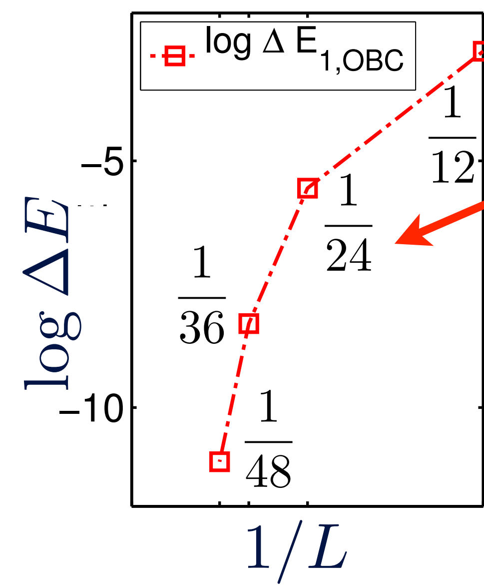

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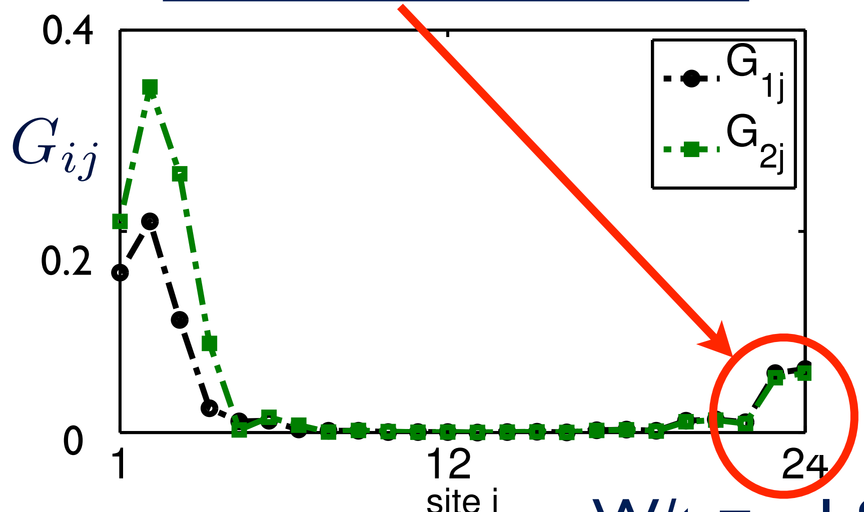


$G_{ij} = \langle a_i^\dagger a_j \rangle$

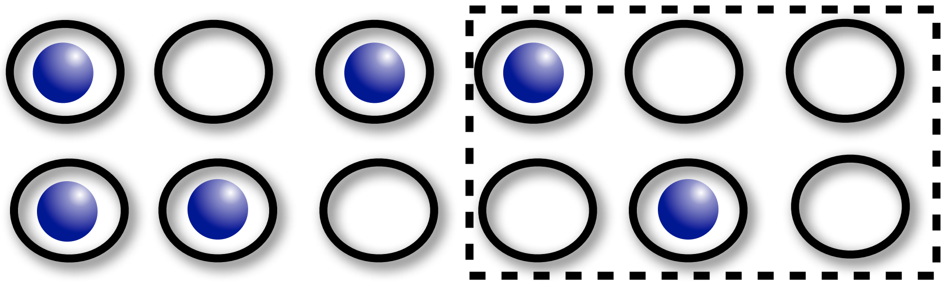
W/t = -1.8, n = 1/3, L = 24

✓Twofold degenerate ground state with different parities on the wires
✓Non-local correlations

Topological Order

Topologically ordered system ↔ Degeneracy of the entanglement spectrum

A. Turner, F. Pollmann, E. Berg, PRB 83 (2011)



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$\lambda_j^{(N)}$ come in degenerate pairs: topological phase

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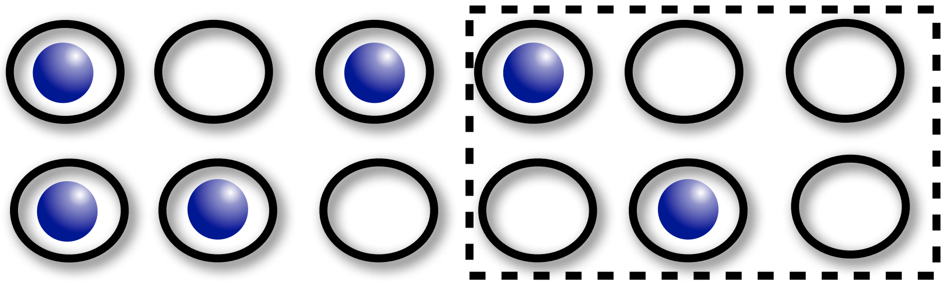

