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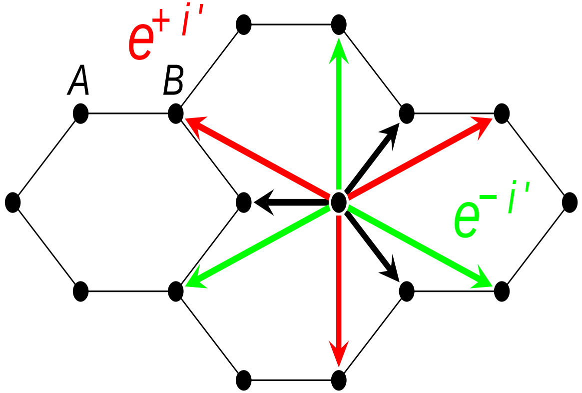
Nonlinear transport of Rydberg excitations:
From topological lattice models to emerging gauge fields

Michael Fleischhauer

Simon Ohler, Maximilian Kiefer-Emmanoulidis



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Spin models using Rydbergs

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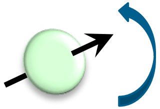
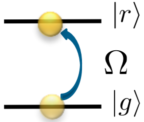
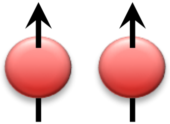
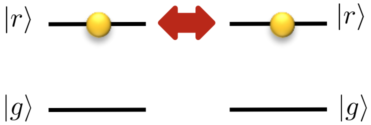
- Spin rotation $\Omega\,\hat{\sigma}_j^x$



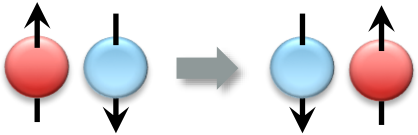


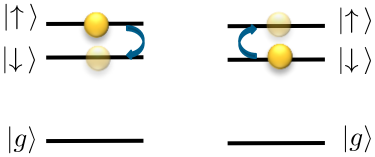
- Ising interaction $\frac{C_6}{r^6}\,\hat{\sigma}_i^z\hat{\sigma}_j^z$





- XY interaction $\frac{C_6}{r^6}\left(\hat{\sigma}_i^+\hat{\sigma}_j^- + \hat{\sigma}_i^-\hat{\sigma}_j^+\right)$





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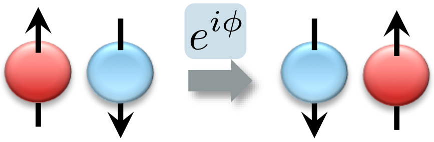
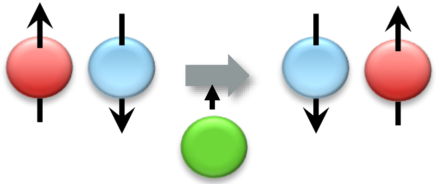
Spin models using Rydbergs

- Gauge fields $$\frac{C_6}{r^6}\left(e^{i\phi}\hat{\sigma}_i^+\hat{\sigma}_j^- + e^{-i\phi}\hat{\sigma}_i^-\hat{\sigma}_j^+\right)$$

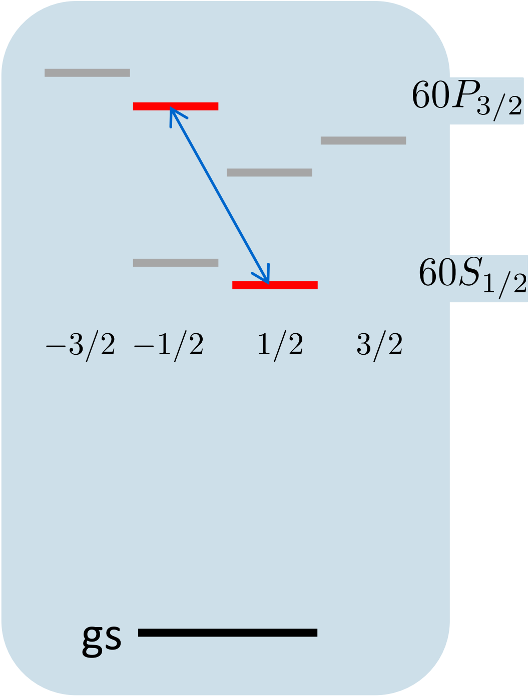


- Nonlinear transport $$\left(e^{i\phi\hat{\Sigma}_z}\,\hat{\sigma}_i^+\hat{\sigma}_j^- + e^{-i\phi\hat{\Sigma}_z}\,\hat{\sigma}_i^-\hat{\sigma}_j^+\right)$$

