Dynamics across quantum phase transitions in Rydberg atom arrays

Simone Notarnicola, University of Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

DARPA

MARIE CURIE ACTIONS

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New Frontiers in Theoretical Physics - XXXVIII Convegno Nazionale di Fisica Teorica

Palazzone della Scuola Normale Superiore di Pisa, Cortona

May, 21st 2025

https://quantum.dfa.unipd.it/
https://qcsc.dfa.unipd.it/

Introduction

Main goal of quantum processors:

- Assemble quantum many-body states
- Preserve and manipulate their information

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Trapped ions, neutral atoms, superconducting qubits, photons

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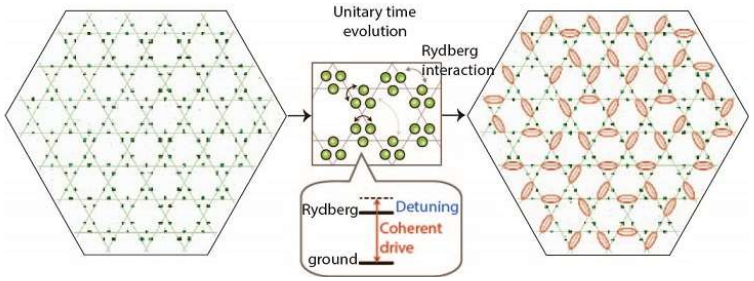


Semeghini et al, Science (2021) Harvard

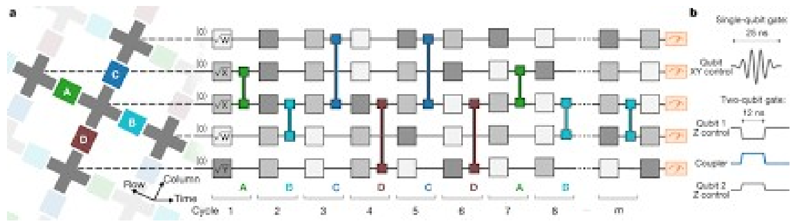
Noisy Intermediate Scale Quantum era

Analog platforms

Dynamics under effective Hamiltonians

Digital platforms

Gate-based state preparation



Omran et al, Nature (2019) Google

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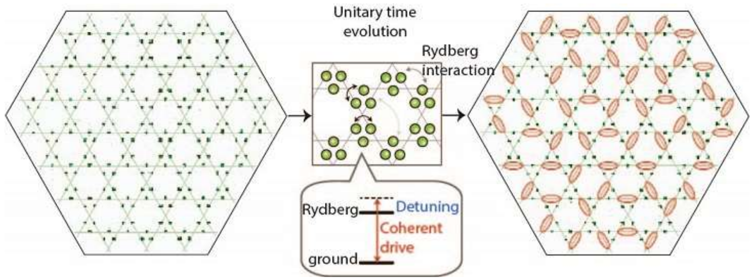

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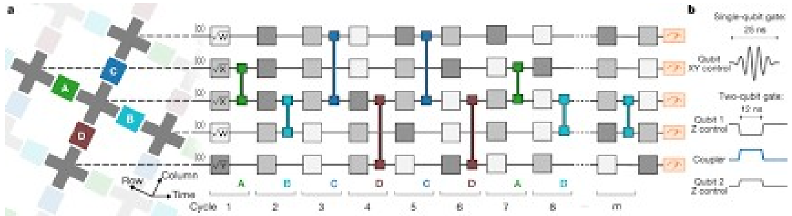
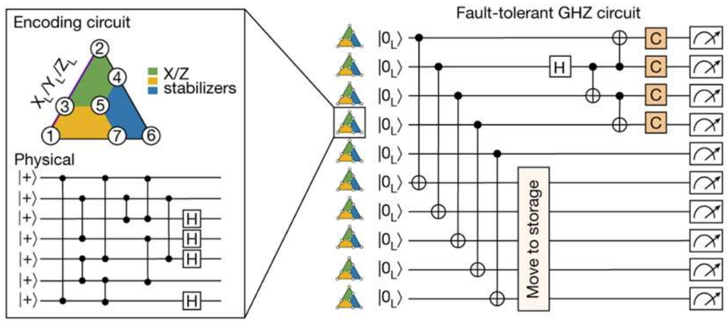


Omran et al, Nature (2019) Google

Early Fault Tolerant Quantum Computing era

Logical protocols

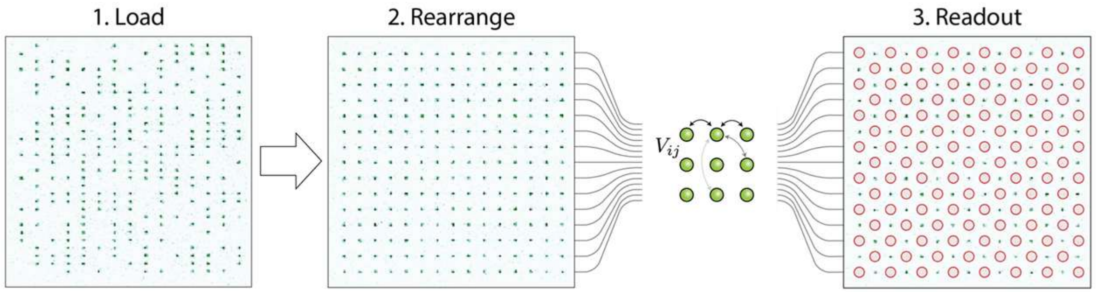
Operations on logical qubits



Bluvstein et al, Nature (2024) Harvard

Outline

✓ Rydberg atom arrays



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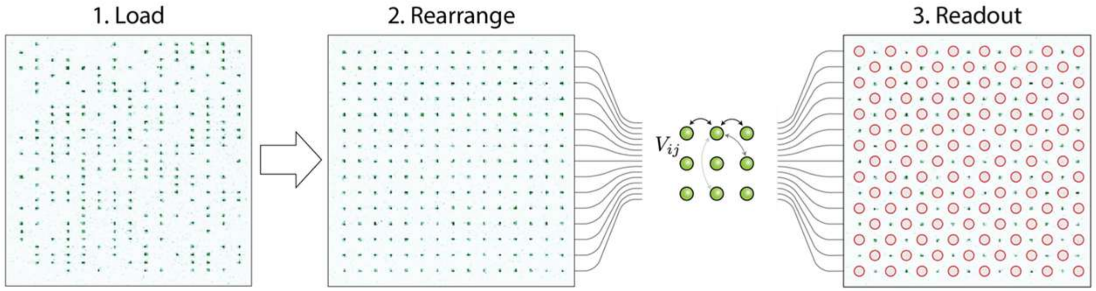

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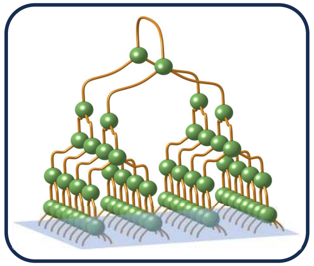

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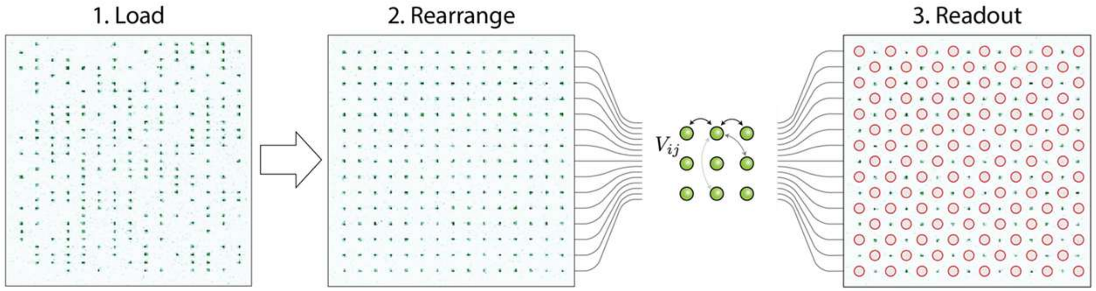

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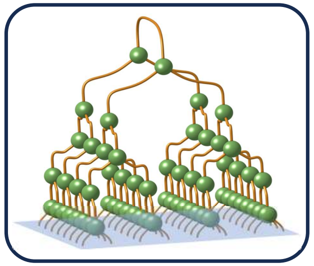

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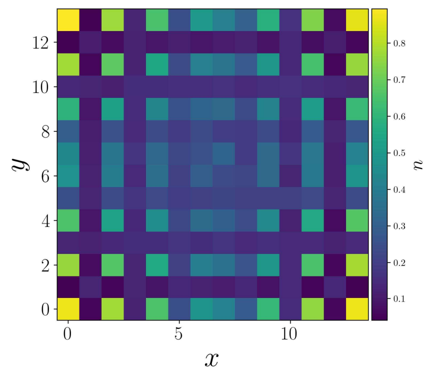
- ✓ Boundary frustration in the striated phase of the Rydberg atom square lattice



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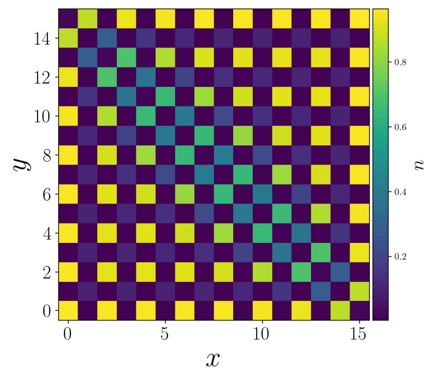

- ✓ Conclusions

Rydberg atom arrays

Qubit $\equiv$ atom

$Rb\ \mathbf{70}^1s \sim \mathbf{10^{-6}}\boldsymbol{m}$ $\quad |r\rangle$

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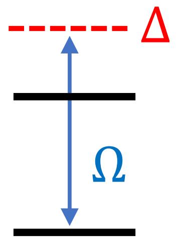

$$H_{Ryd} = \boxed{\frac{\Omega}{2}\sum_i (|g_i\rangle\langle r_i| + h.c.)} - \boxed{\Delta \sum_i n_i}$$

Quantum driver

Chemical potential

Rescaled Hamiltonian: $\frac{\Delta}{\Omega} \equiv \Delta$

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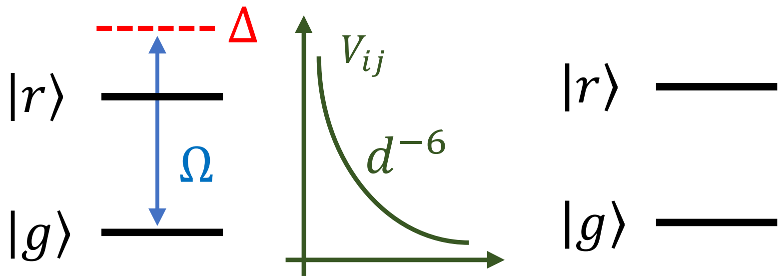

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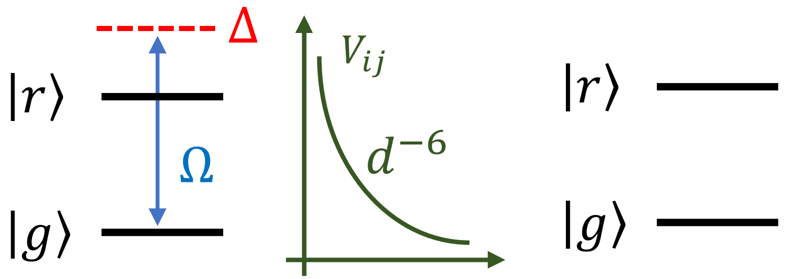

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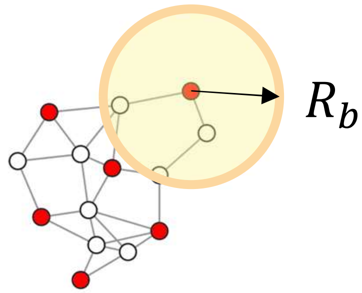
- $d \sim 4\ \mu\text{m}$
- No simultaneous excitations if $d < R_b$ (blockade radius)



$$H_{Ryd} = \underbrace{\boxed{\frac{\Omega}{2}\sum_i (|g_i\rangle\langle r_i| + h.c.)}}_{\text{Quantum driver}} - \underbrace{\boxed{\Delta \sum_i n_i}}_{\text{Chemical potential}} + \underbrace{\boxed{\sum_{i<j} V_{ij}\, n_i n_j}}_{\text{Van der Waals interactions}}$$

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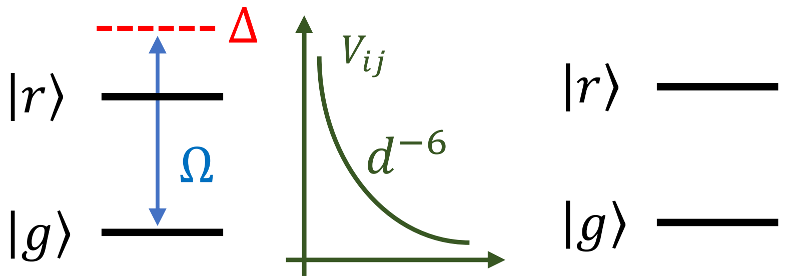

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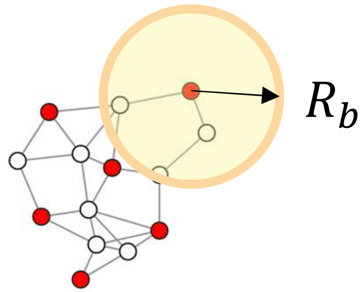

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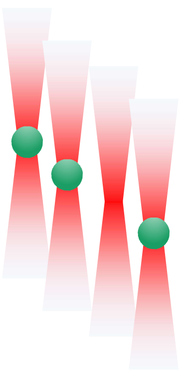
Lattice loading with one atom per tweezer



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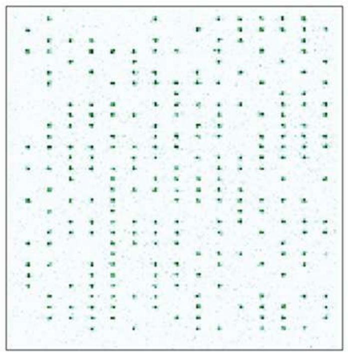

S. Ebadi et al., Nature **595**, (2021)

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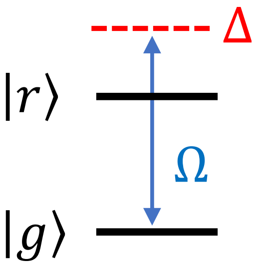

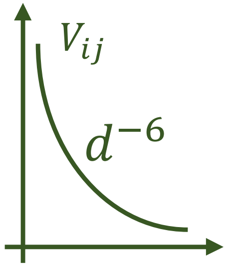

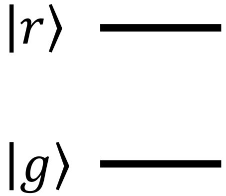

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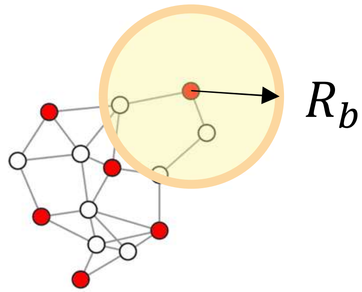

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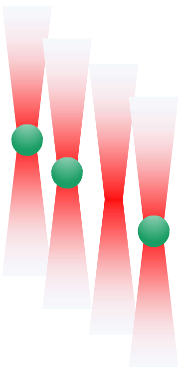

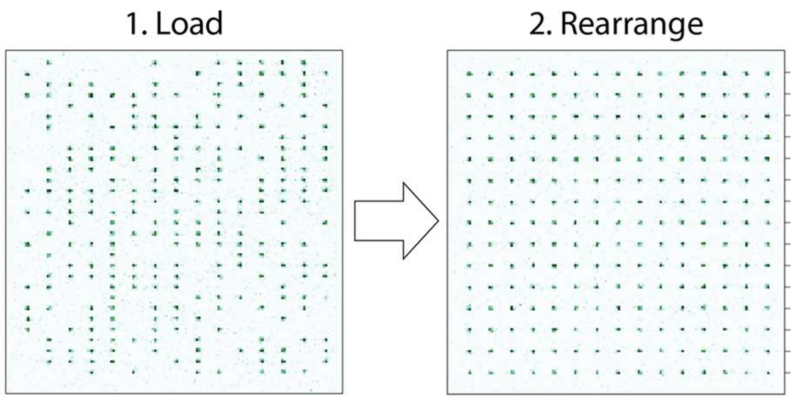

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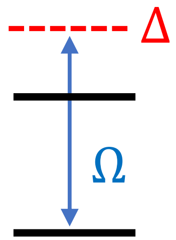

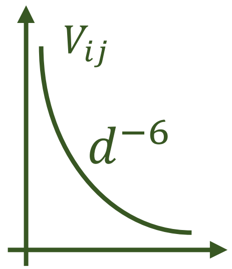

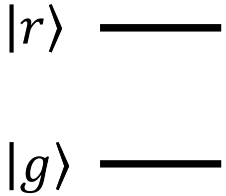

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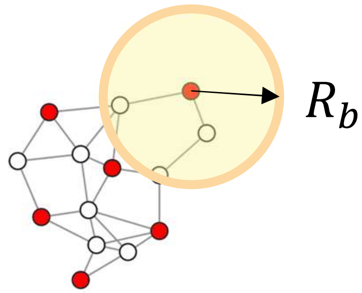

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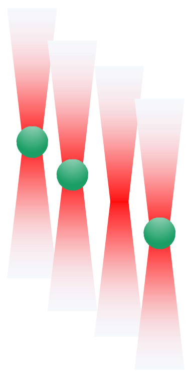

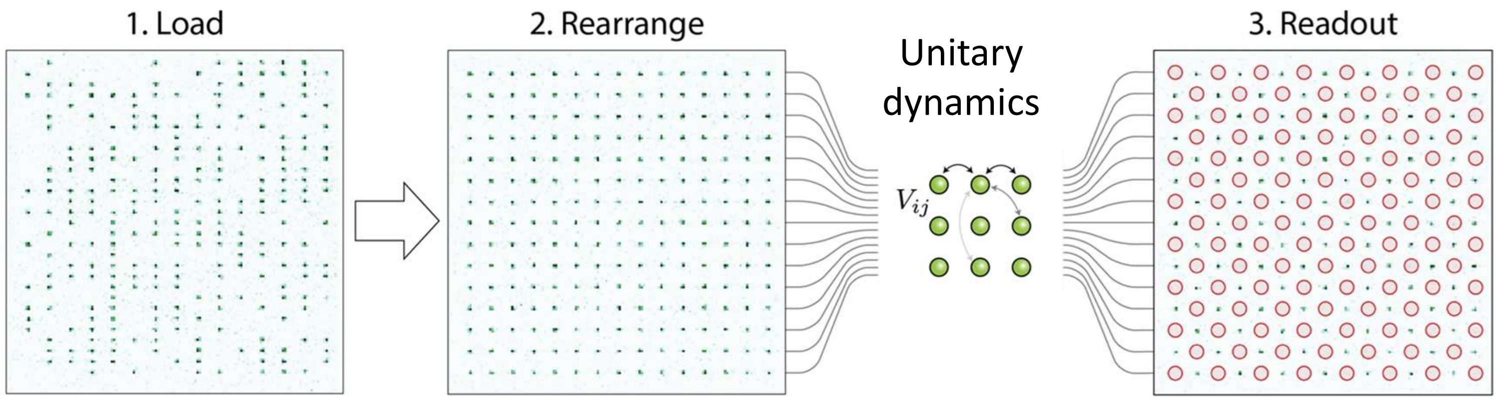

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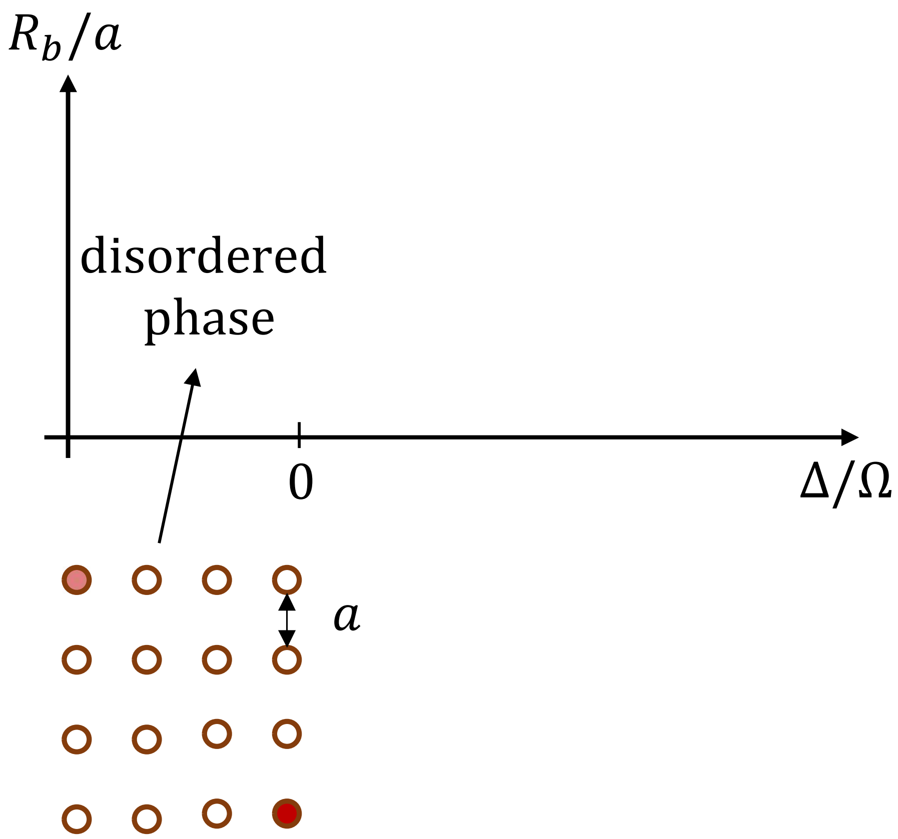
Ground state phase diagram