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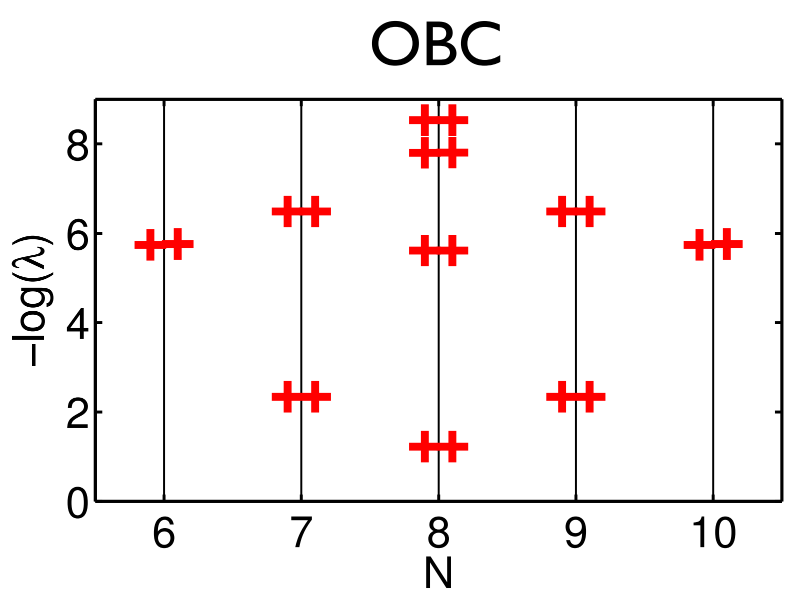

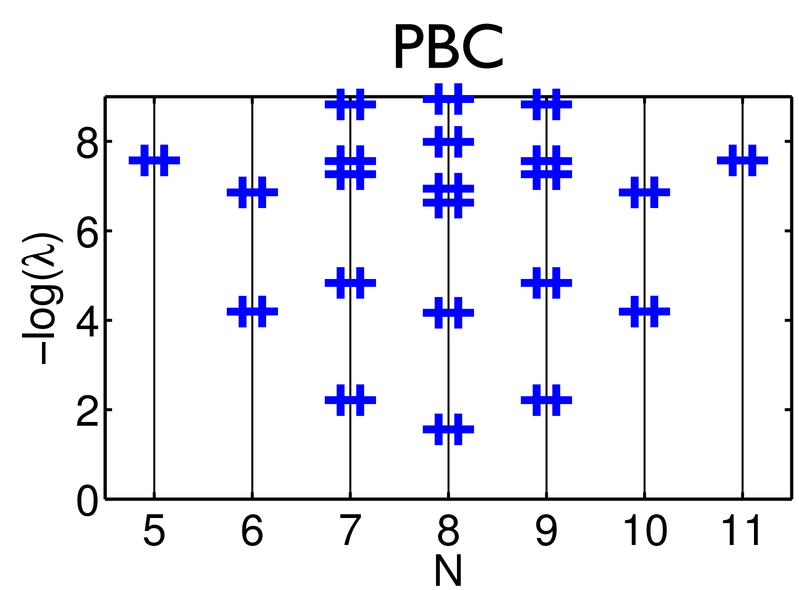

W/t = -1.8,
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- Spectrum doubly degenerate for OBC and PBC
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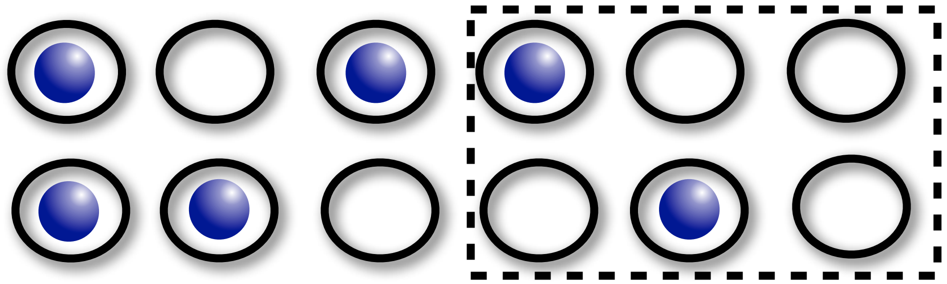