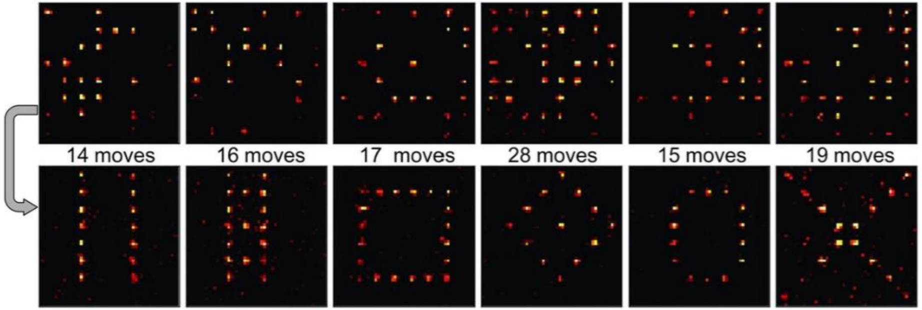


Density-dependent Peierls phases

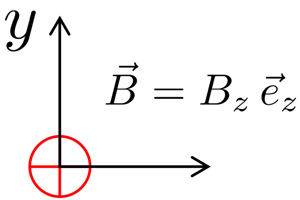
Rydberg atom arrays



- atoms in tweezer arrays = lattice structures



Barredo et al.:Science 6315, 1021



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Peierls phases

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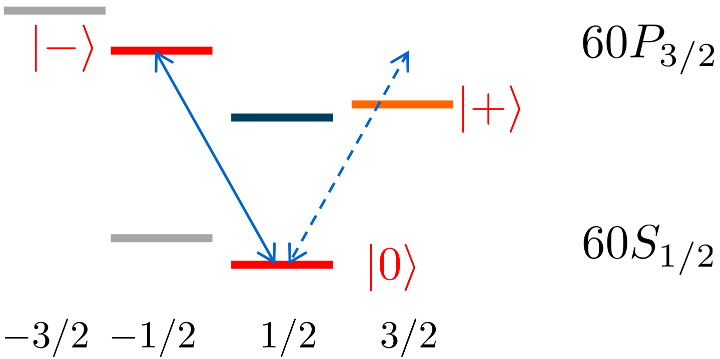
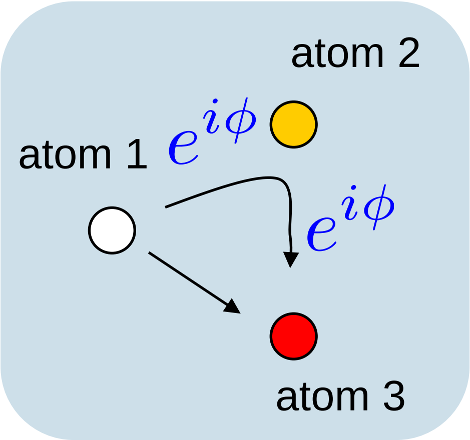
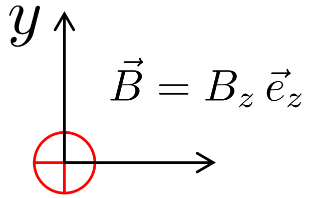
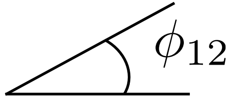