Negative detuning →
Disordered phase
With no localized excitations

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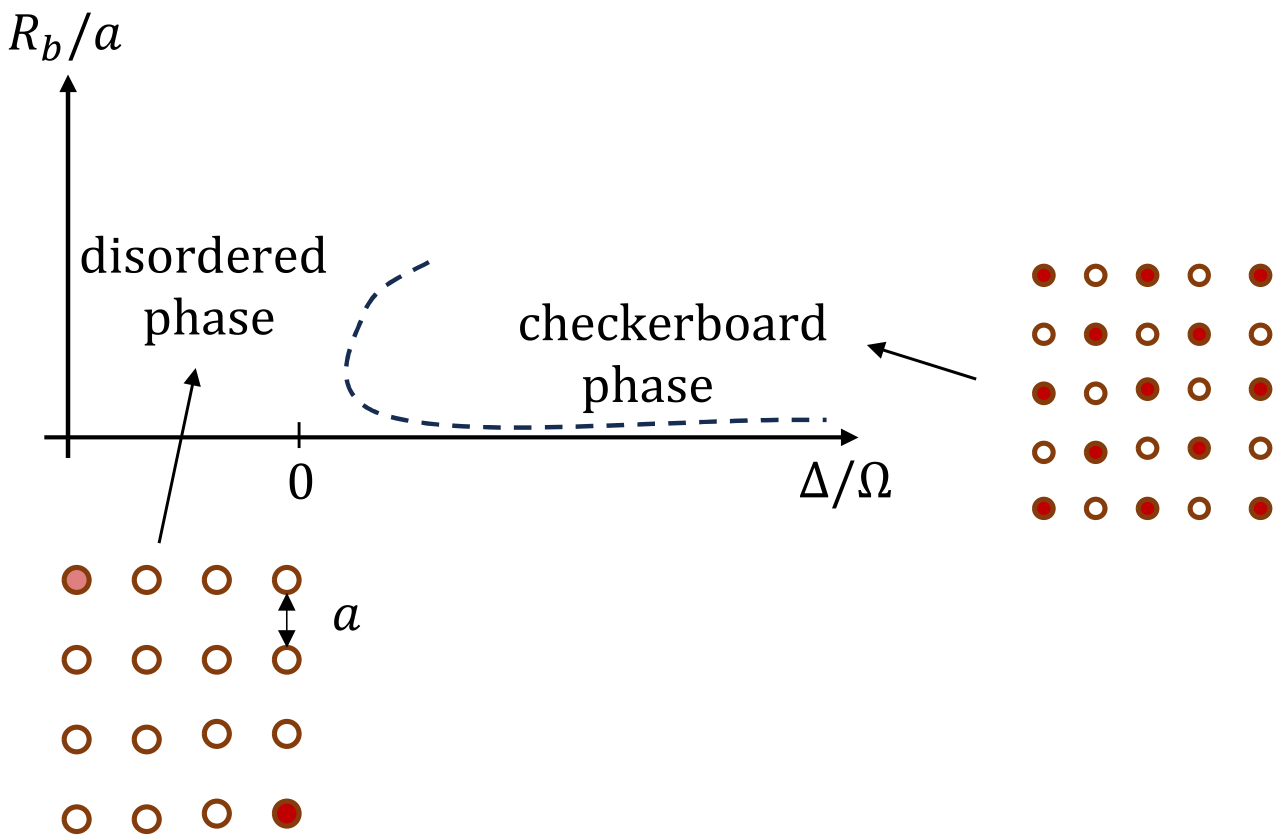

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Positive detuning →
Charge density waves
With localized excitations

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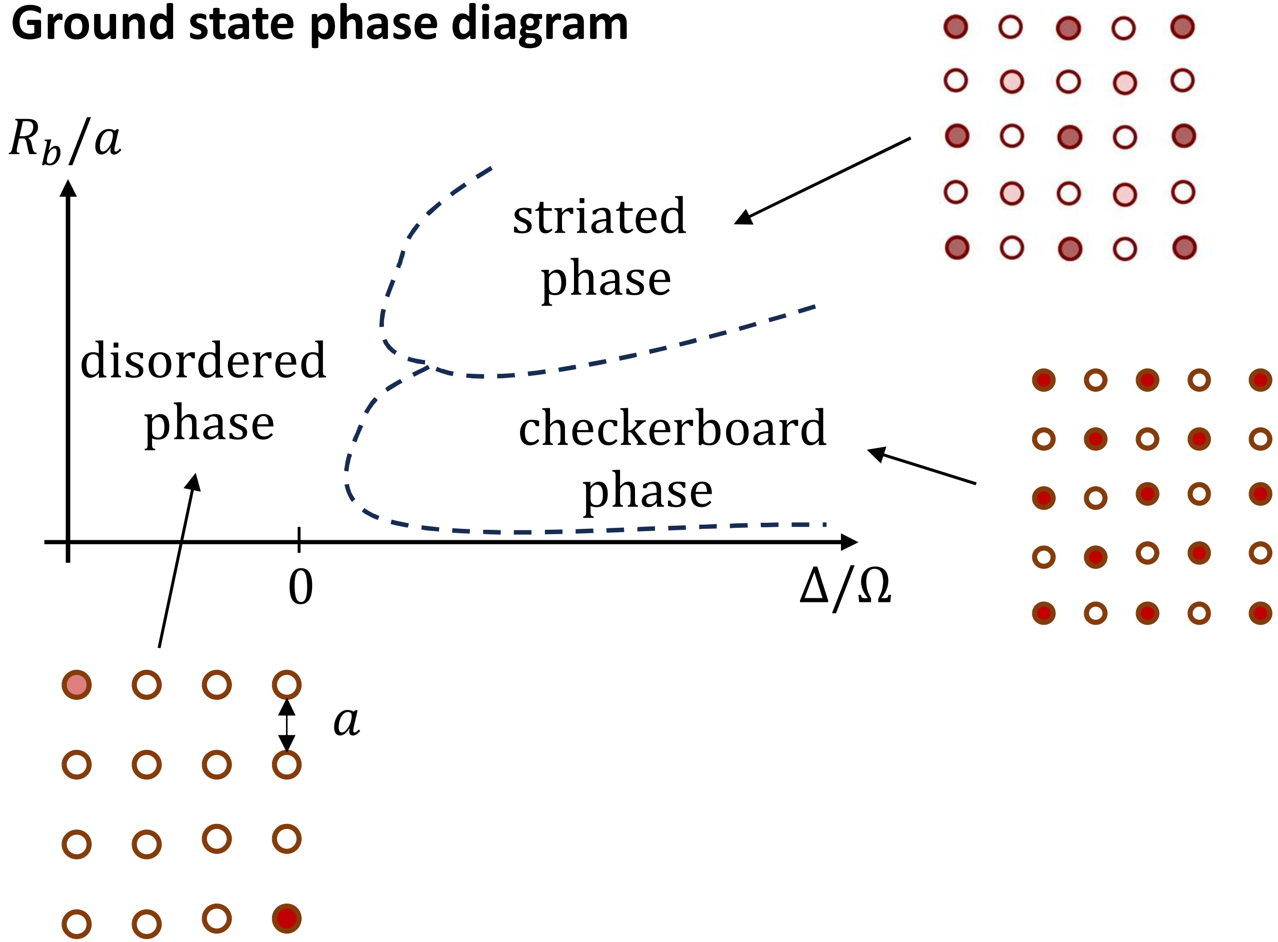

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Positive detuning →
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Smaller spacing a →
Lower excitation density

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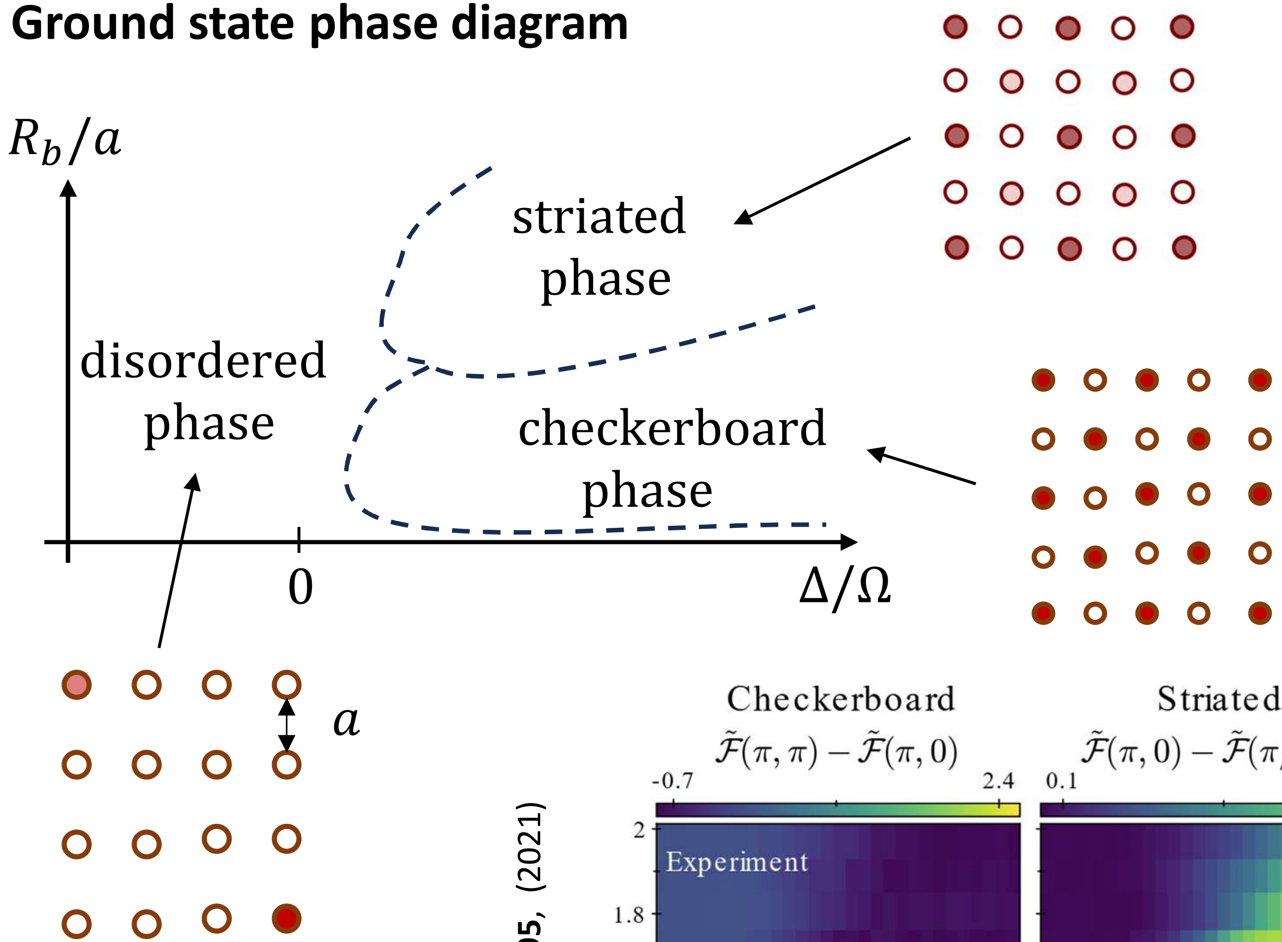

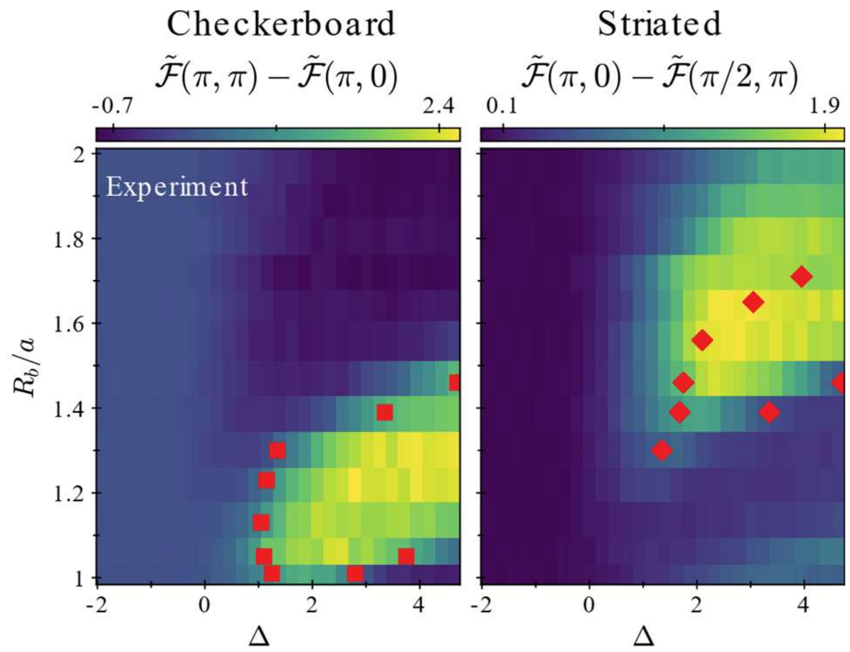

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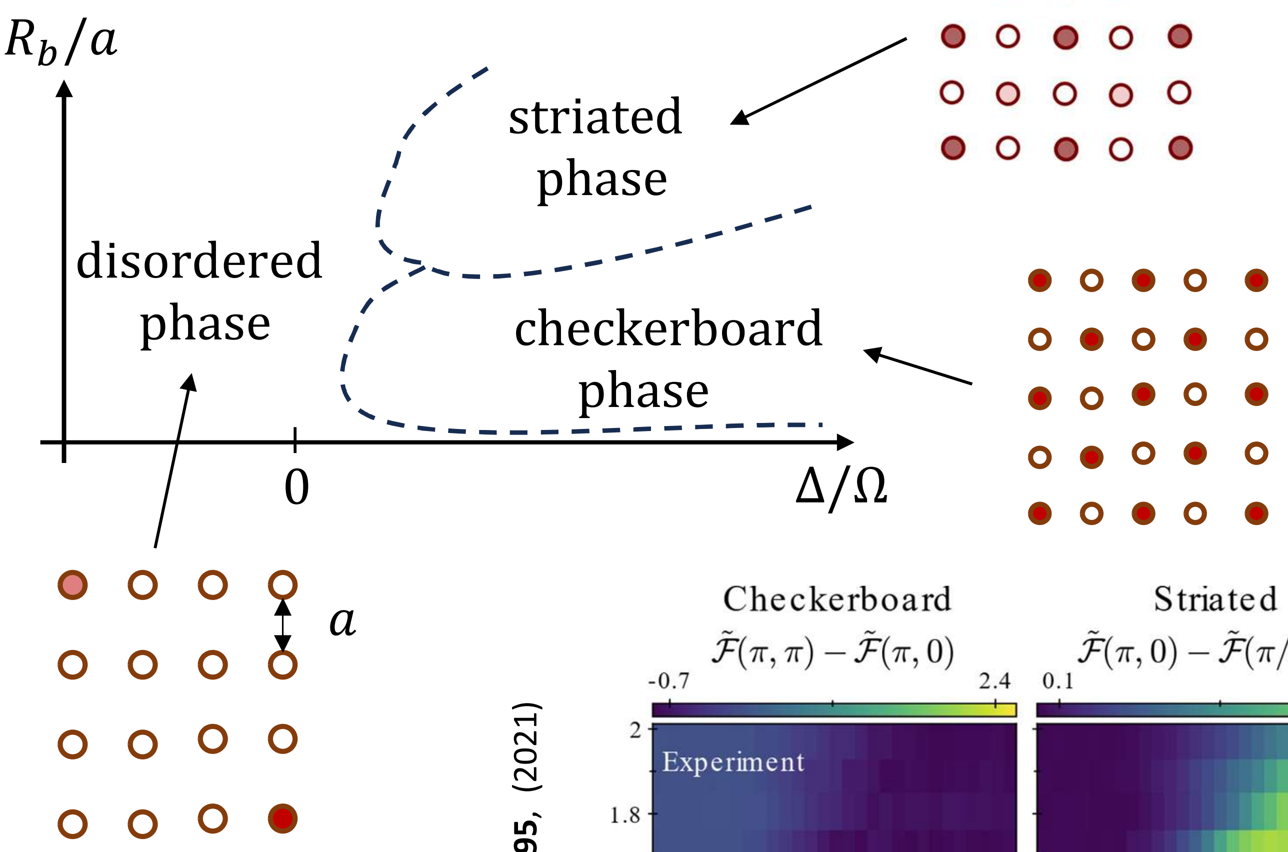

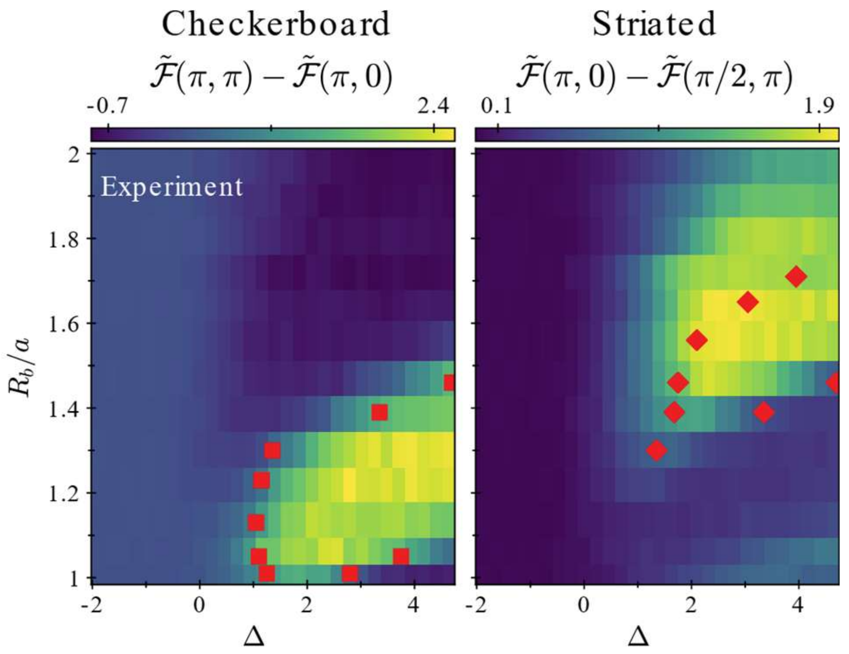

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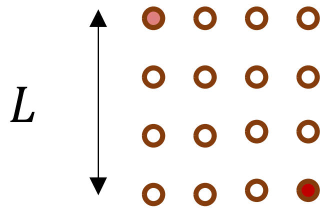
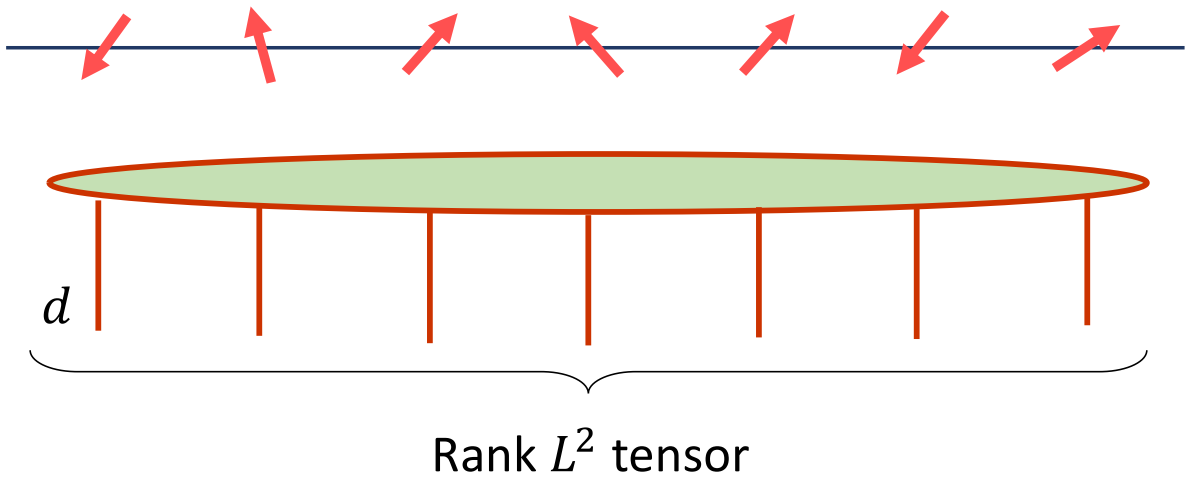
Striated phase:
Frustration induced by the size of the system

Tree Tensor Networks

$$|\Psi\rangle = \sum_{\alpha_1,\dots,\alpha_{L^2}} c_{\alpha_1,\dots,\alpha_{L^2}} |\alpha_1,\dots,\alpha_L\rangle$$





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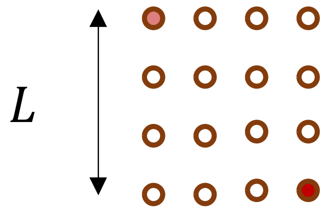

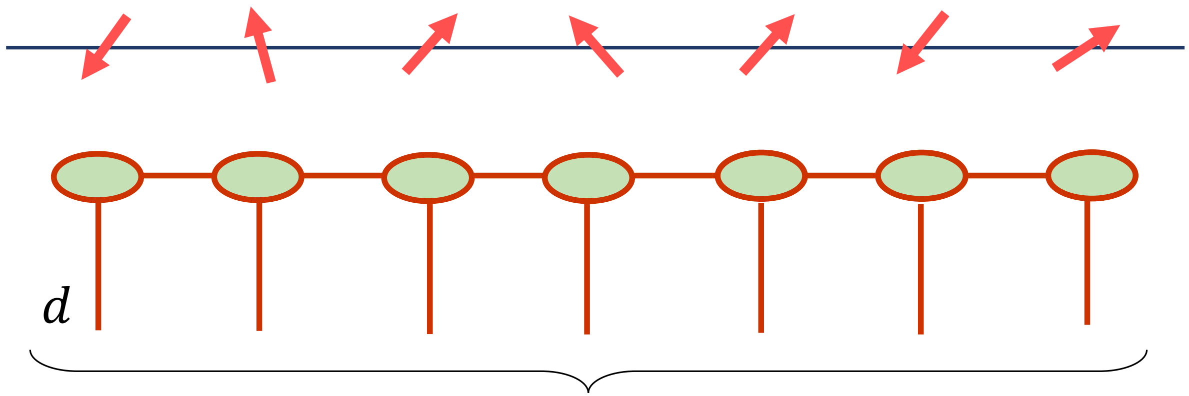

L^2 Rank $d \cdot m^2$ tensors

Efficient method to compress information when correlations fastly decay in space

Bond dimension m:
maximum amount of mutual information between subsystems

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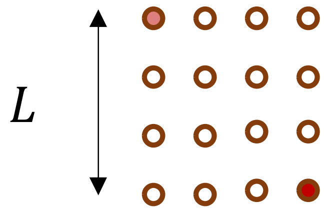

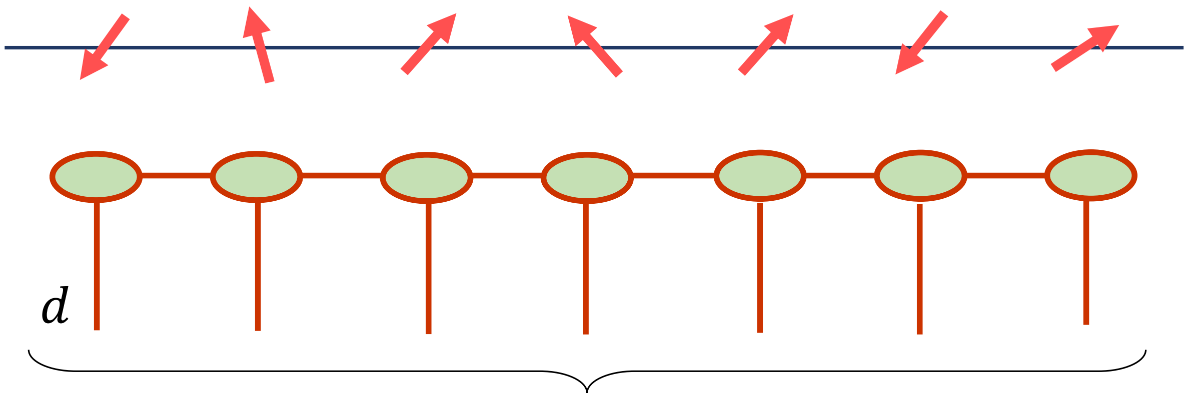

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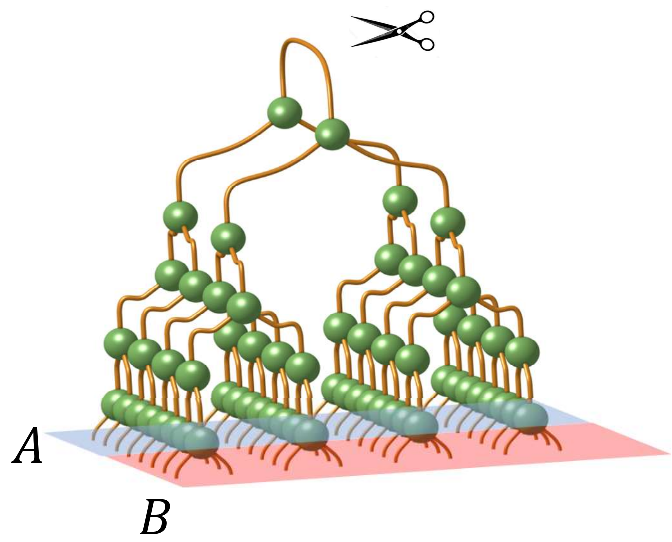