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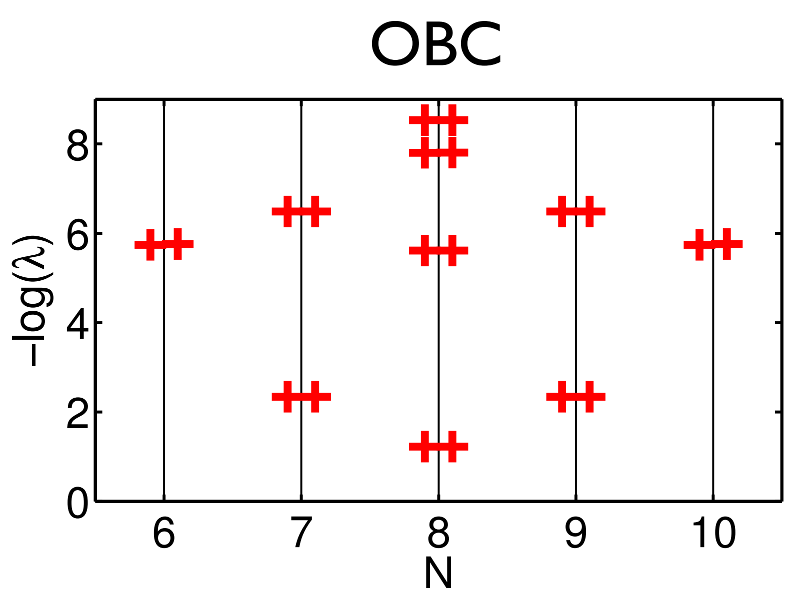

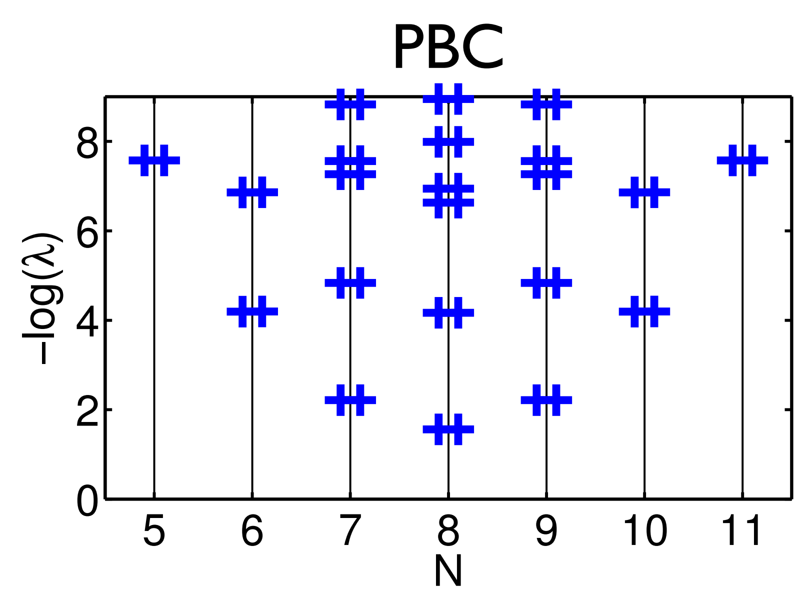

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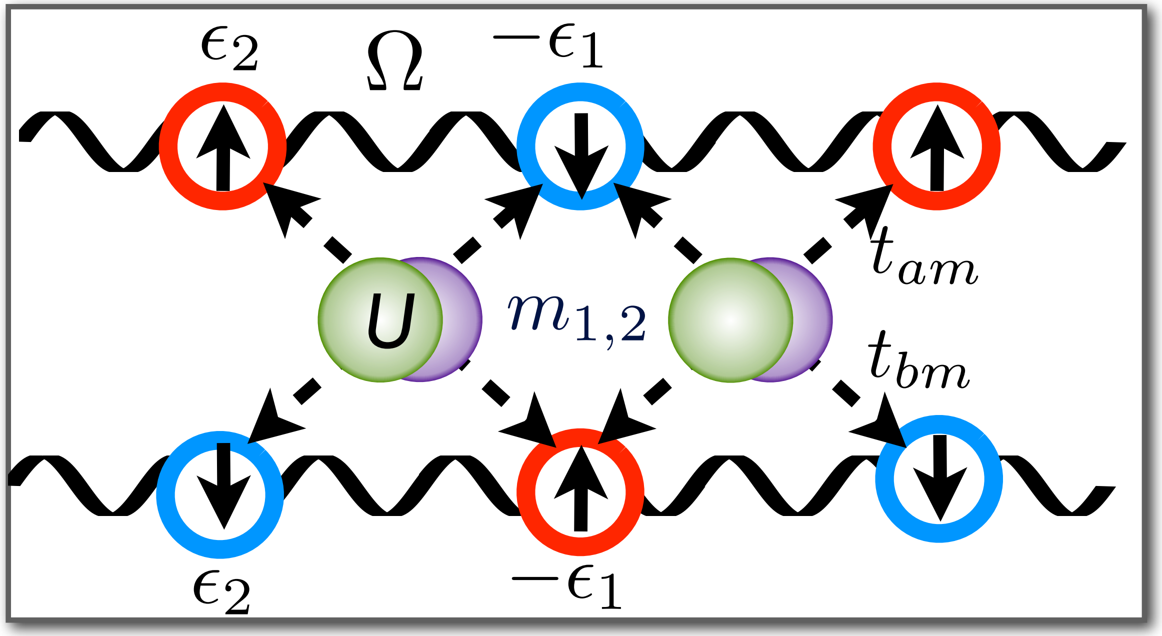
✓Double wire is in a topological phase.

Engineering of the Pair Hopping



- Raman assisted tunneling along the wires
- Central site: two levels, interaction U
- Energy offsets allow pair hopping and forbid single particle hopping

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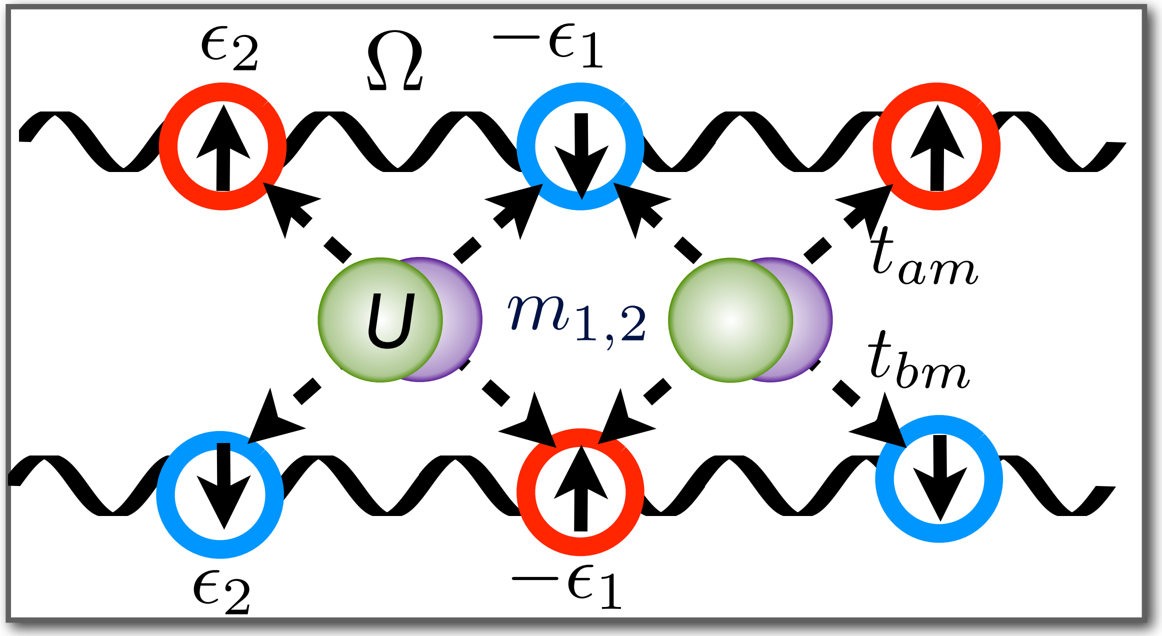

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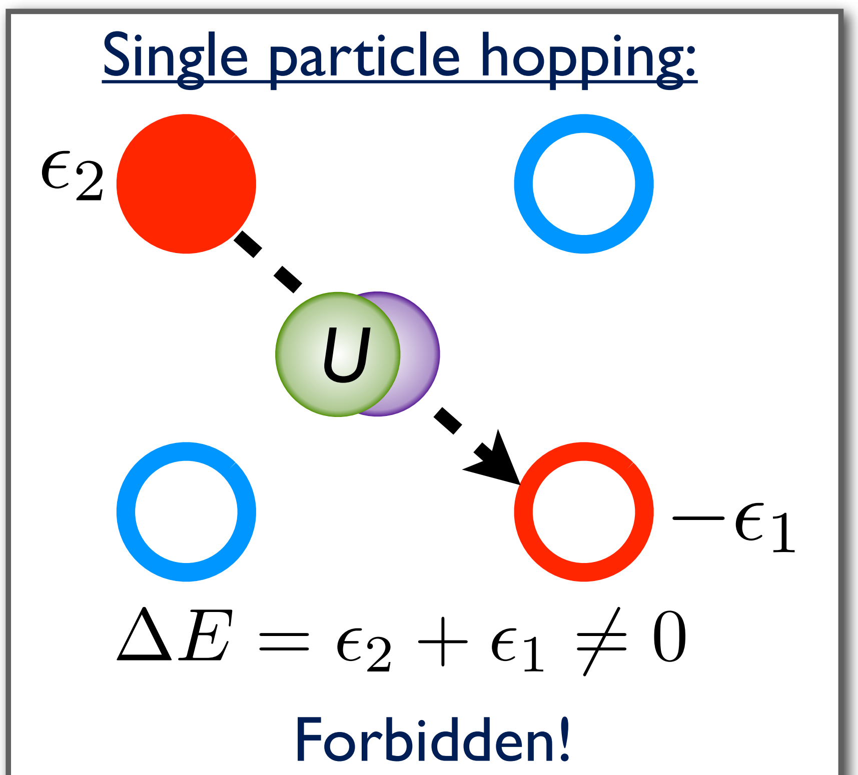