Tree Tensor Networks: suited for high-dimensional systems

- Ground state, dynamics
- Closed/open systems
- Condensed matter, high energy physics, optimization problems

Experimental realization

Cloud available analog quantum processor

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- **256 entangled qubits**
  Coherence throughout the full computation
- **Field-programmable qubit arrays (FPQA™)**
  Programmable connectivity of near-arbitrary qubit layout configurations

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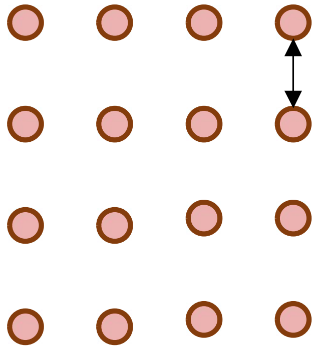

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$p_{fill} \sim 99.5\%$

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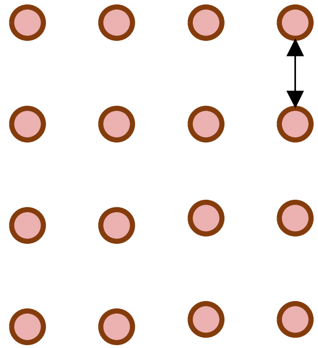

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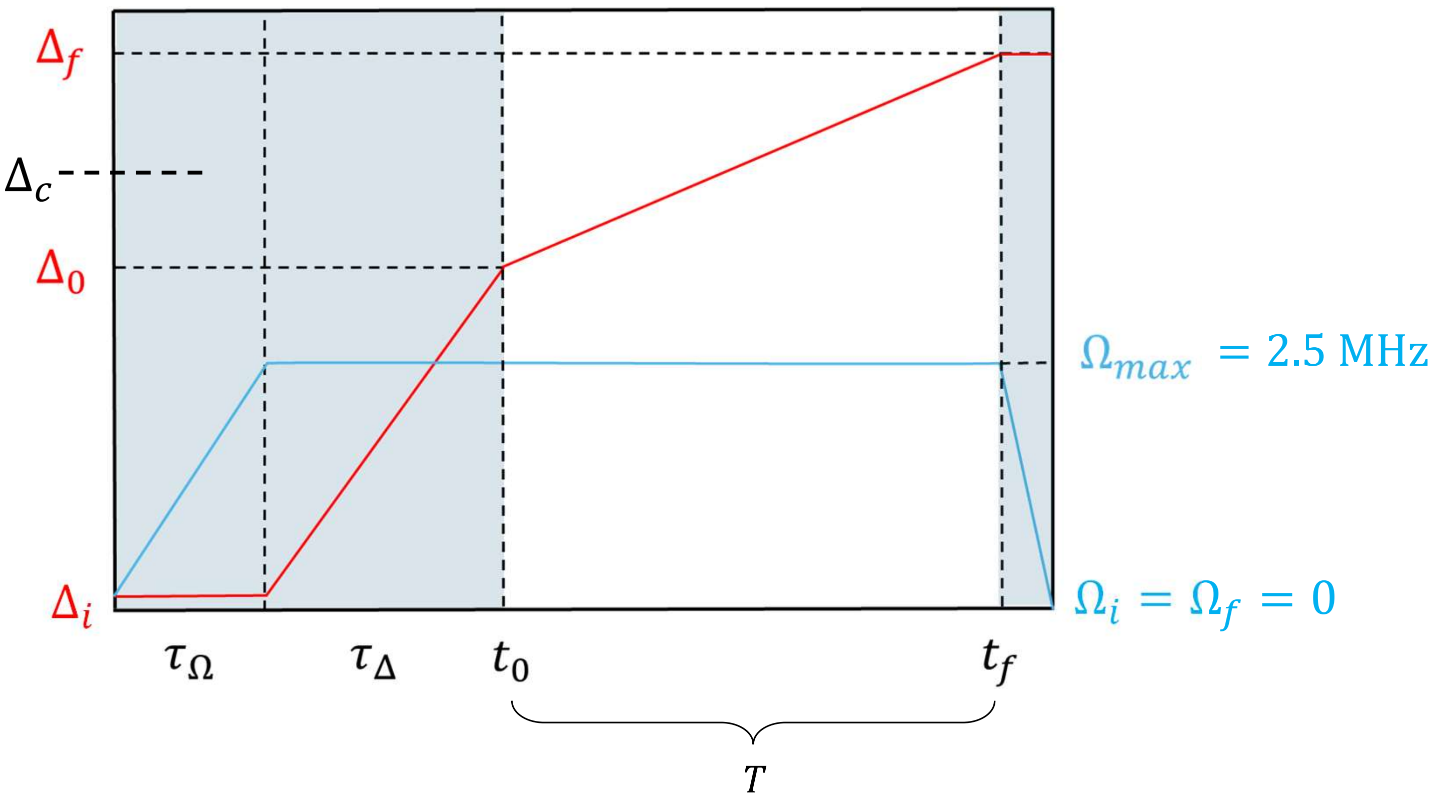
Fixed spacing a

Ordered phase

Disordered phase

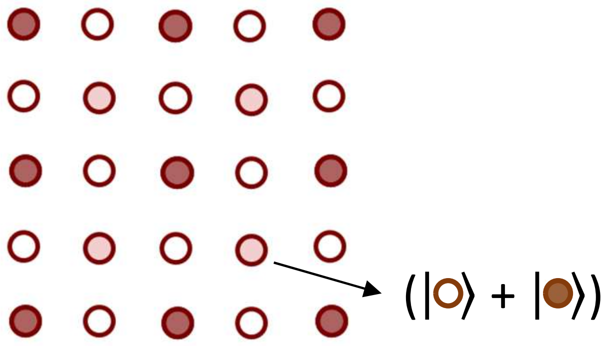
All atoms in the ground state



Boundary frustration in the striated phase

Striated phase

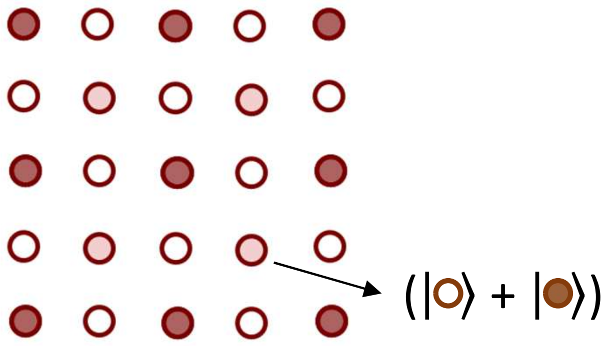
Driven by long-range interactions



Boundary frustration in the striated phase

Striated phase

Driven by long-range interactions

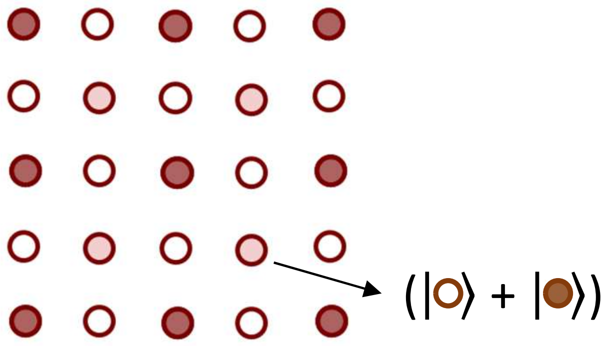


- Compute the ground state of H_{Ryd}
- Measure n local Rydberg excitation density

Boundary frustration in the striated phase

Striated phase

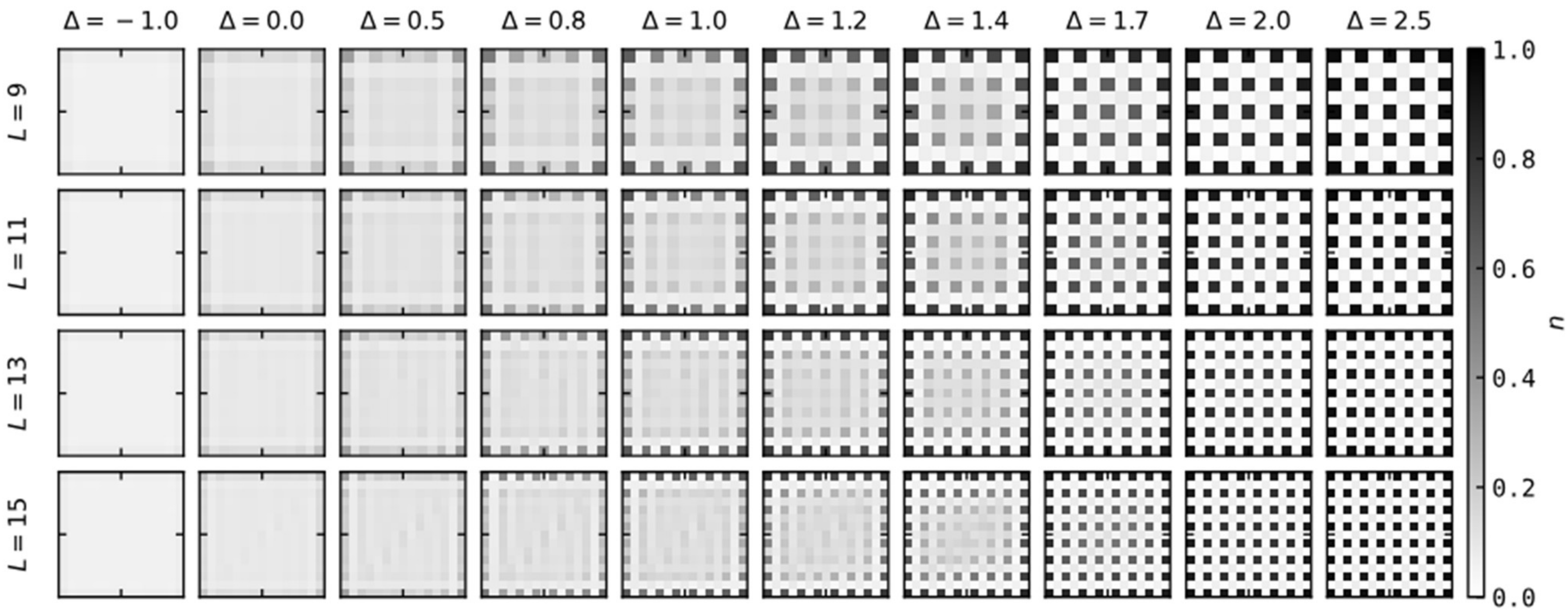
Driven by long-range interactions



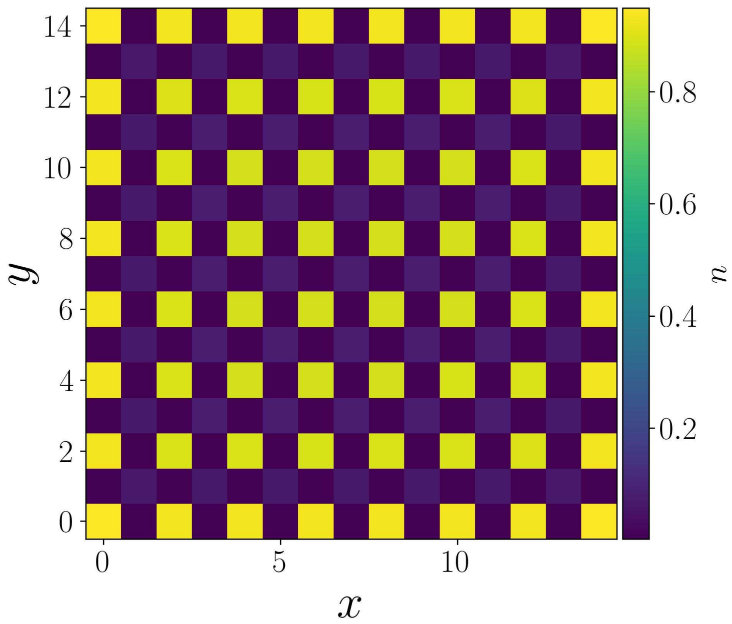
- Compute the ground state of H_{Ryd}
- Measure n local Rydberg excitation density

Disordered phase
Low density of excitations

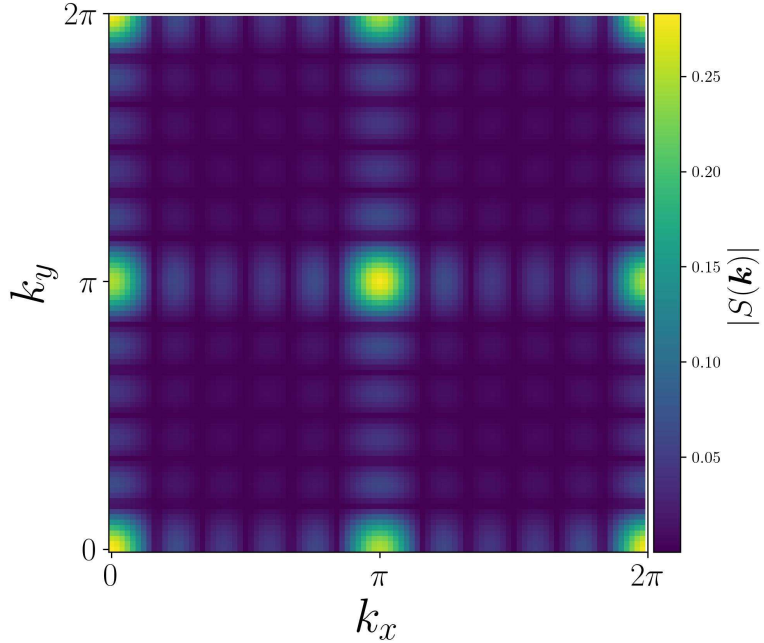
Striated phase
Density-wave phase



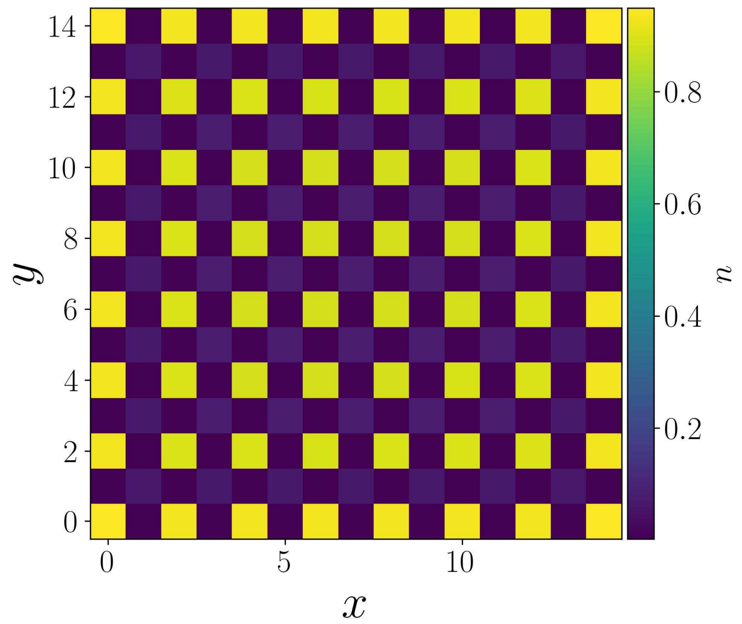
Boundary frustration in the striated phase



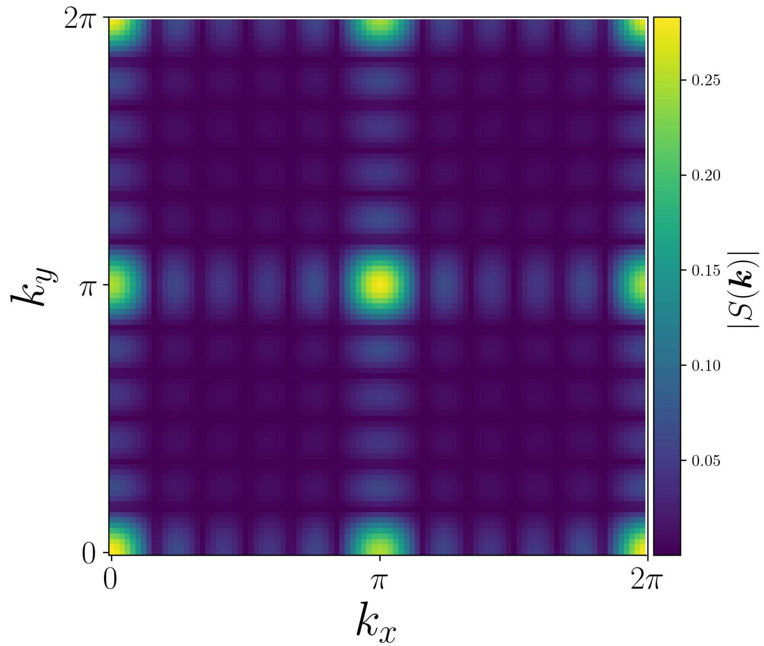
$(0, \pi)$ peak of the density FT

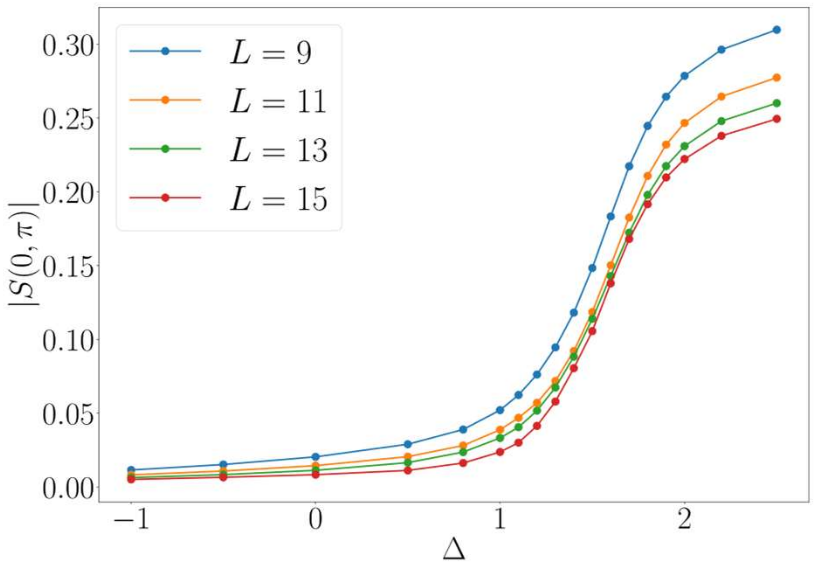


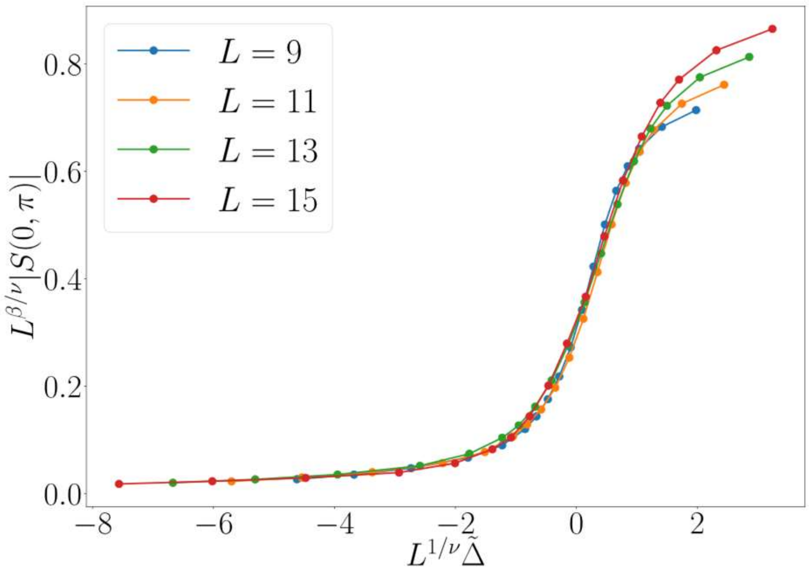
Boundary frustration in the striated phase



$(0, \pi)$ peak of the density FT



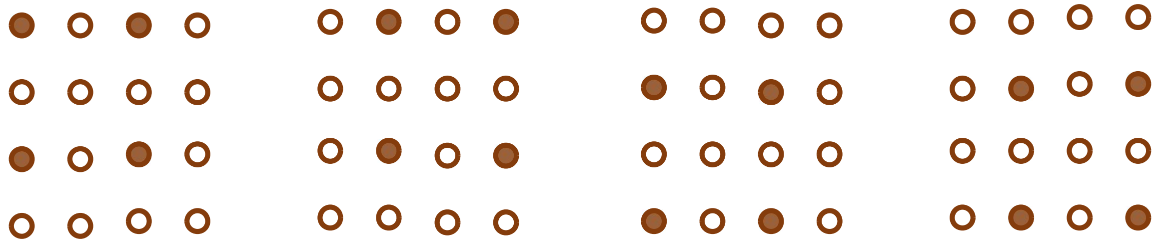




Emergent scaling in the bulk of the lattice

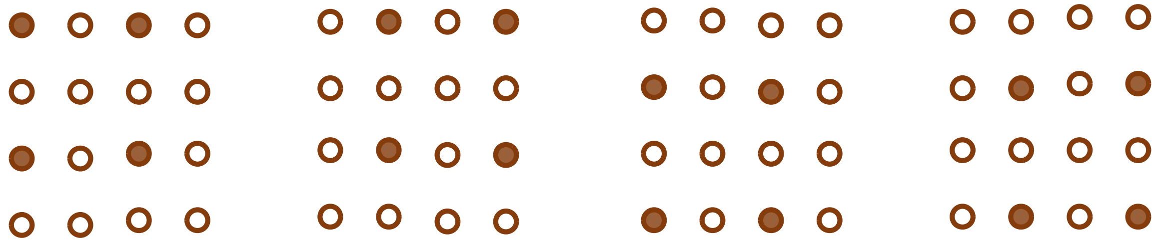
Boundary frustration in the striated phase

Degeneracy with
even x even
lattice sizes



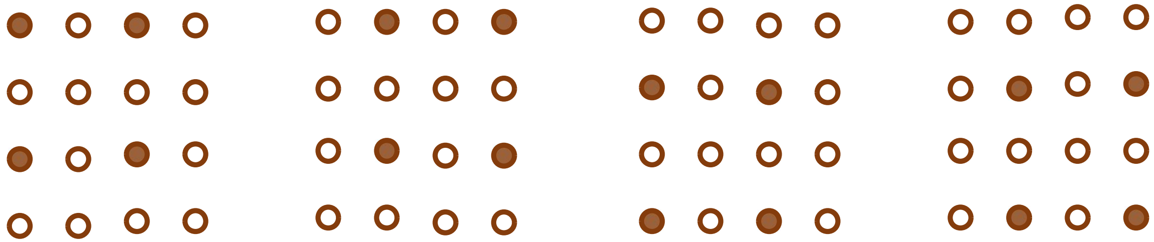
Boundary frustration in the striated phase