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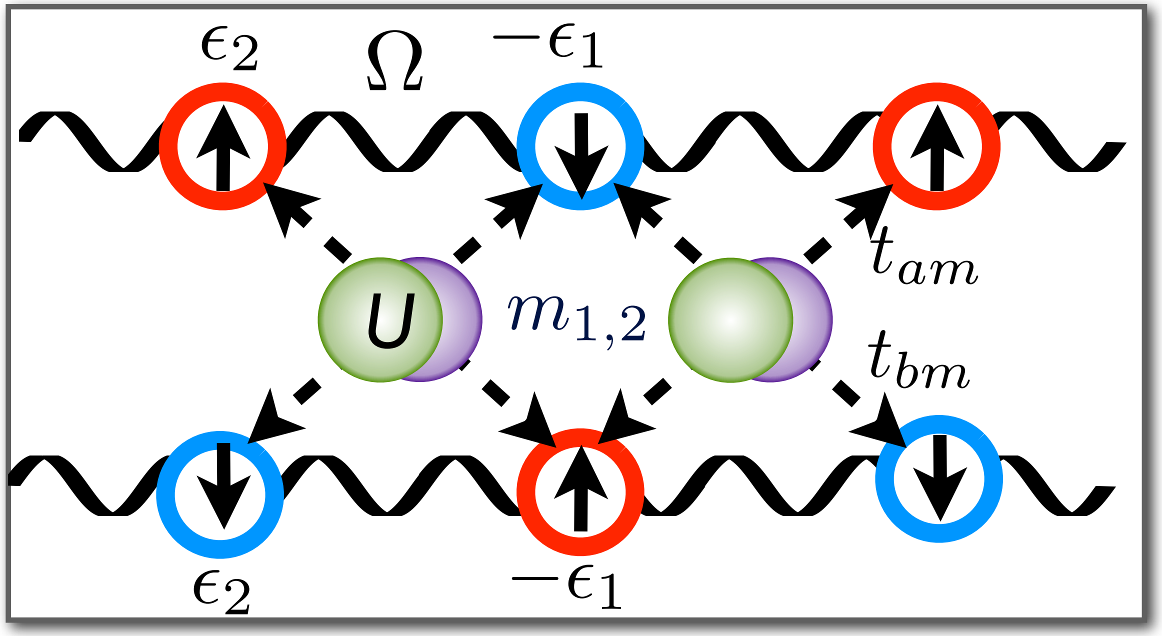

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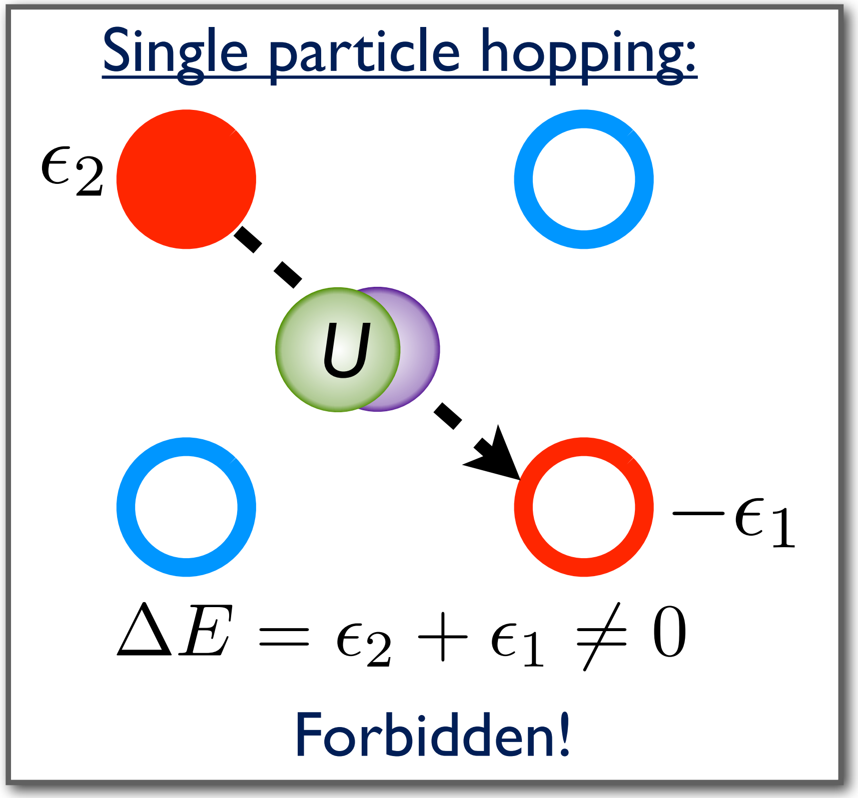

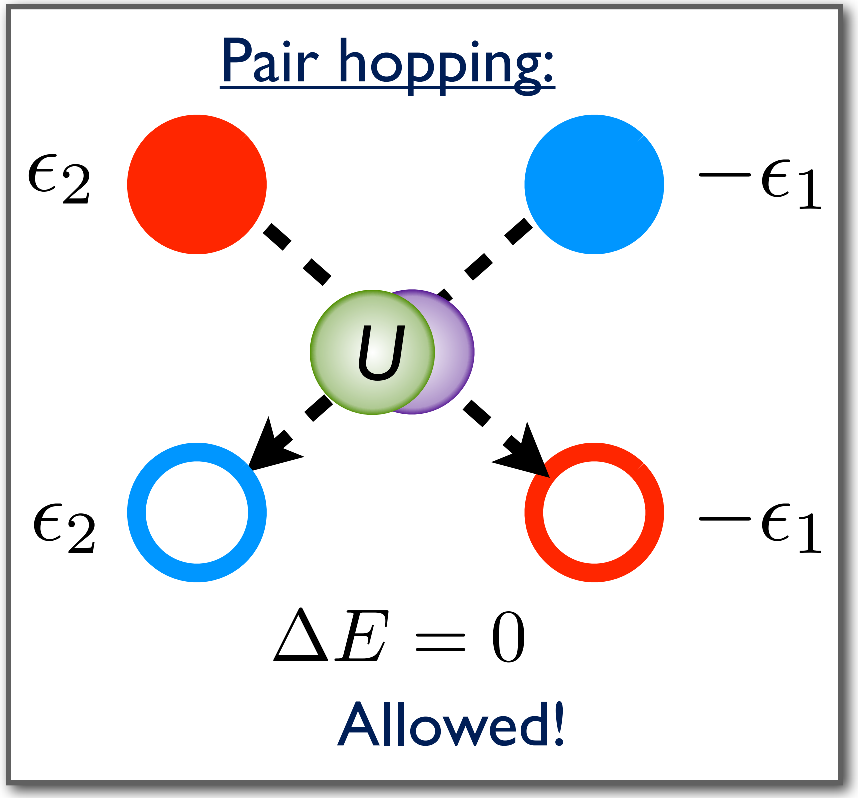

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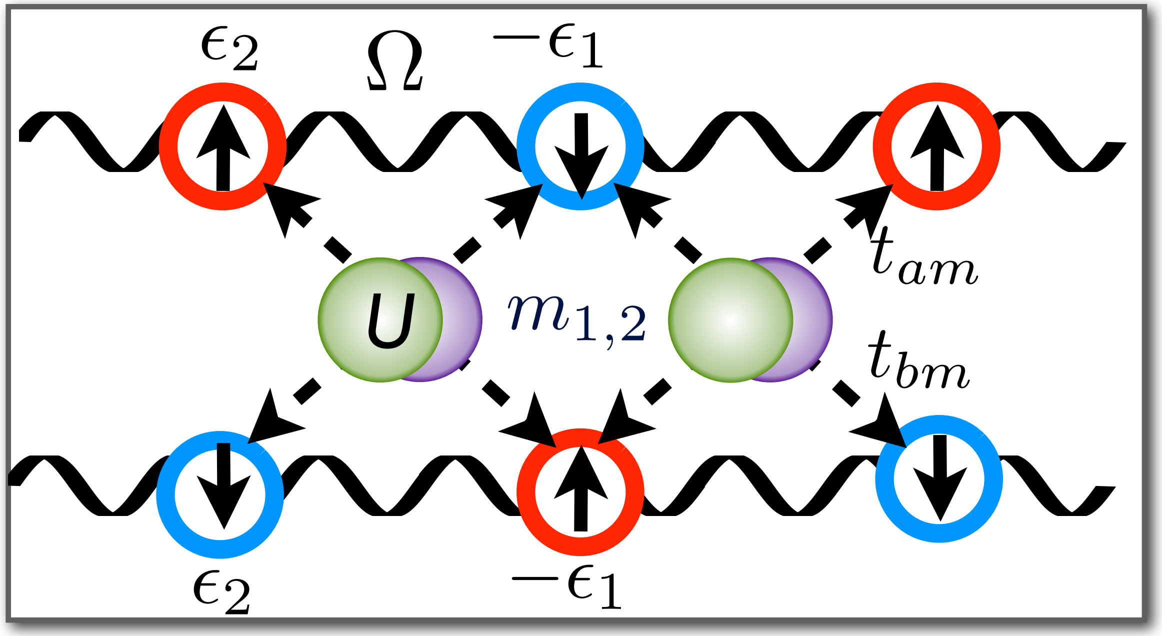