Degeneracy with
<u>even x even</u>
lattice sizes



Boundary frustration in the striated phase

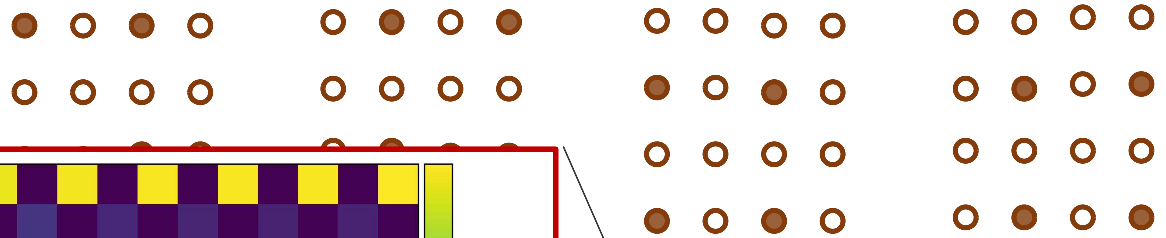
Degeneracy with
even x even
lattice sizes

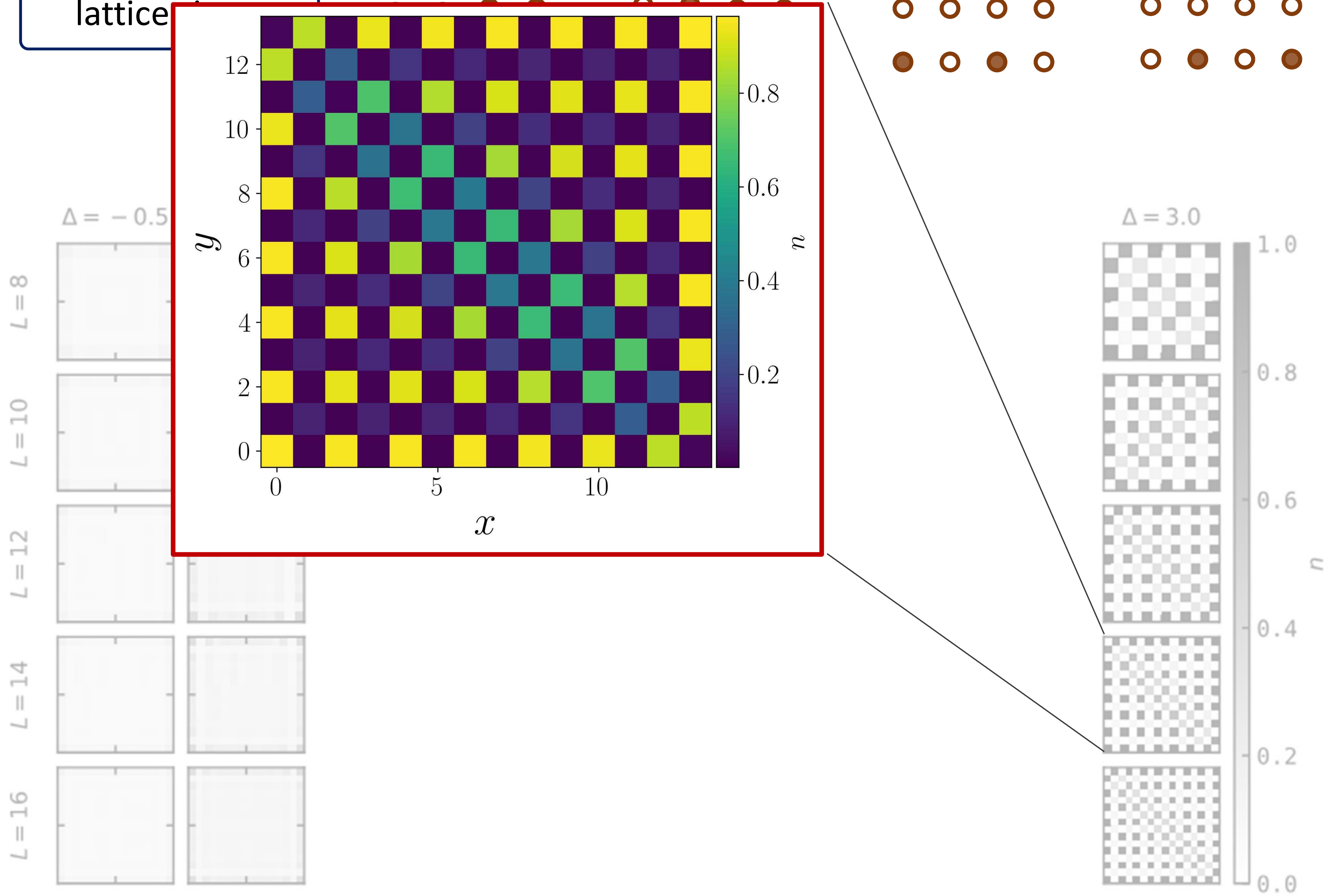


Ordered phase
Domains with
diagonal interface

Boundary frustration in the striated phase

Degeneracy with
<u>even x even</u>
lattice

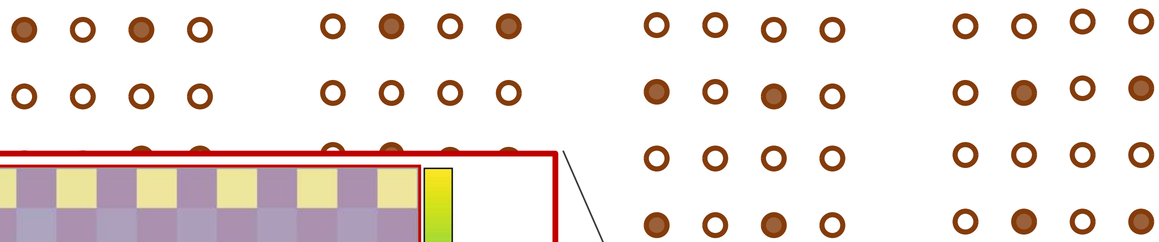


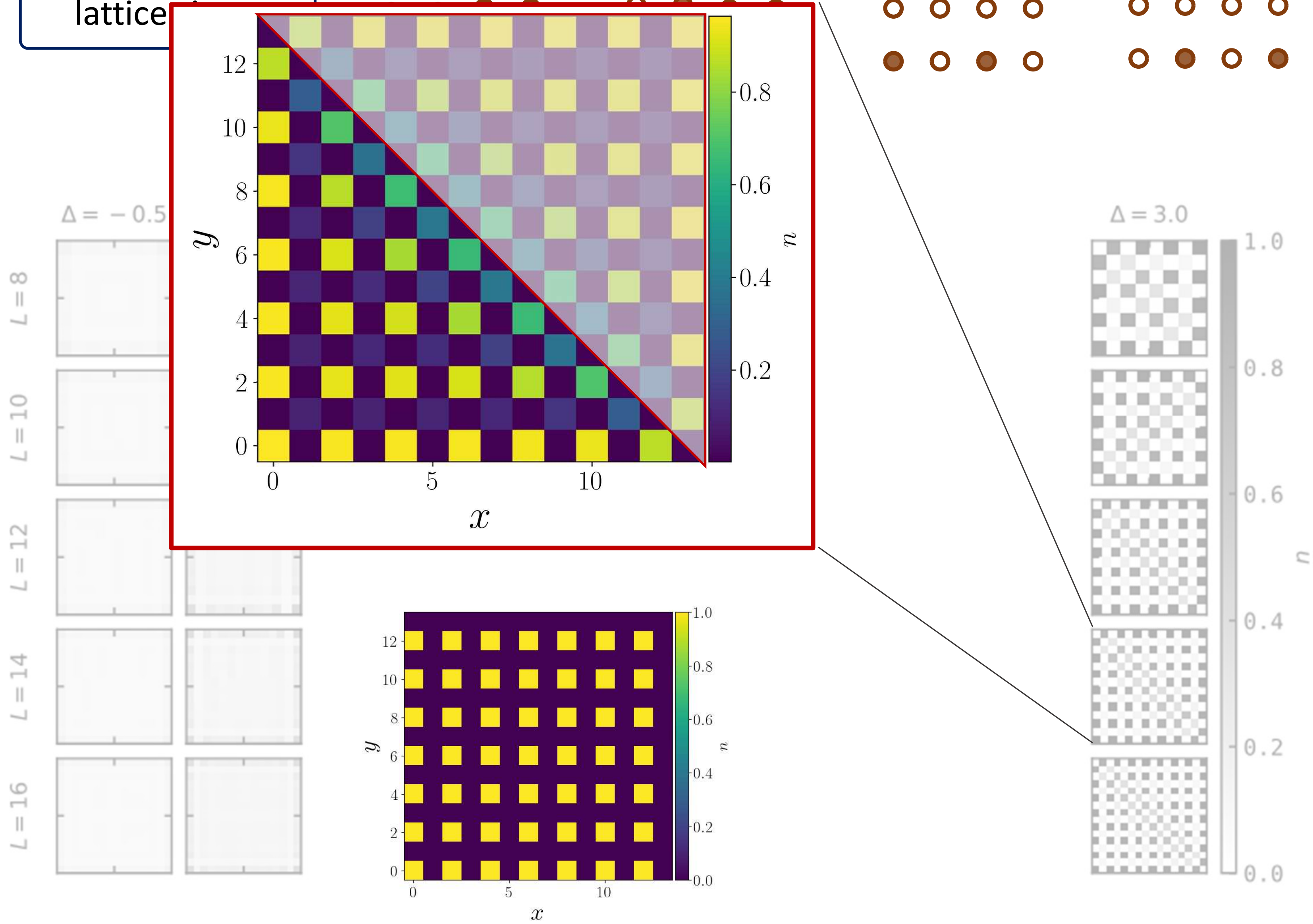


Ordered phase
Domains with
diagonal interface

Boundary frustration in the striated phase

Degeneracy with
<u>even x even</u>
lattice

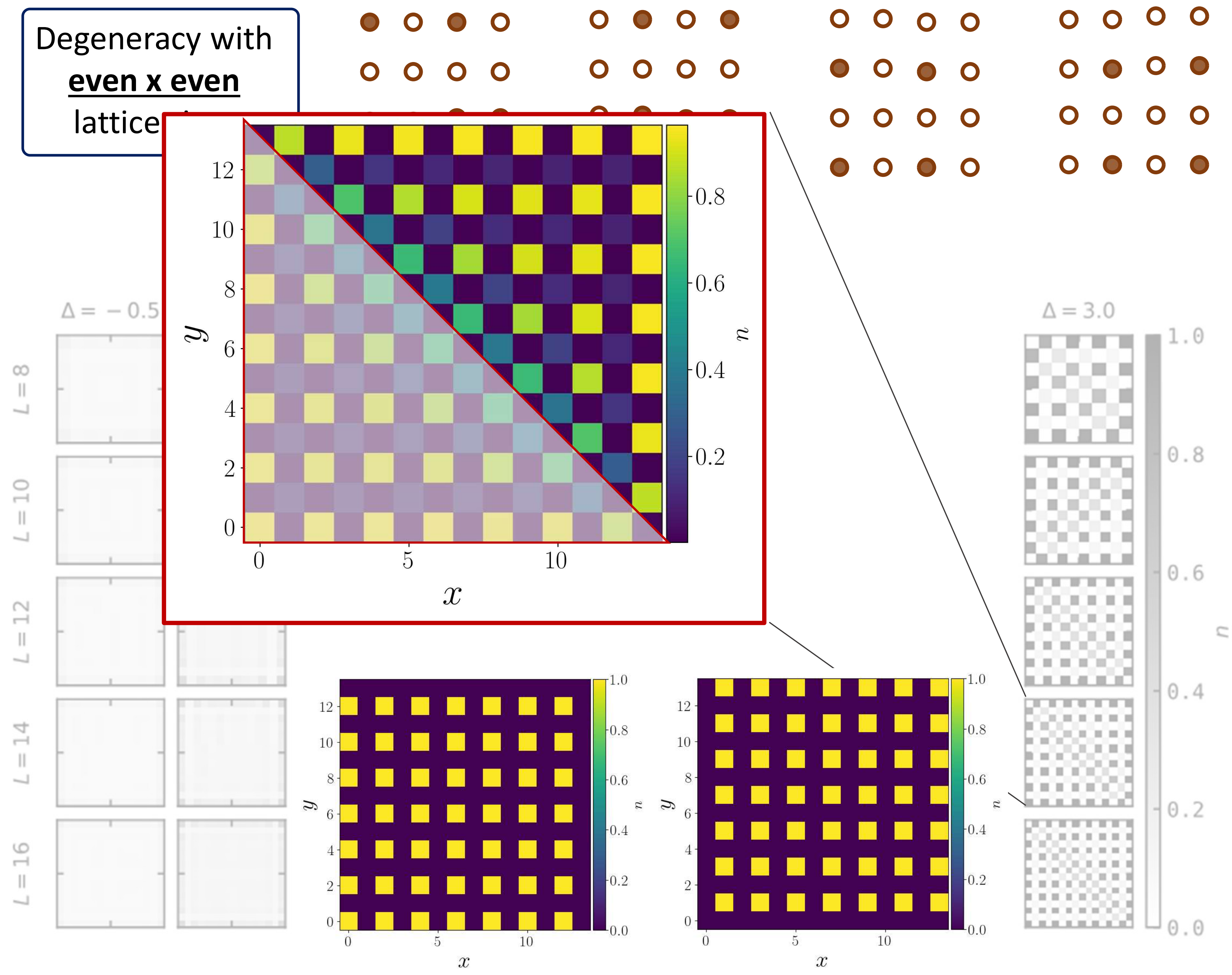




Ordered phase
Domains with
diagonal interface

Boundary frustration in the striated phase

Degeneracy with **even x even** lattice



Ordered phase
Domains with diagonal interface

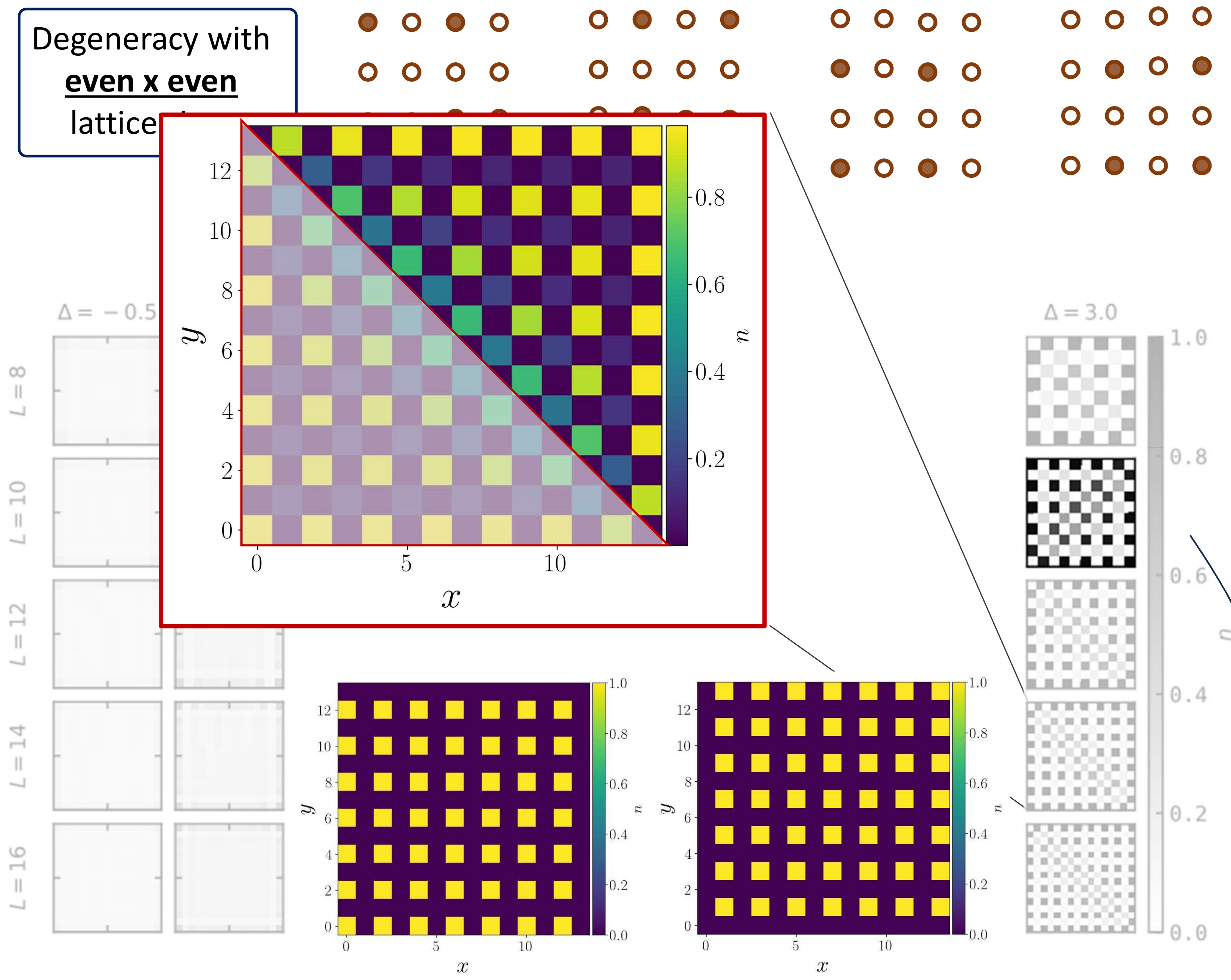
Competition between
- Boundary
- Interface

↓

Stable at large L

Boundary frustration in the striated phase

Degeneracy with
<u>even x even</u>
lattice

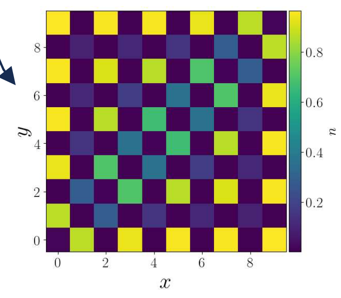


Ordered phase
Domains with
diagonal interface

Competition between
- Boundary
- Interface

↓

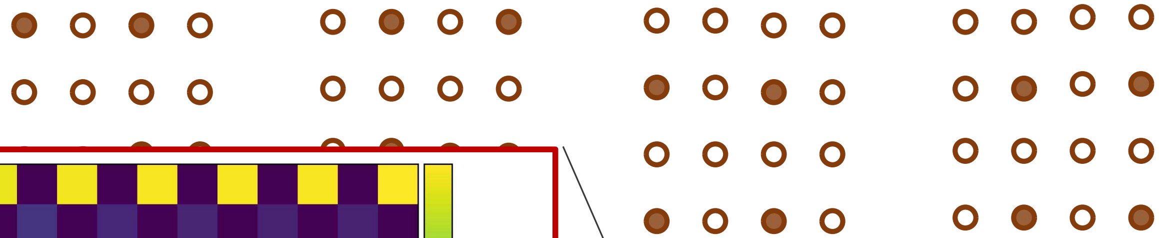
Stable at large L

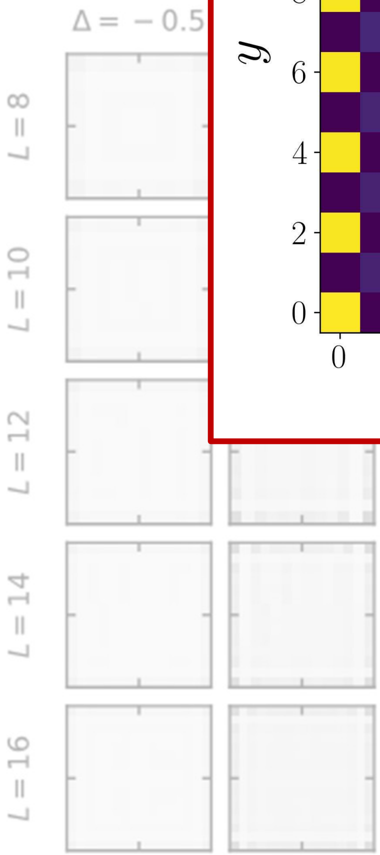


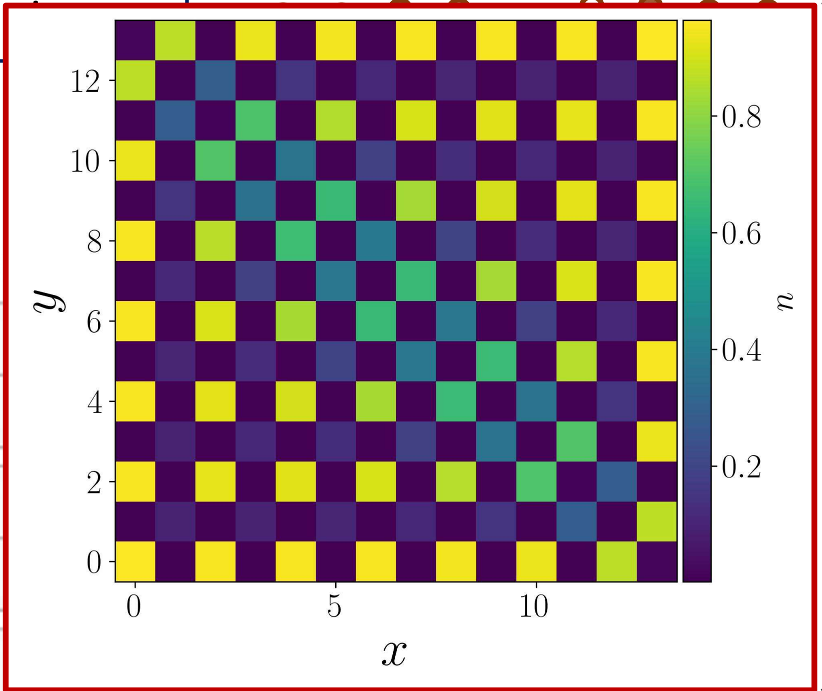
Double degenerate

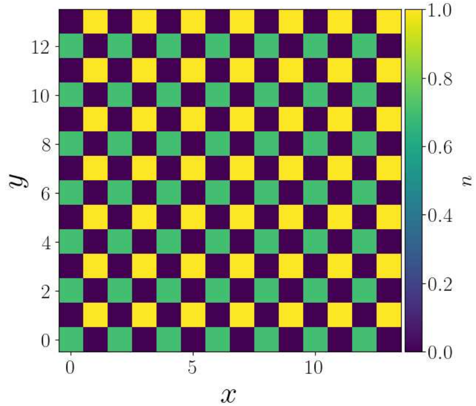
Boundary frustration in the striated phase