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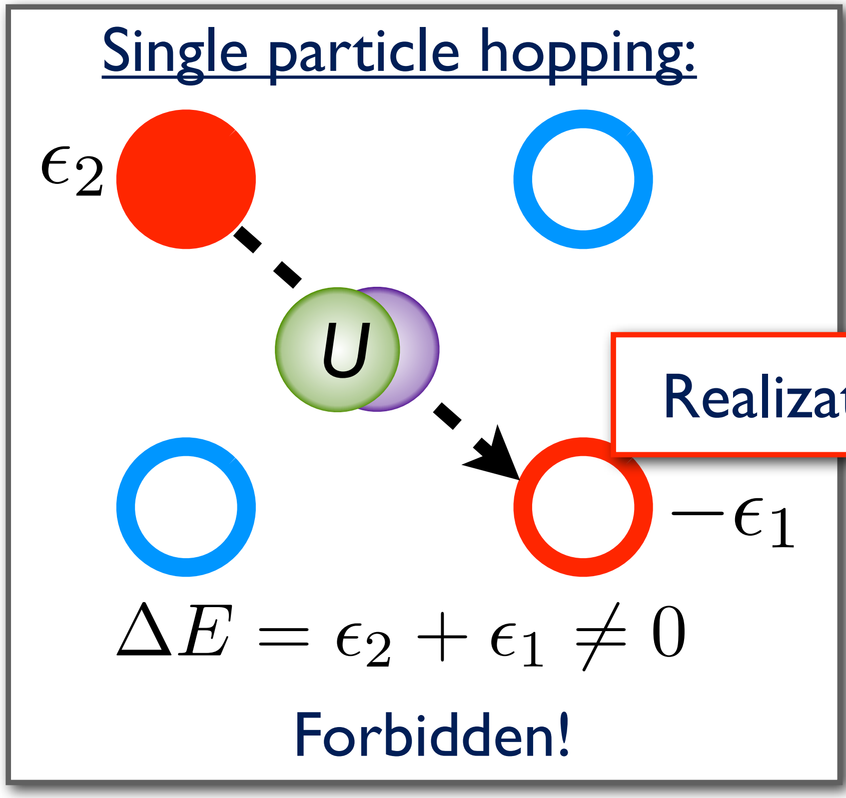
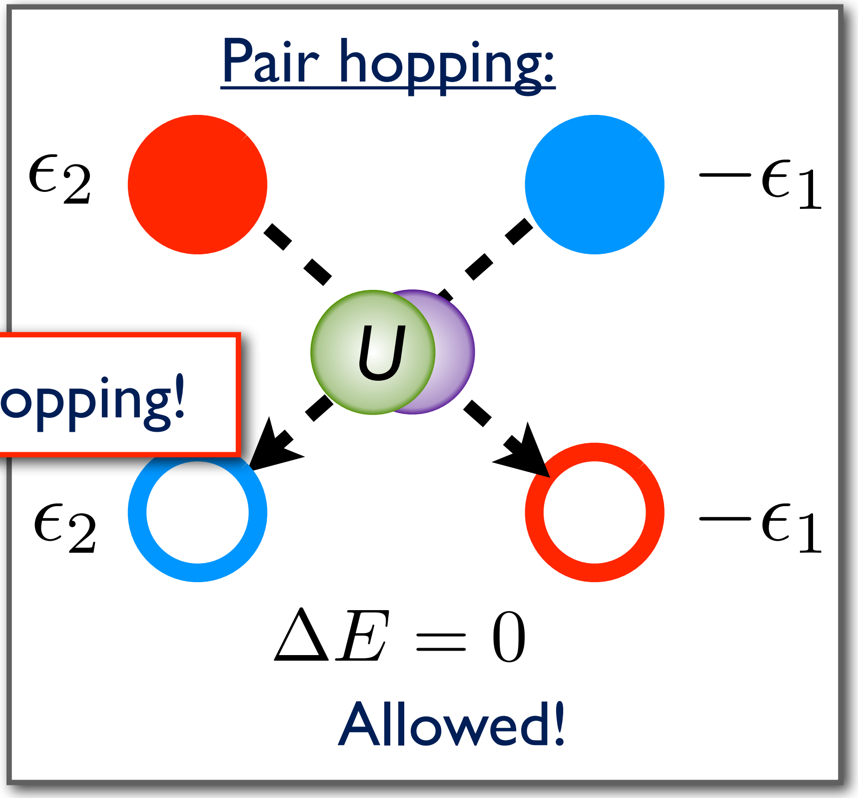


Realization of the pair hopping!



Effects of Perturbations

AMO Realization

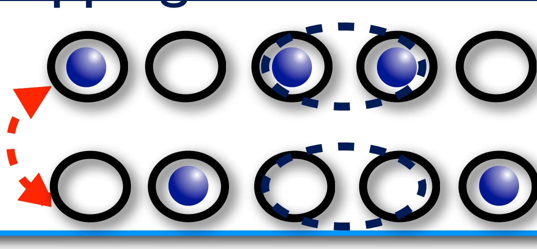
- Single particle intra-chain hopping
- Assisted single particle hopping
- Density-density interactions

Perturbations

Topological Order

- Random local potentials
- Randomness in W

Hopping between the chains



...breaks Z_2 symmetry

Effects of Perturbations

AMO Realization

- Single particle intra-chain hopping
- Assisted single particle hopping
- Density-density interactions