Degeneracy with **even x even** lattice

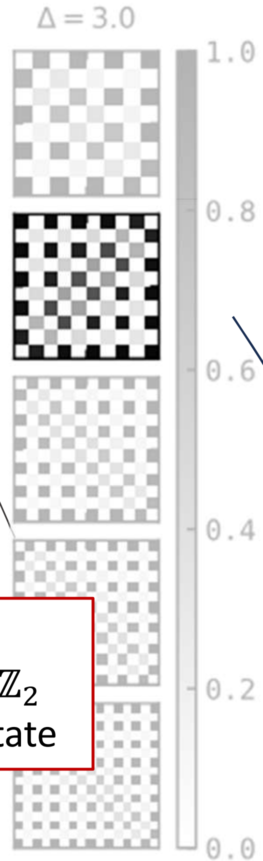








The two domains belong to the same $\mathbb{Z}_2$ antiferromagnetic state

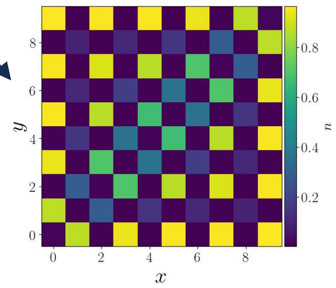


Ordered phase
Domains with diagonal interface

Competition between
- Boundary
- Interface

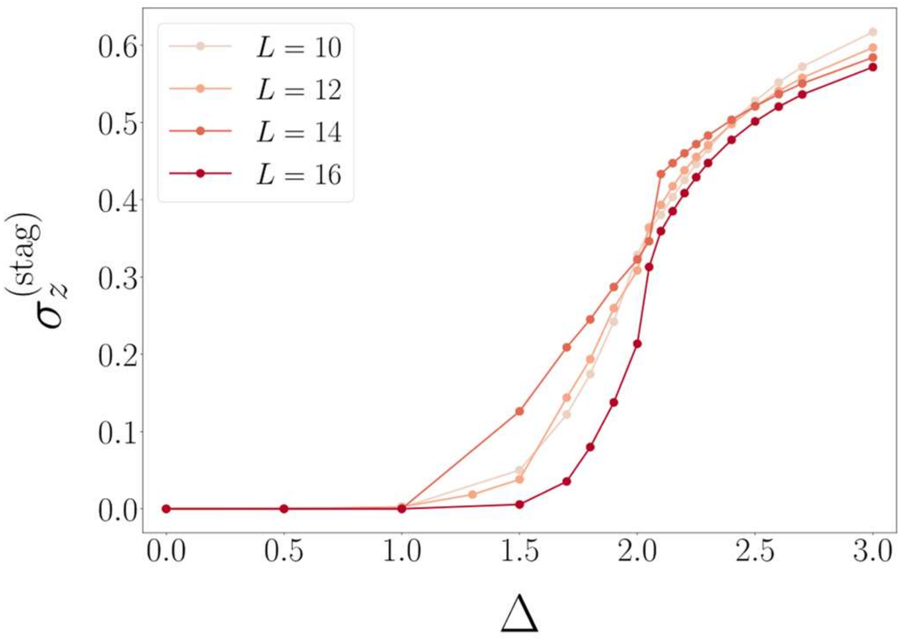
↓

Stable at large L

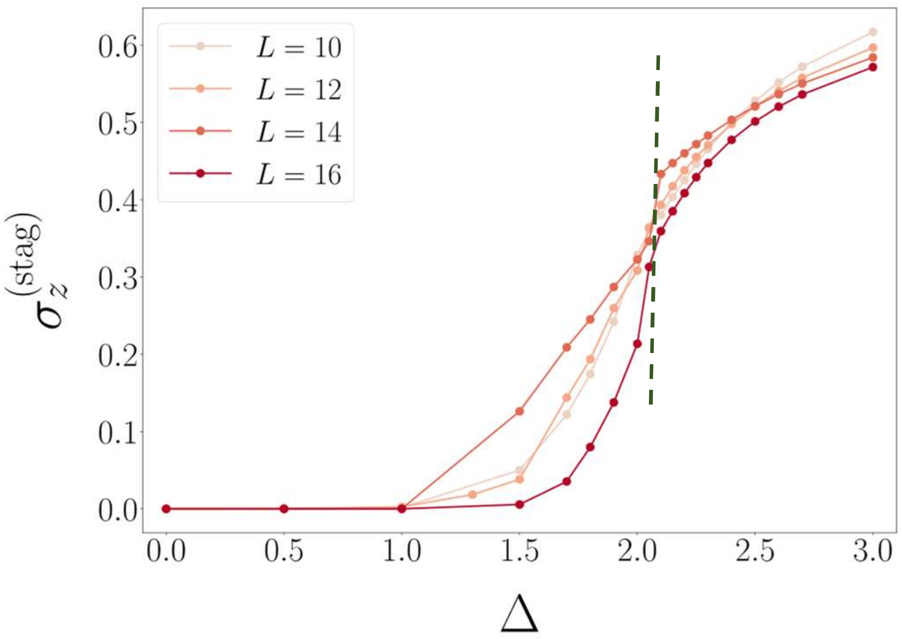


Double degenerate

Boundary frustration in the striated phase



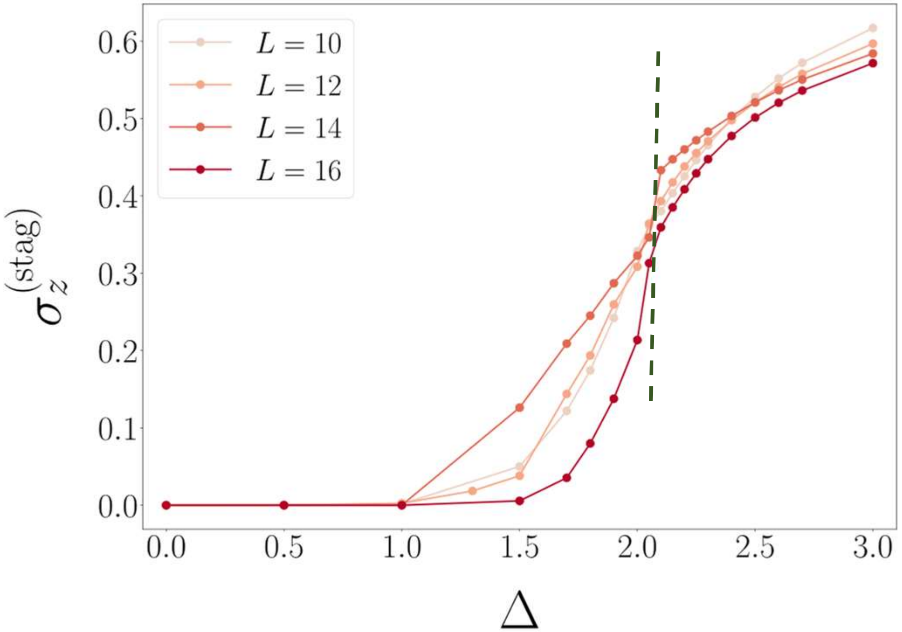
Boundary frustration in the striated phase



Even size:

- Discontinuous staggered magnetization
- Singlet formed by the two degenerate ground states

Boundary frustration in the striated phase



Even size:

- Discontinuous staggered magnetization
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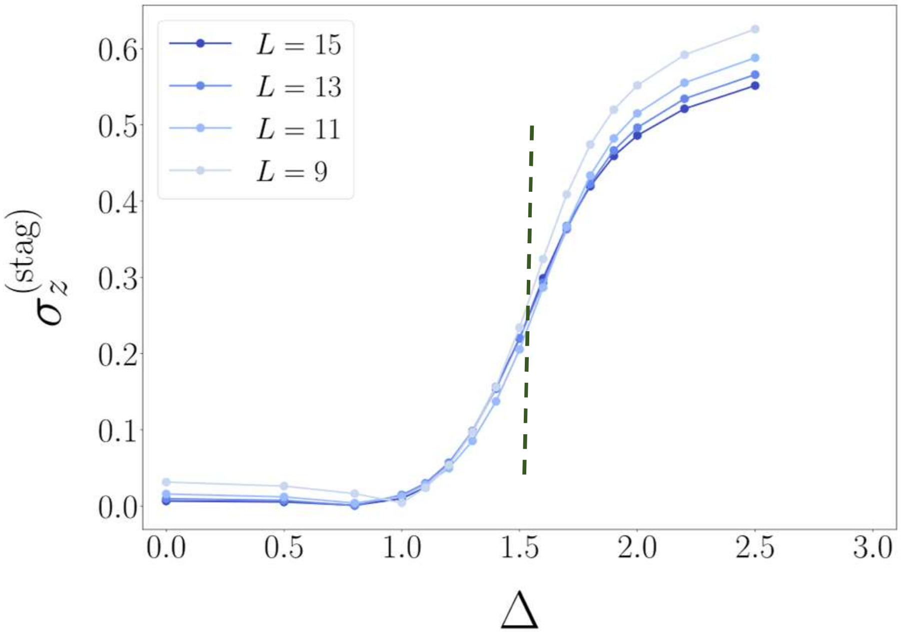
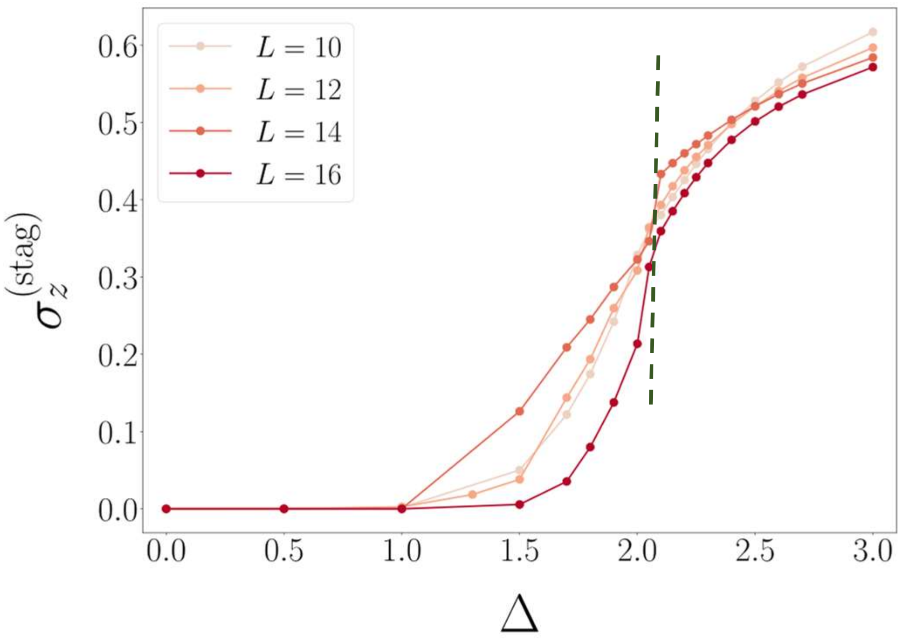


Odd size:

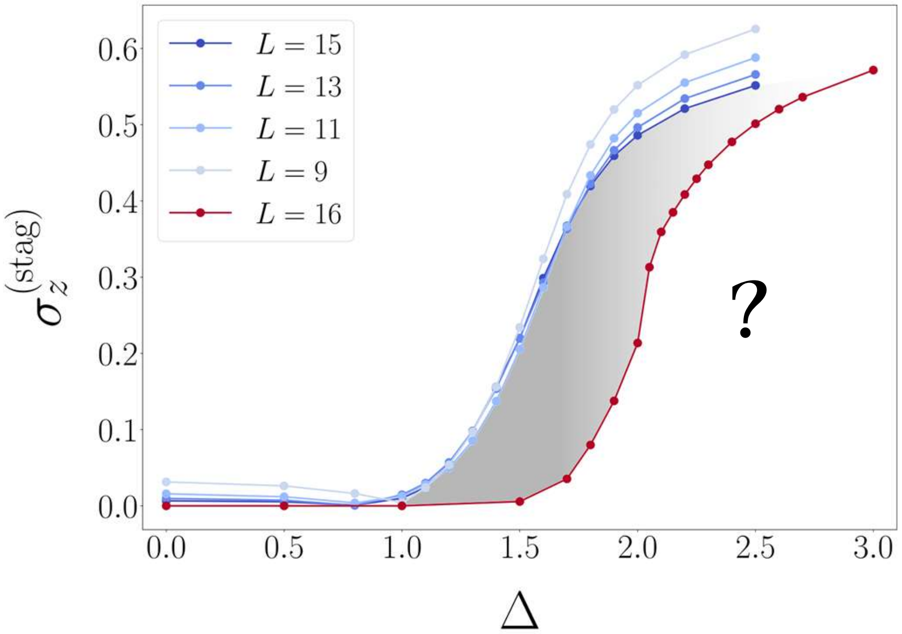
- Unique, ordered ground state

Boundary frustration in the striated phase



Even size:

- Discontinuous staggered magnetization
- Singlet formed by the two degenerate ground states



Odd size:

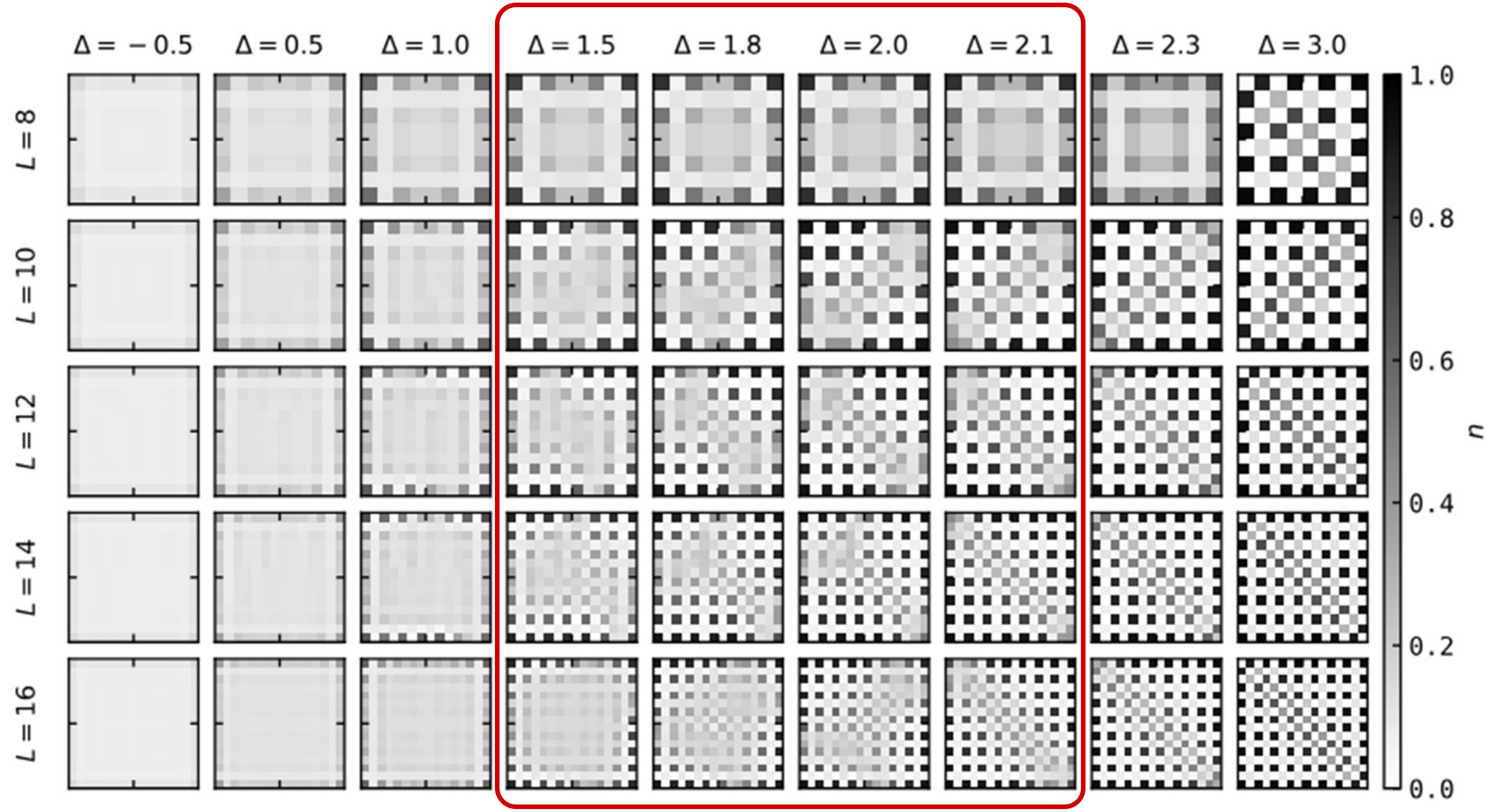
- Unique, ordered ground state

Boundary frustration in the striated phase

Degeneracy is not broken
anymore by the boundary

Disordered phase
Low density of excitations
No density-wave order

Ordered phase
Twofold degenerate state
Domains with diagonal interface



Competition between
- Boundary
- Interface

↓

Stable at large L

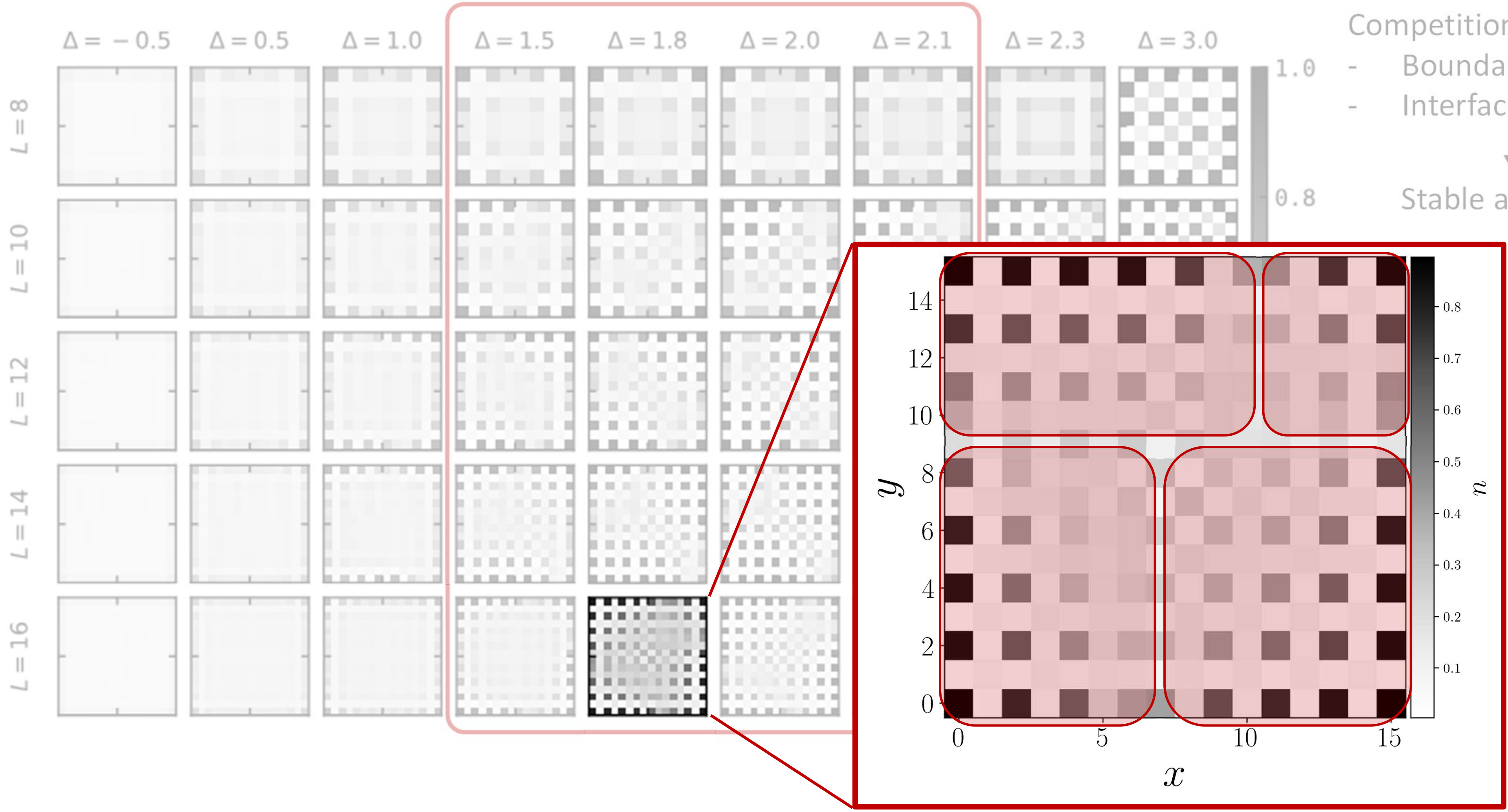
Boundary frustration in the striated phase

Degeneracy is not broken
anymore by the boundary

Disordered phase
Low density of excitations
No density-wave order

Intermediate regime
Competing domains
enucleated by the corners

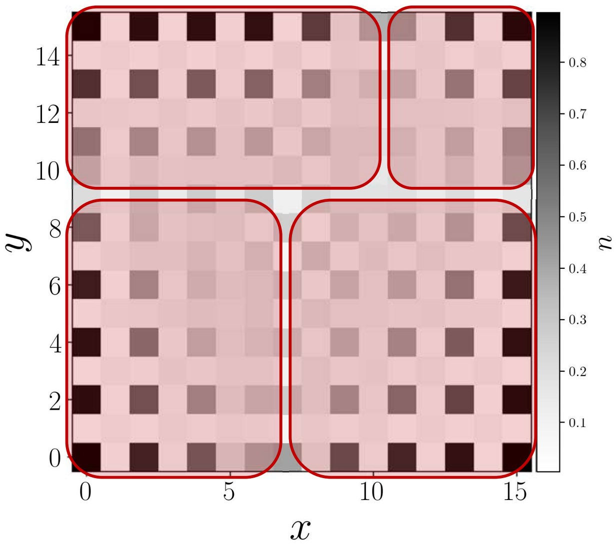
Ordered phase
Twofold degenerate state
Domains with diagonal interface

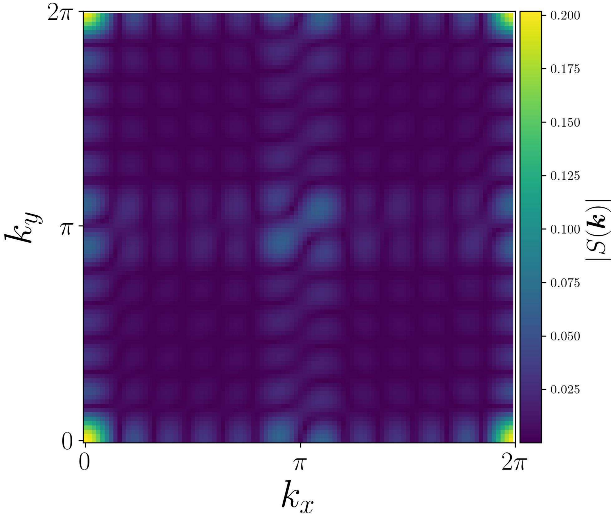


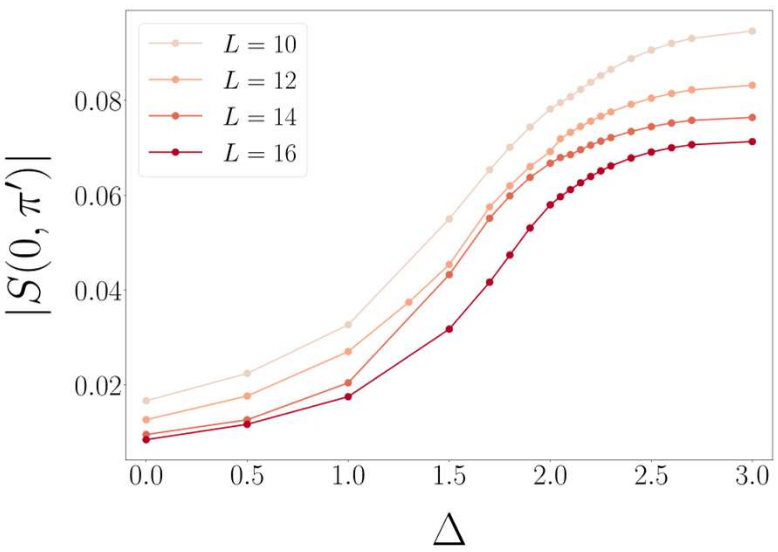
Competition between
- Boundary
- Interface

Stable at large L

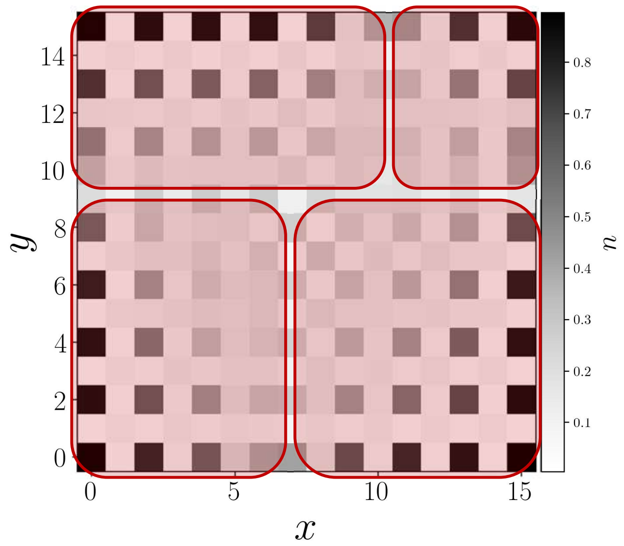
Boundary frustration in the striated phase

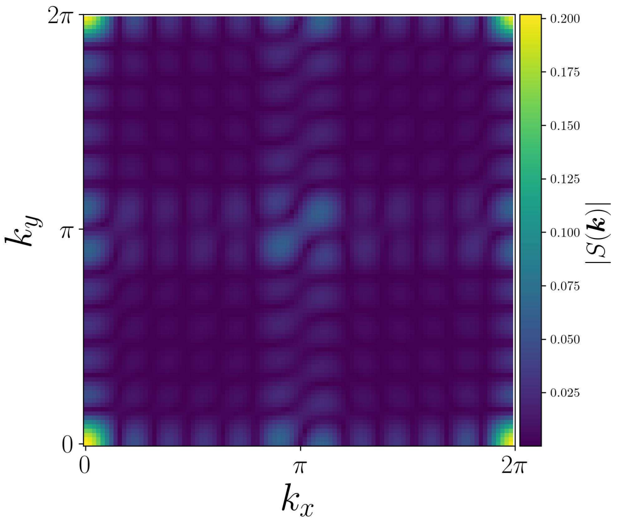


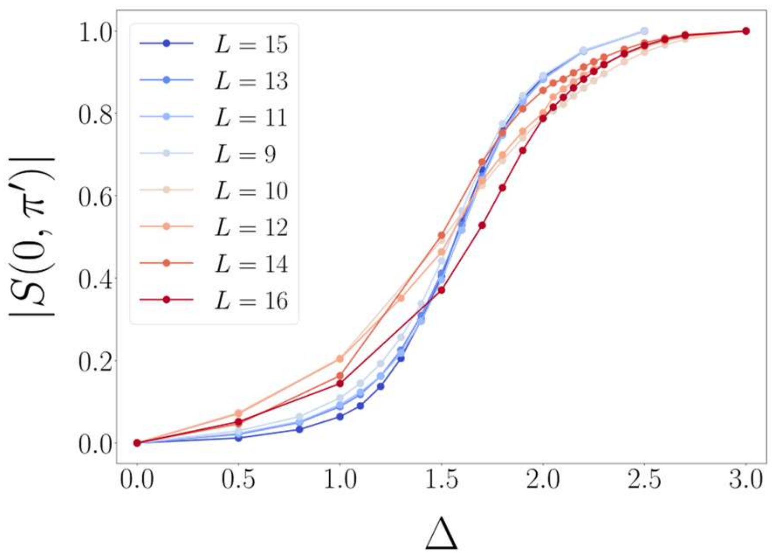




Boundary frustration in the striated phase

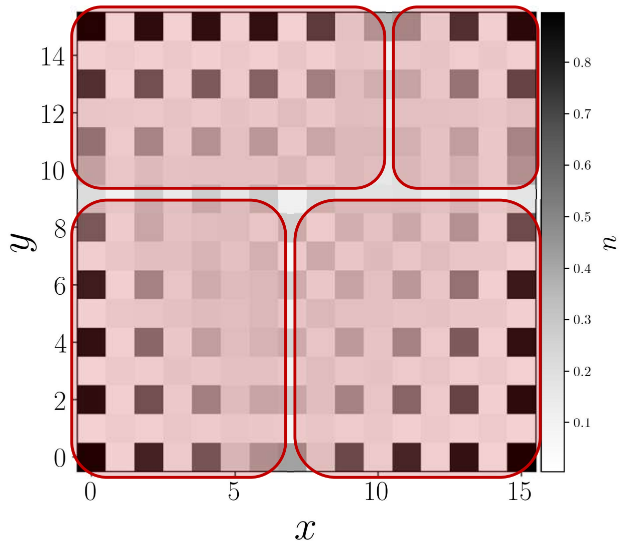


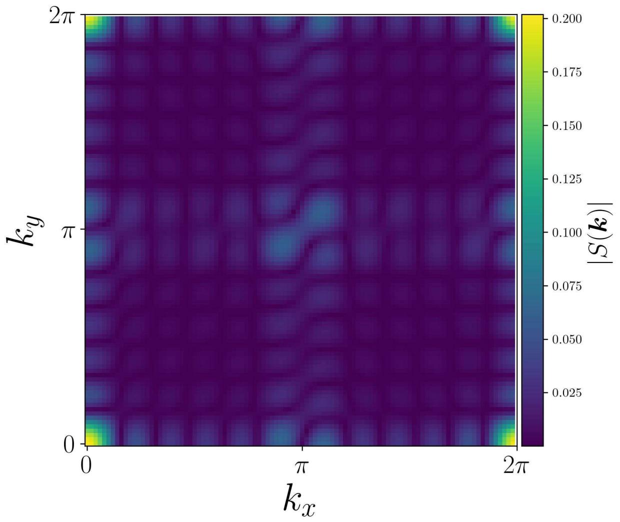


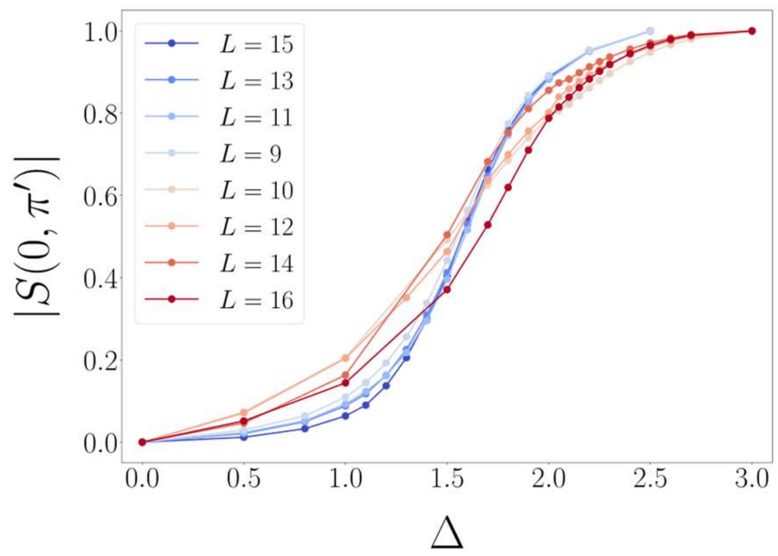


The striated order emerges around the same Δ in the even and odd case

Boundary frustration in the striated phase







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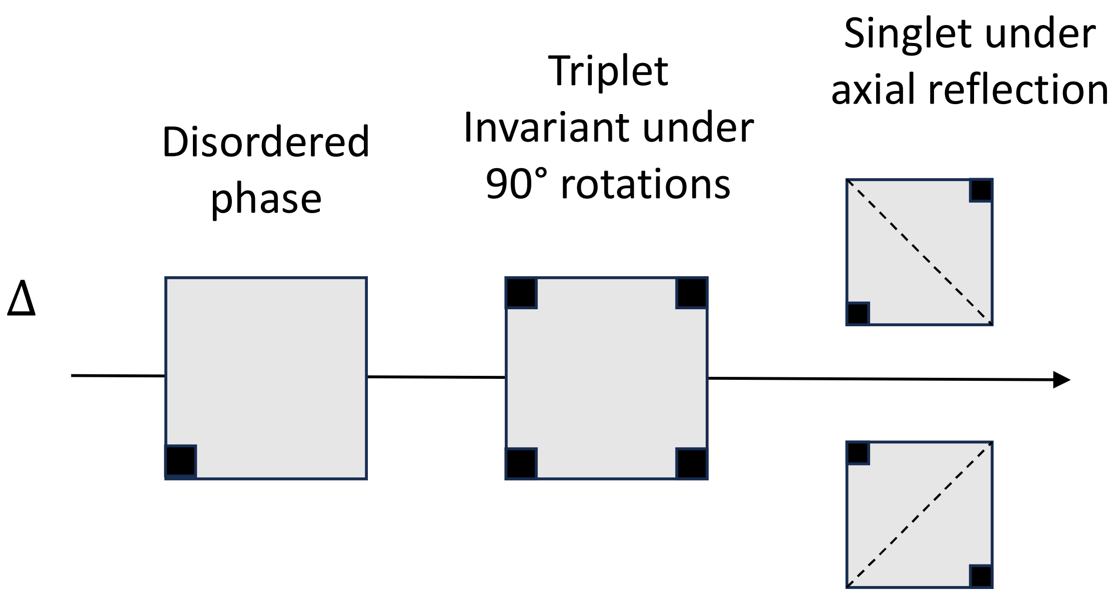
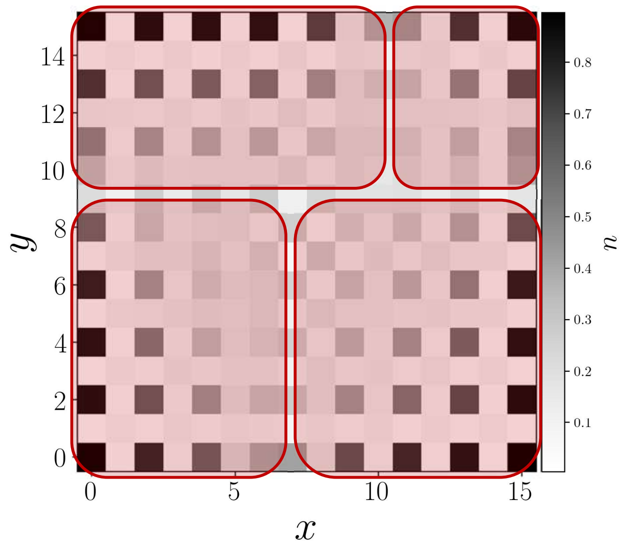
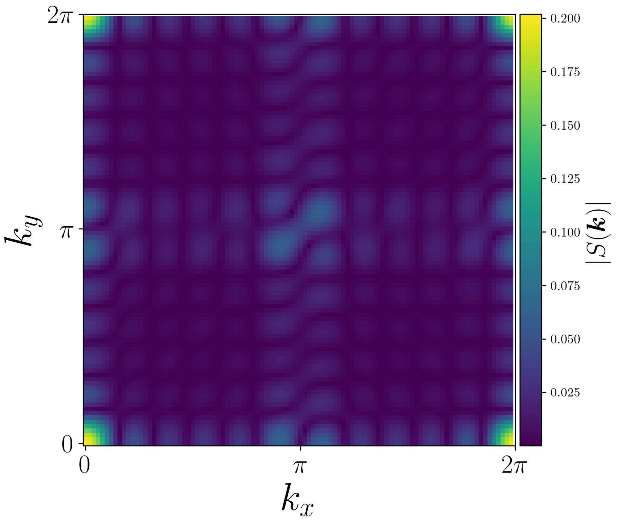
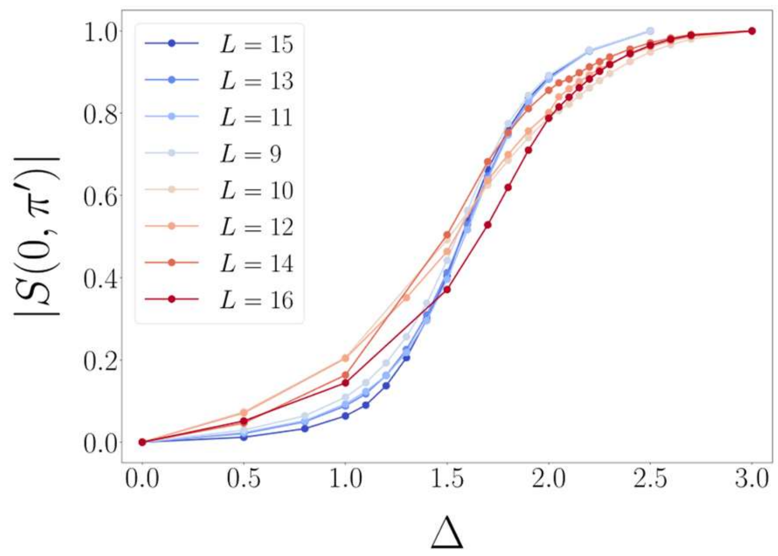


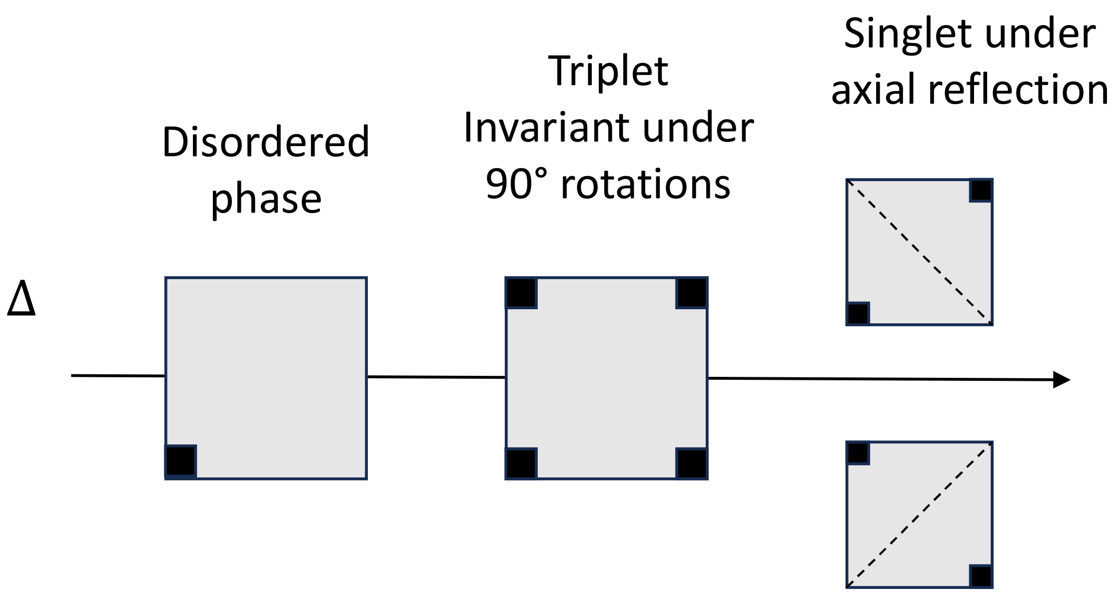
Boundary frustration in the striated phase



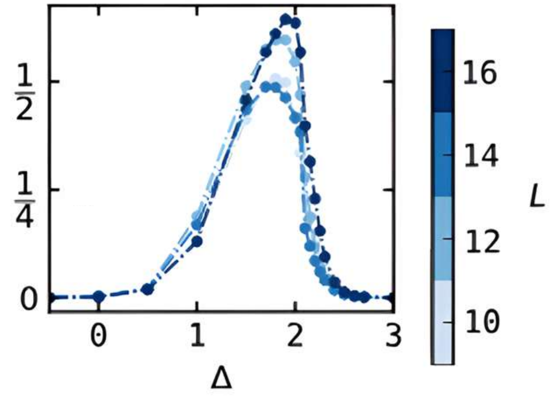




The striated order emerges around the same Δ in the even and odd case



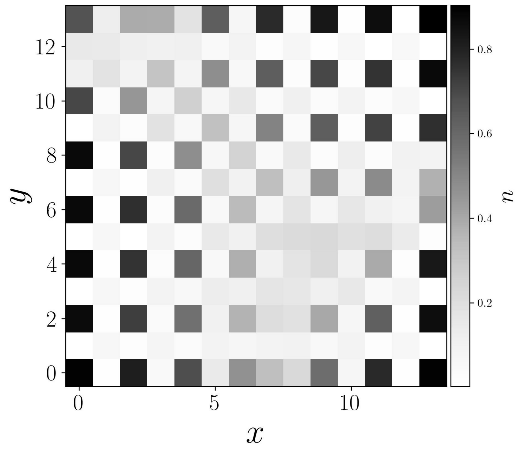
4-corners correlator



Boundary frustration in the striated phase

Ground state

$\Delta = 1.8$



Boundary frustration in the striated phase

Ground state

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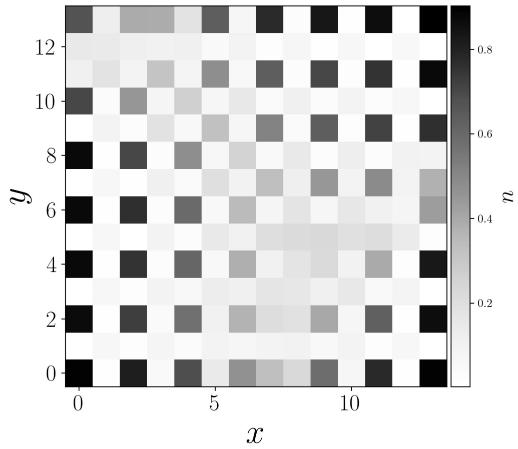
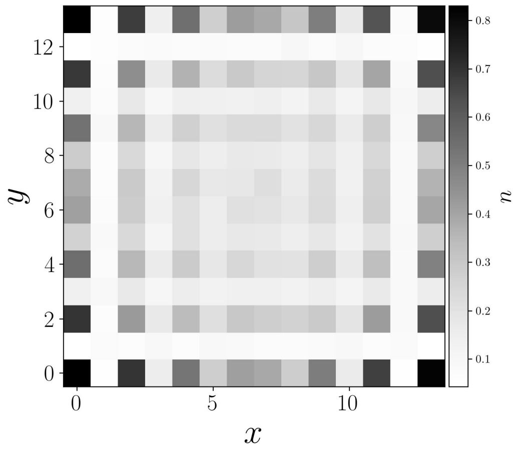


Experiment

$\Delta_{\mathrm{f}} = 1.8$



Boundary frustration in the striated phase

Ground state

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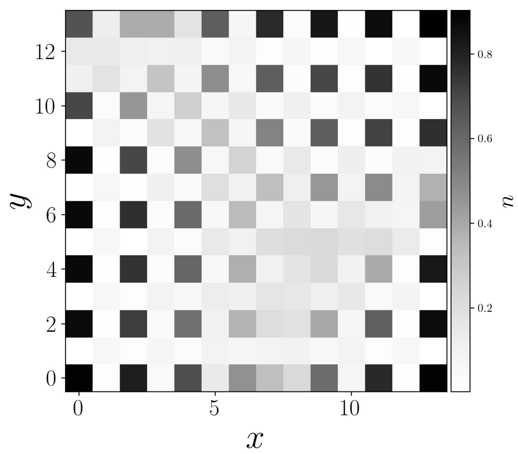
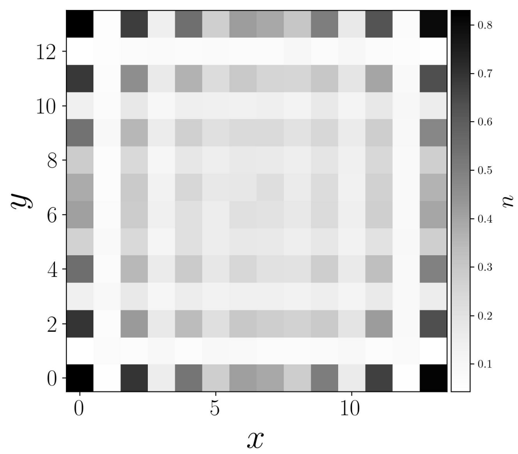


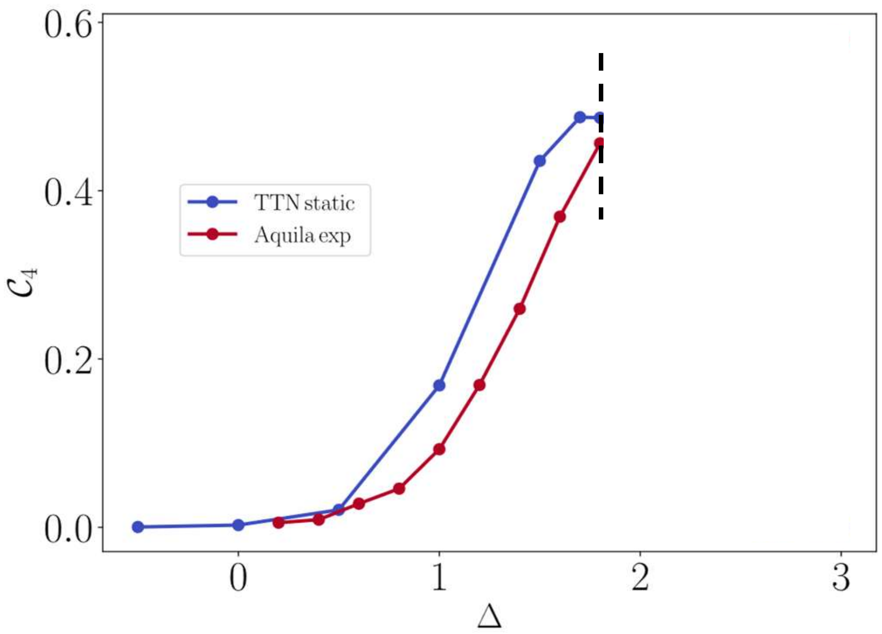
Experiment

$\Delta_f = 1.8$



Four corners correlator:

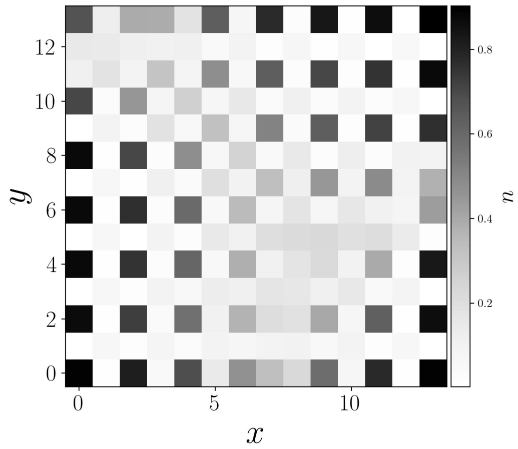
Qualitative agreement in the intermediate region