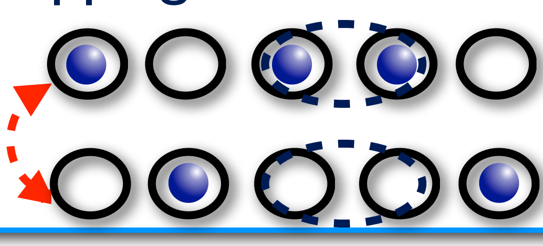
Perturbations

No qualitative effect!
(at least in the experimentally relevant regime)

Topological Order

- Random local potentials
- Randomness in W

Hopping between the chains

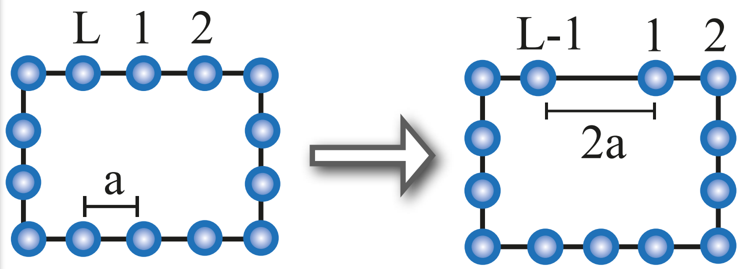


...breaks Z_2 symmetry

Summary and Outlook

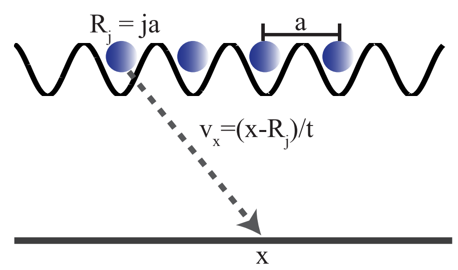
Majorana Physics in the Kitaev Wire

Preparation of ground state with a definite parity



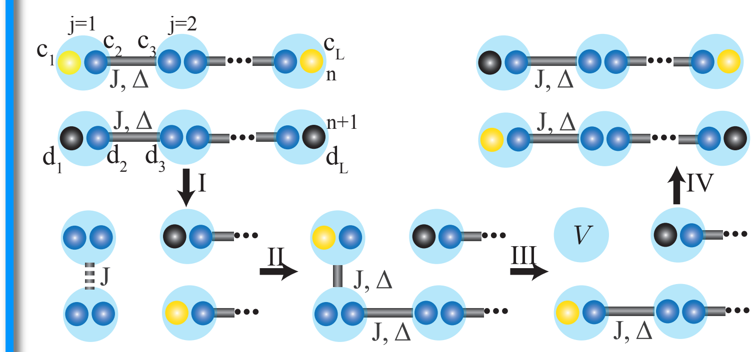
Detection with AMO tools

- Time-of-flight imaging
- Spectroscopy



C.K, S. Diehl, P. Zoller, M. Baranov (NJP ‘12)

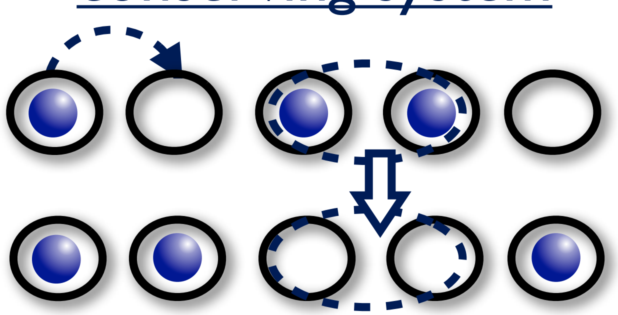
Braiding of MFs and TQC



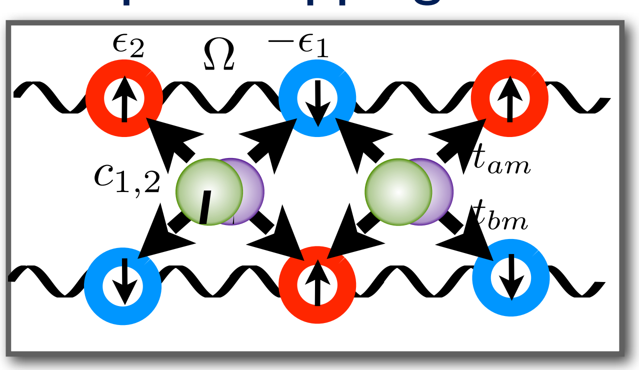
C.K, P. Zoller, M. Baranov, arxiv, ’13

Majorana Physics in a double wire with pair hopping

MFs in an interacting number conserving system



Engineering of the pair hopping



C.K, M. Dalmonte, M. Baranov,
A. Läuchli, P. Zoller, arxiv ’13

Outlook

- Hybrid system for TQC
- Braiding in the double wire system
- Further applications of pair hopping