Boundary frustration in the striated phase

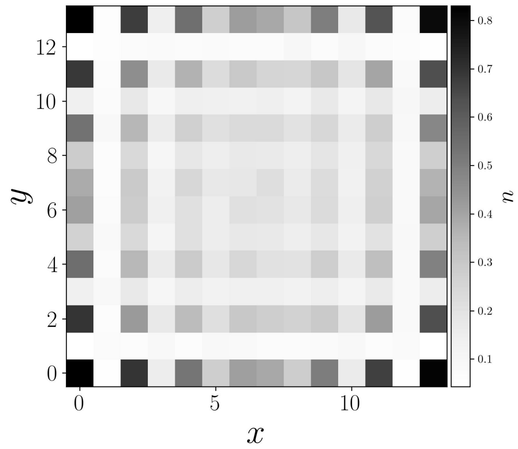
Ground state

$\Delta = 1.8$

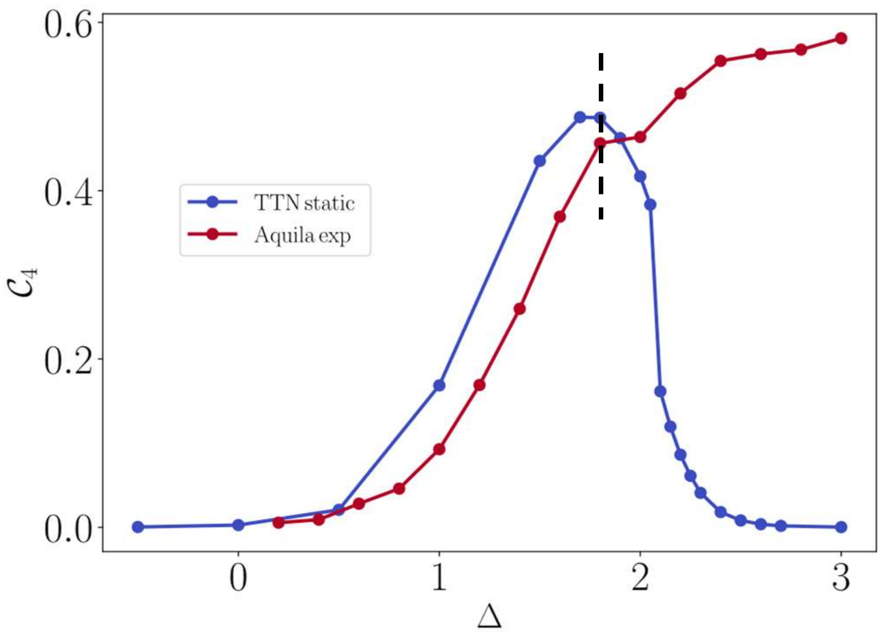


Experiment

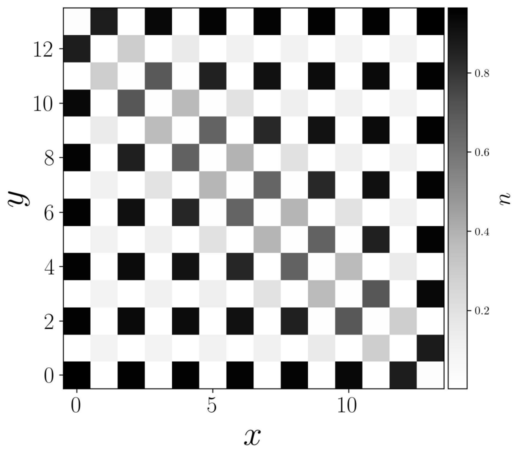
$\Delta_f = 1.8$



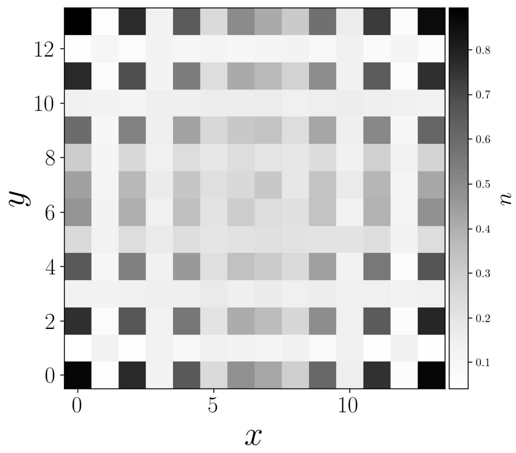
Four corners correlator:
Qualitative agreement in the intermediate region



$\Delta = 3.0$



$\Delta_f = 3.0$

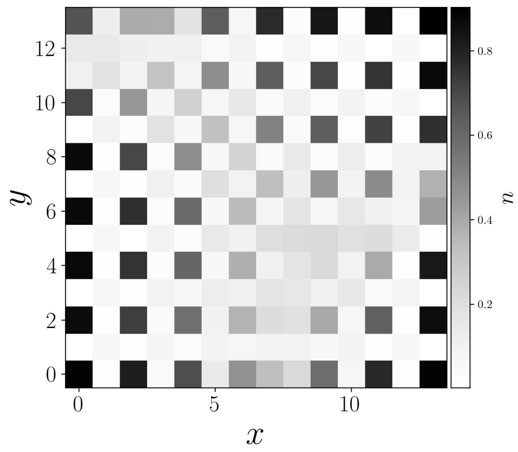


Disagreement in the singlet phase between numerical ground state and experiment!

Boundary frustration in the striated phase

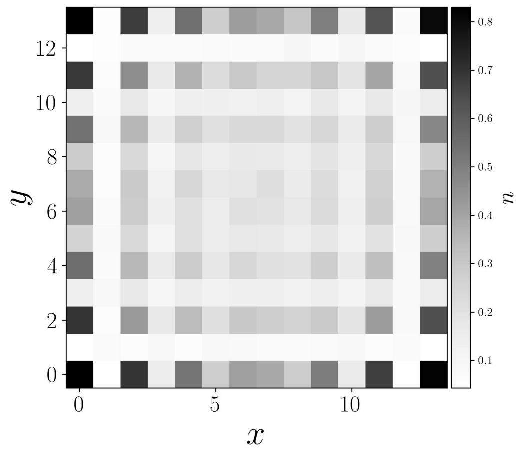
Ground state

$\Delta = 1.8$

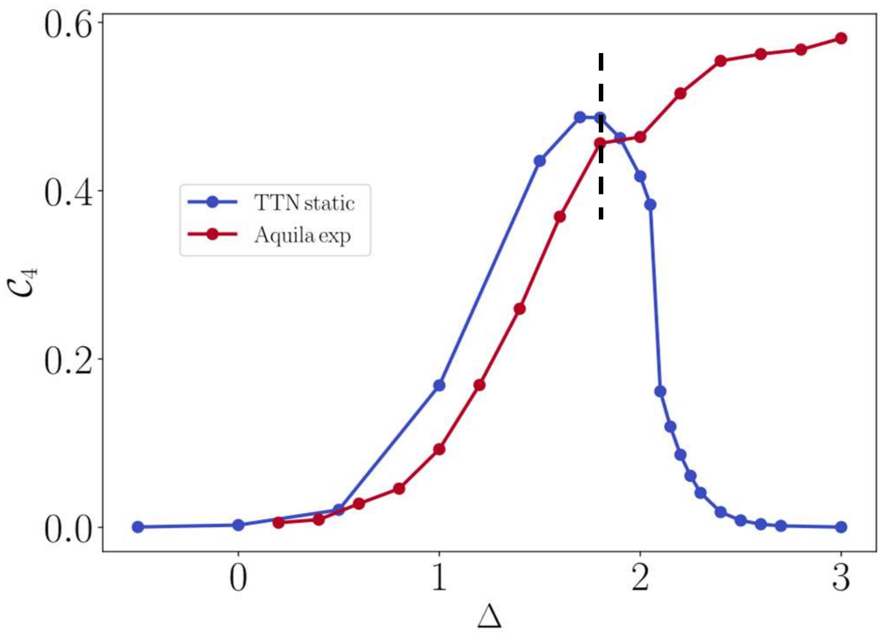


Experiment

$\Delta_f = 1.8$



Four corners correlator:
Qualitative agreement in the intermediate region



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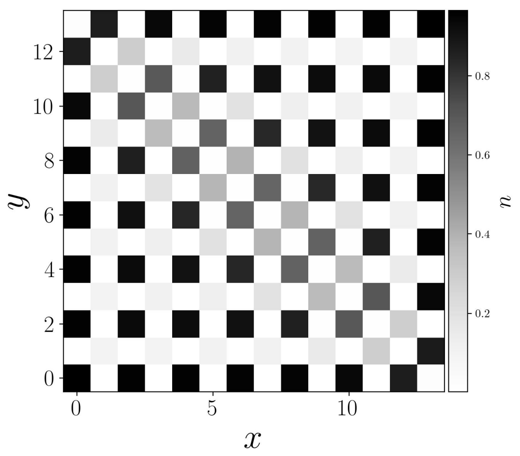
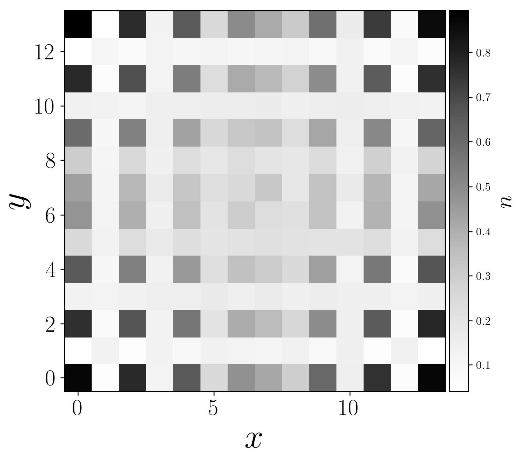
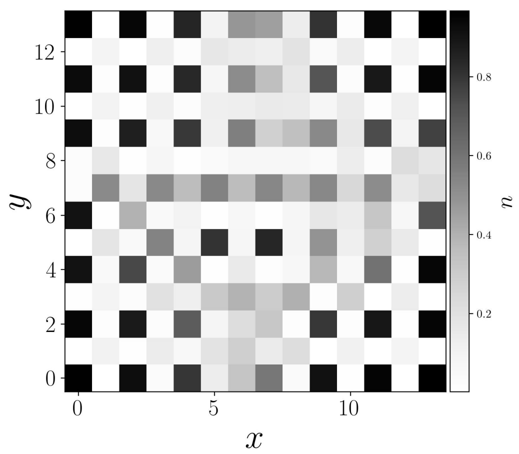


$\Delta_f = 3.0$



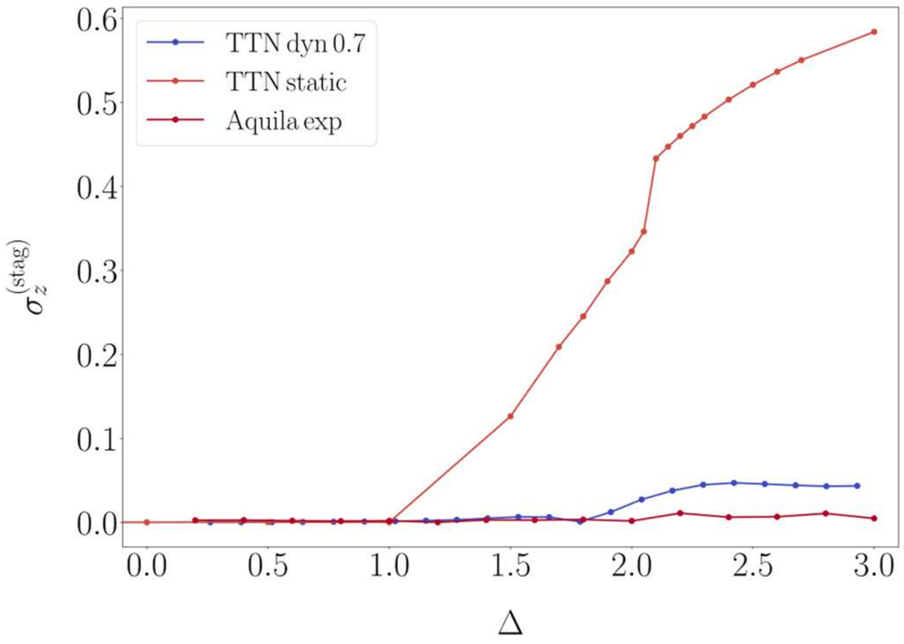
$\Delta_f = 3.0$



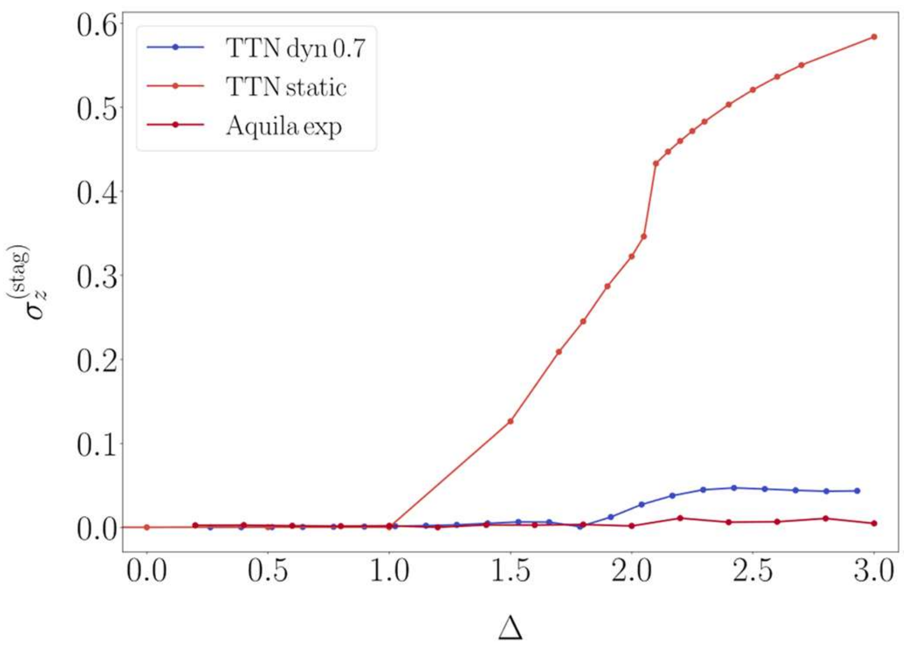
TTN dynamics

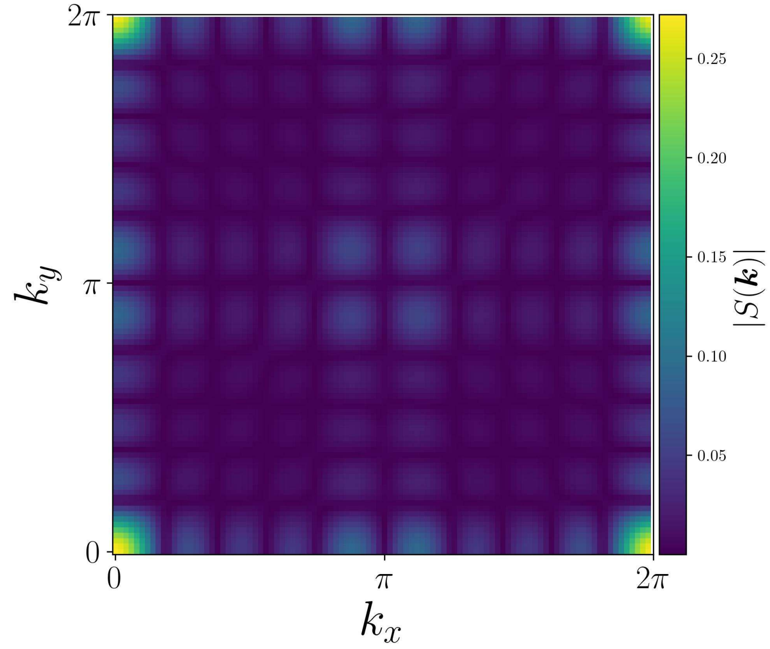
Agreement Numerical dynamics - Experiment

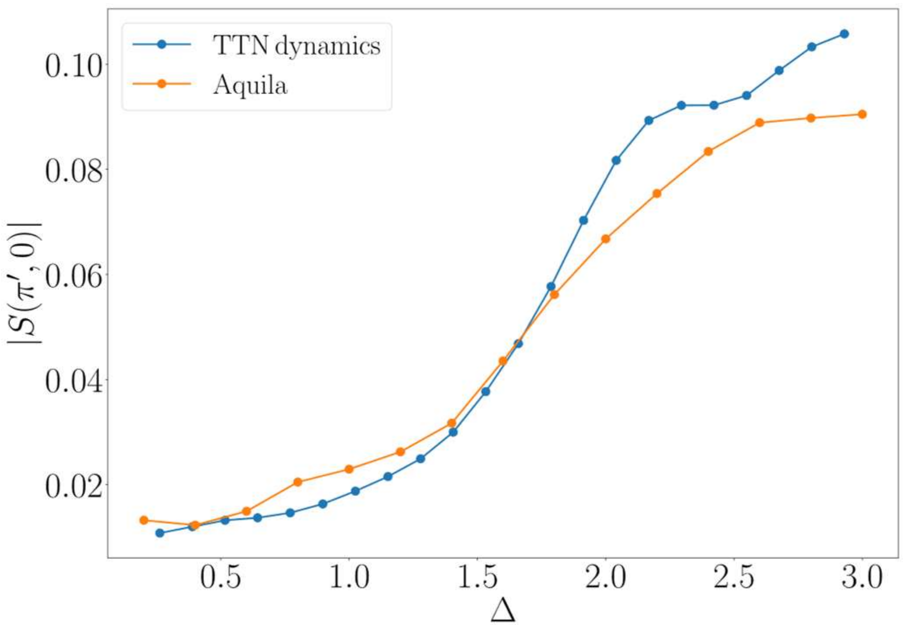
Boundary frustration in the striated phase



Boundary frustration in the striated phase







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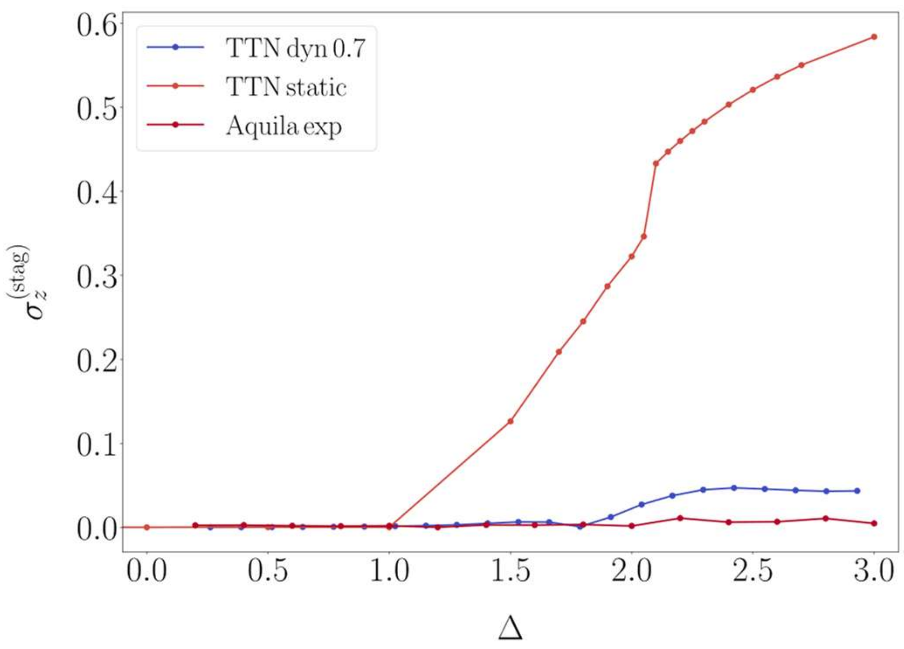
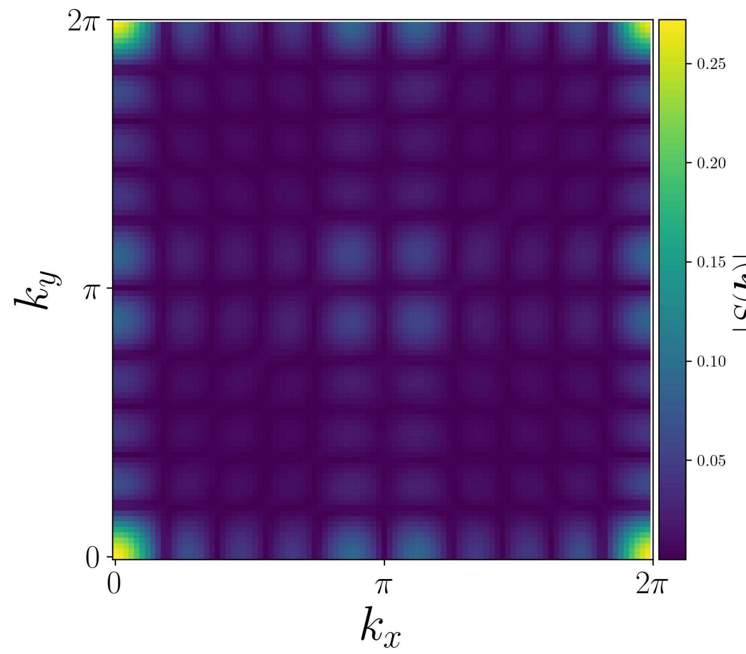
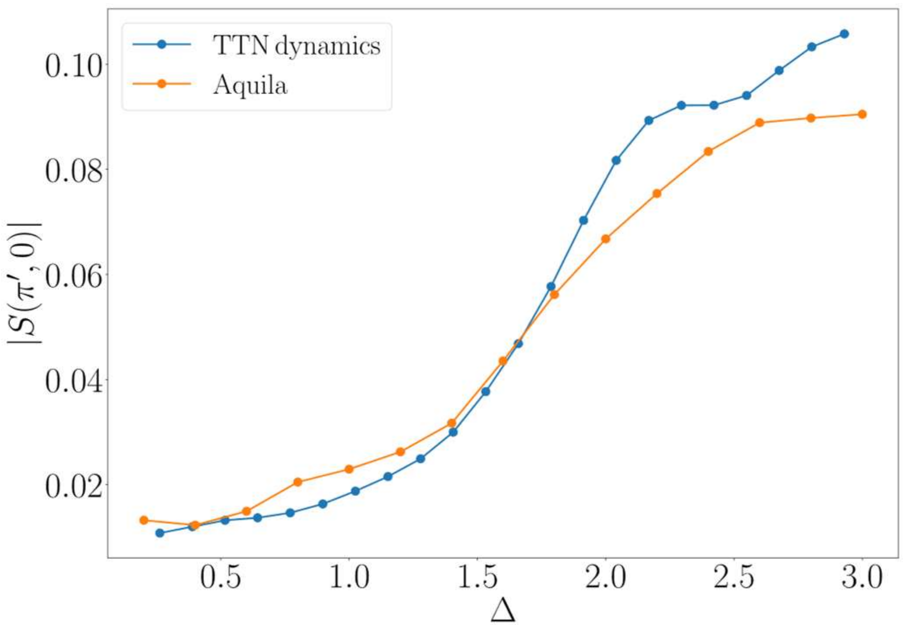




- Discontinuity in the staggered magnetization



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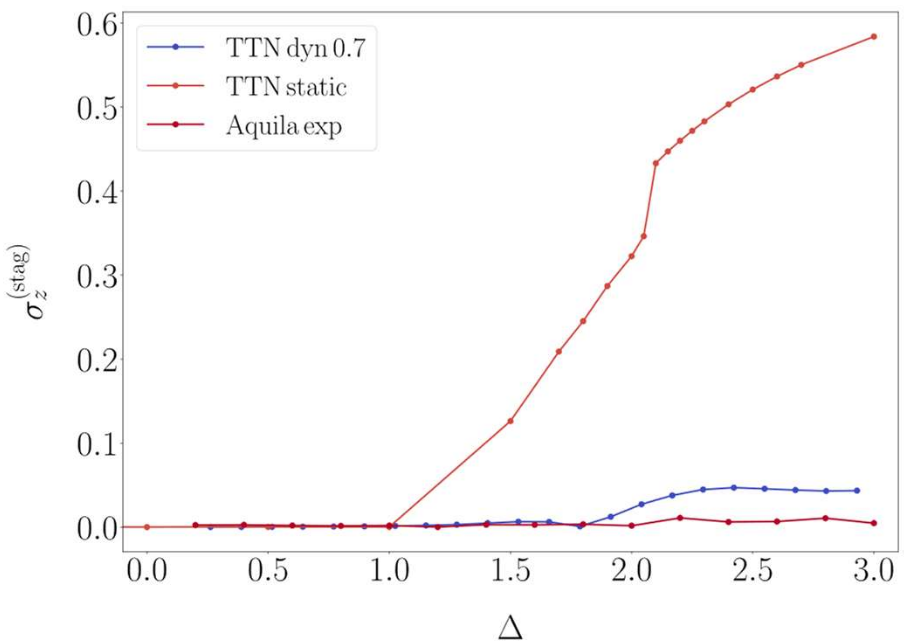
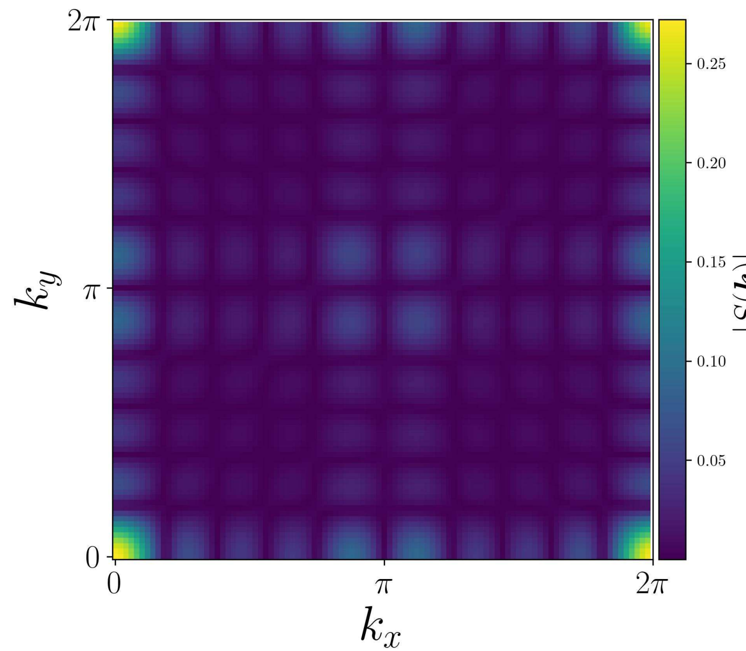
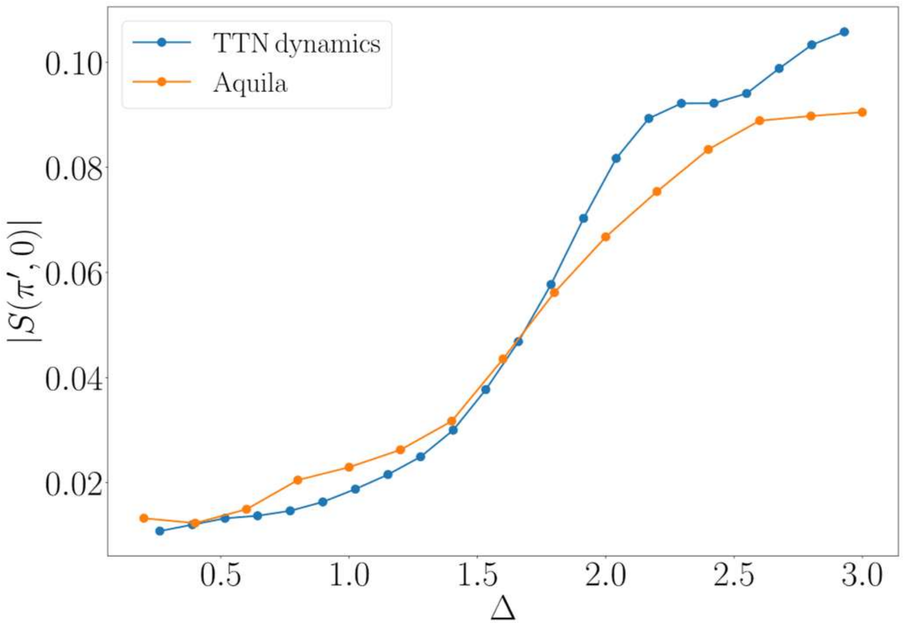
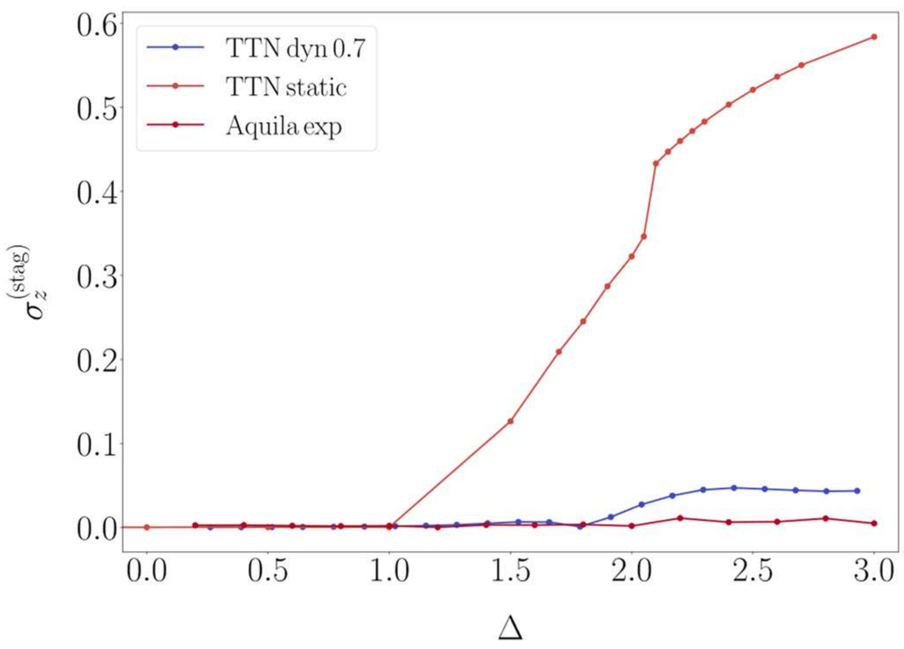


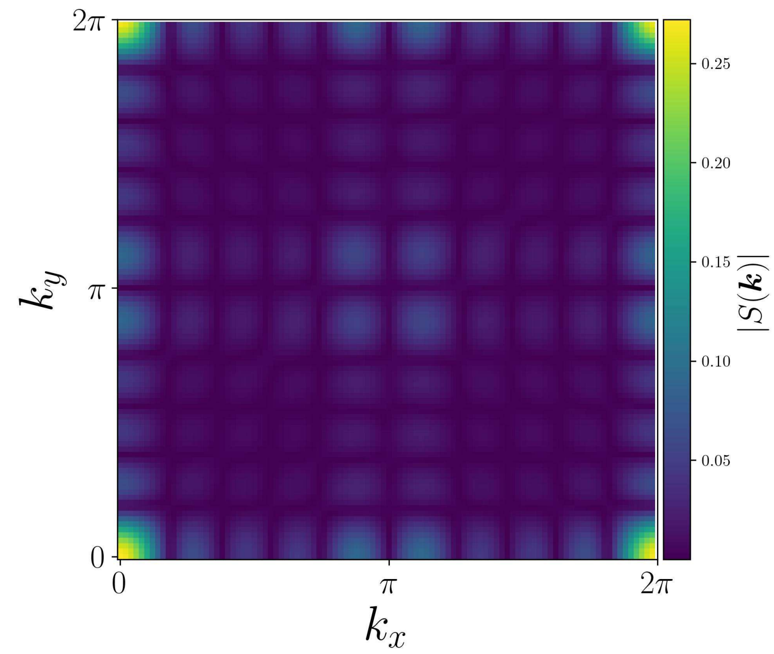


- Discontinuity in the staggered magnetization
- Transition between the singlet and the triplet striated ground state

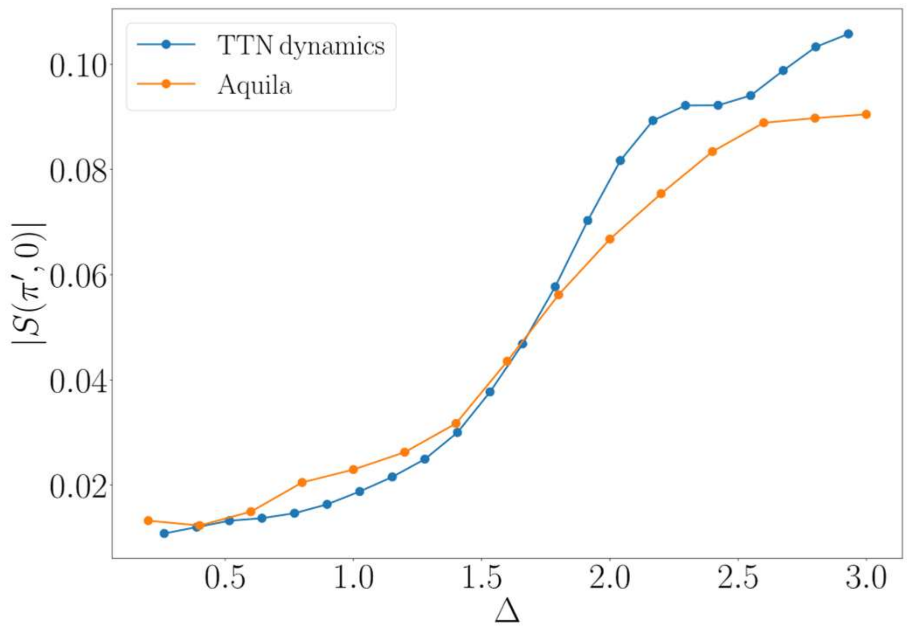


Boundary frustration in the striated phase

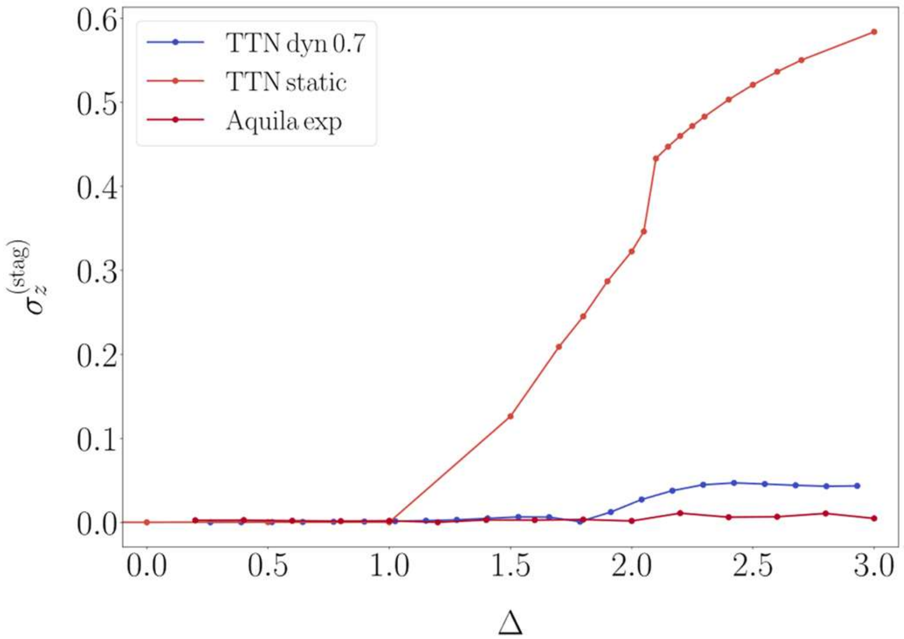


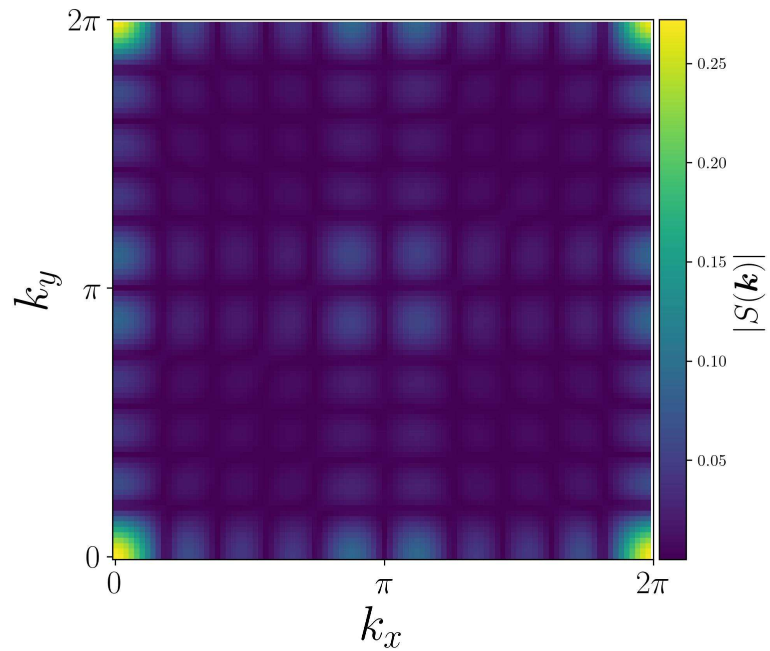


- Discontinuity in the staggered magnetization
- Transition between the singlet and the triplet striated ground state
- Avoided level crossing, exponentially small gap

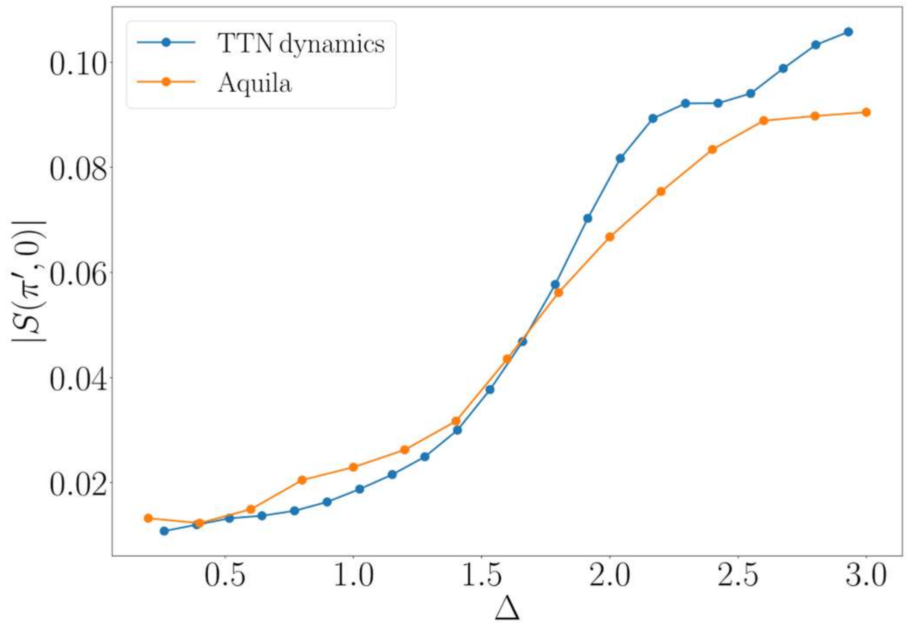


Boundary frustration in the striated phase





- Discontinuity in the staggered magnetization
- Transition between the singlet and the triplet striated ground state
- Avoided level crossing, exponentially small gap
- The time scale to prepare the ordered ground state is not experimentally accessible



Conclusions

- Relevance of quantum simulators to observe quantum many body physics not accessible numerically

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Conclusions

preliminary

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- Boundary frustration changes the nature of the transitions

Conclusions

preliminary

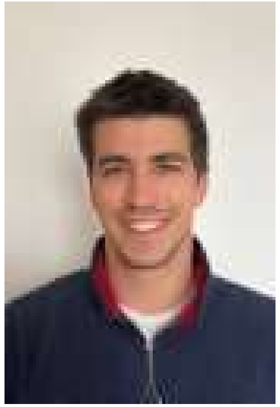
- Relevance of quantum simulators to observe quantum many body physics not accessible numerically

- Two-dimensional square Rydberg lattice as a rich quantum simulation platform

- Boundary frustration changes the nature of the transitions

- Interplay between experiment and numerical simulations

Marco Rigobello



Luka Pavesic

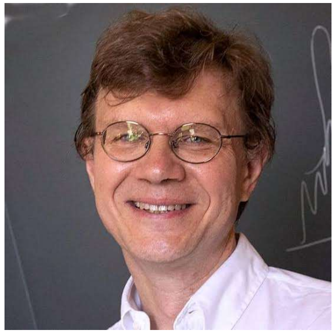
Pietro Silvi

Simone Montangero

Thank you for your attention

Daniel Jaschke

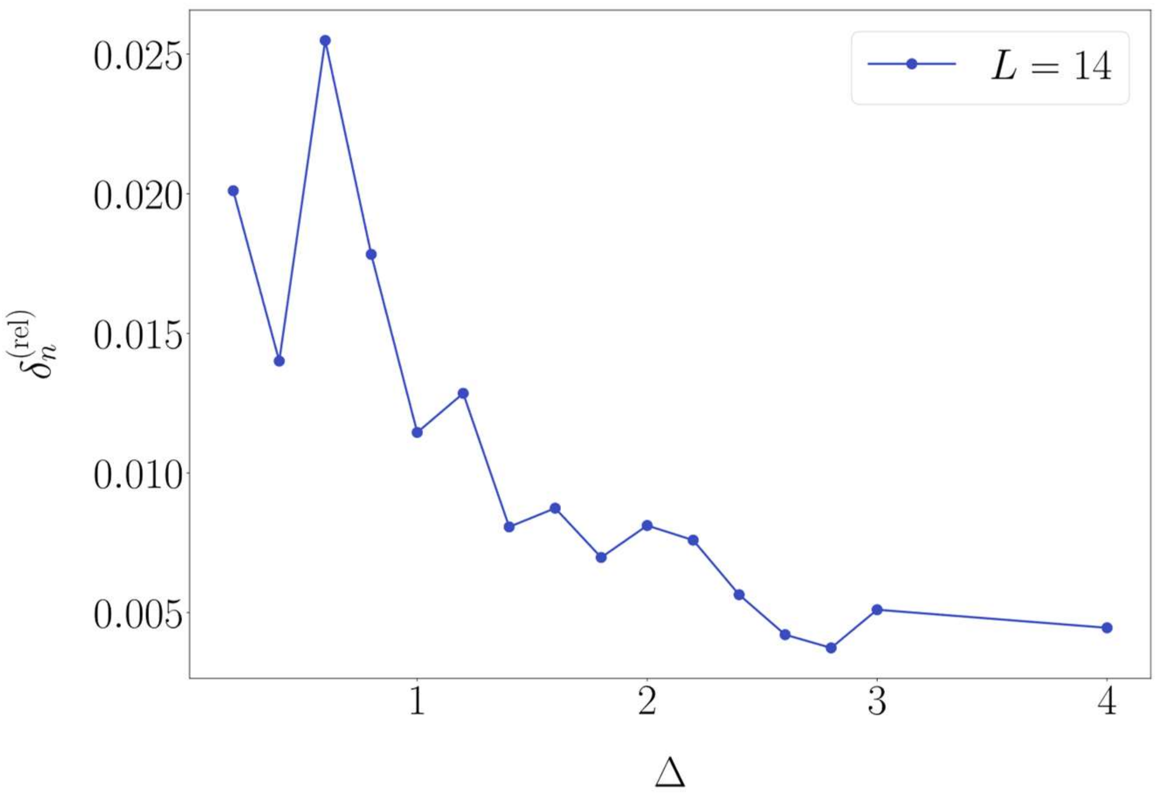
Marco Di Liberto

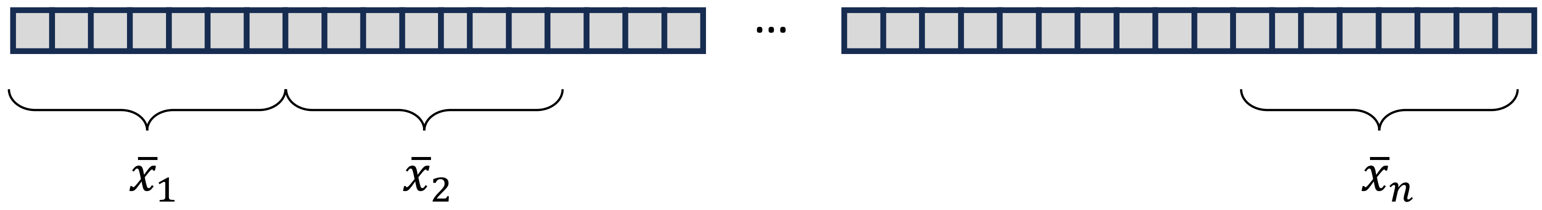


M. Lukin

Quantum TEA

Striated phase – experimental results



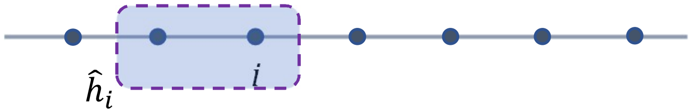


$$\delta_n^{(rel)} = \frac{\sqrt{\mathrm{var}[\{\bar{x}_i\}]}}{\bar{n}}$$

Tensor Network methods

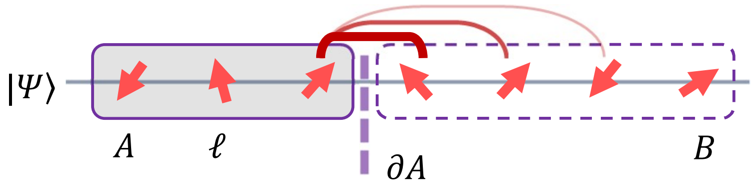
Area laws of entanglement

1-D local Hamiltonian $\hat{H} = \sum_i \hat{h}_i$

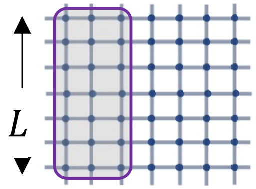


Local correlations

(exponential decaying)



TN in 2-D

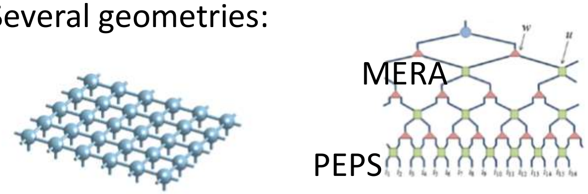


For a 2-D system
$\partial A \sim L \rightarrow S \sim \exp(L)$

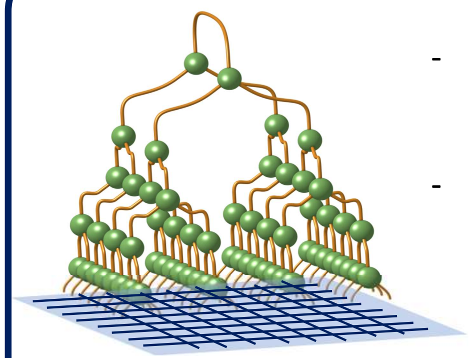
Needed compromise between:

- Computational complexity
- Accuracy

Several geometries:

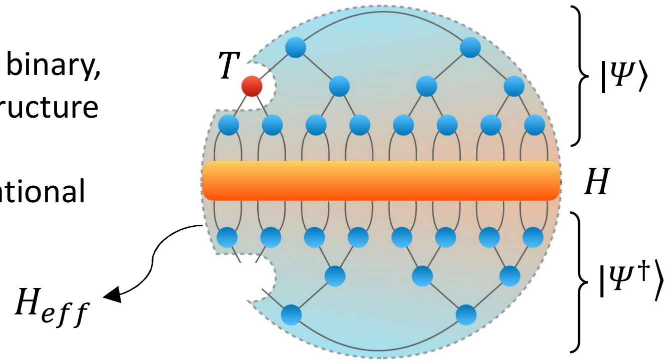


TTN algorithm



physical lattice

- Tree-tensor network: binary, hierarchical tensor structure
- Competitive computational complexity



PhD Thesis, T. Felser

Sequential tensor manipulation

- Ground state:

$\min\{T^\dagger H_{eff} T\}$

- Dynamics:

$T_{t+dt} \simeq \left[e^{-idt\, H_{eff}\left(t+\frac{dt}{2}\right)}\right]_{Kryl} T_t$

Rydberg atom arrays – phase diagram

Physical Review B
105, 174417 (2022)