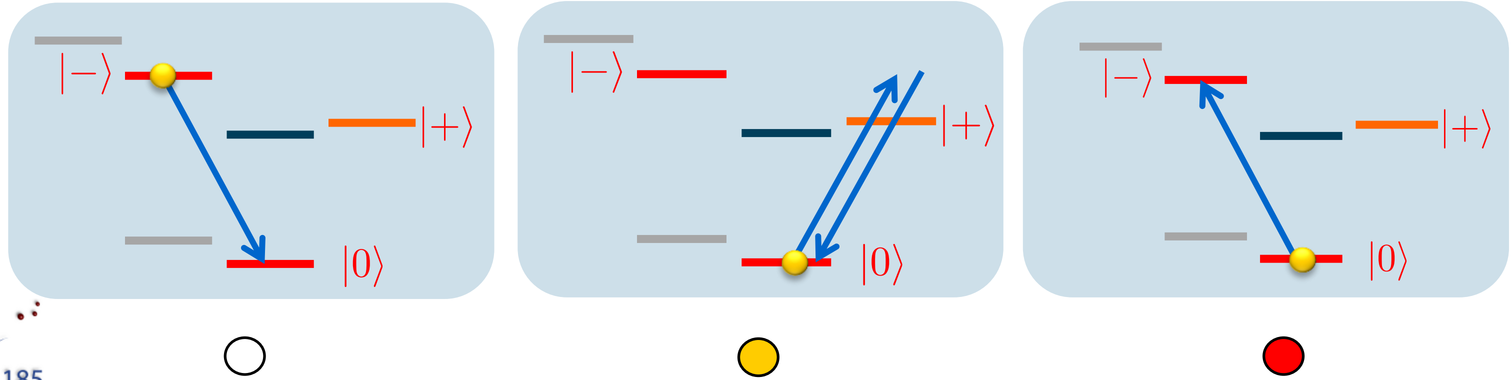






direct hopping

second-order hopping



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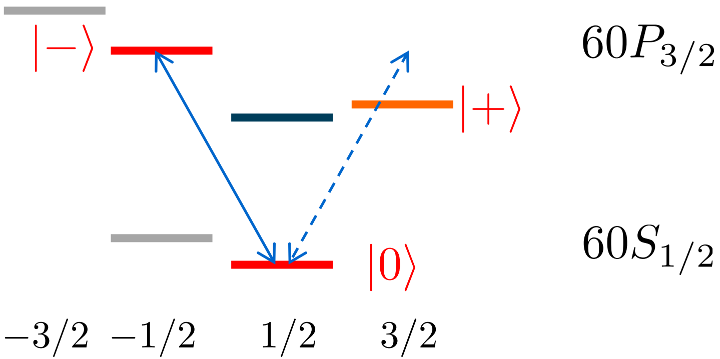
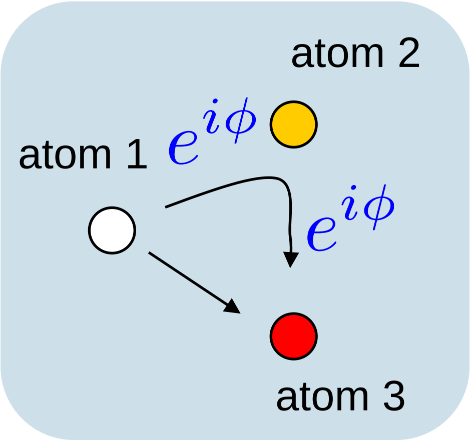
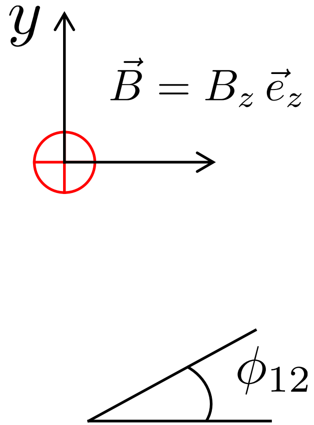
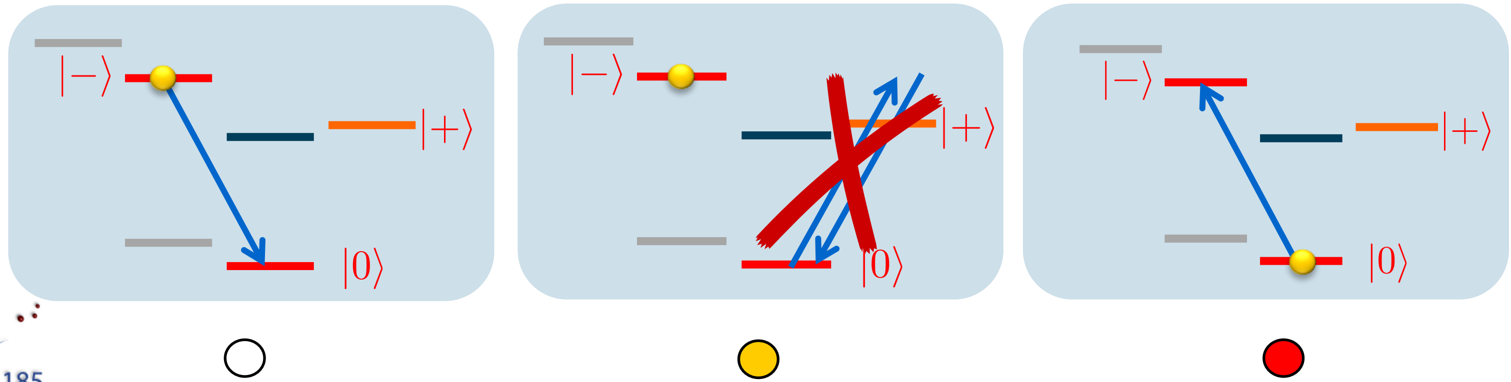
Nonlinear Peierls phases







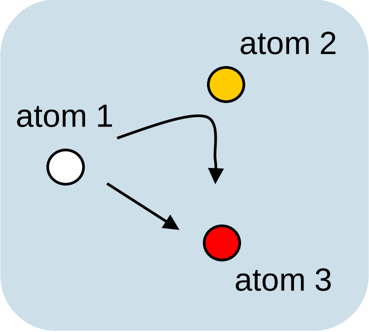
indirect second-order hopping

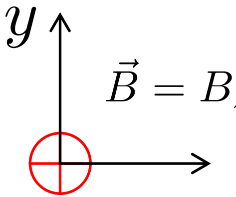


Experiment

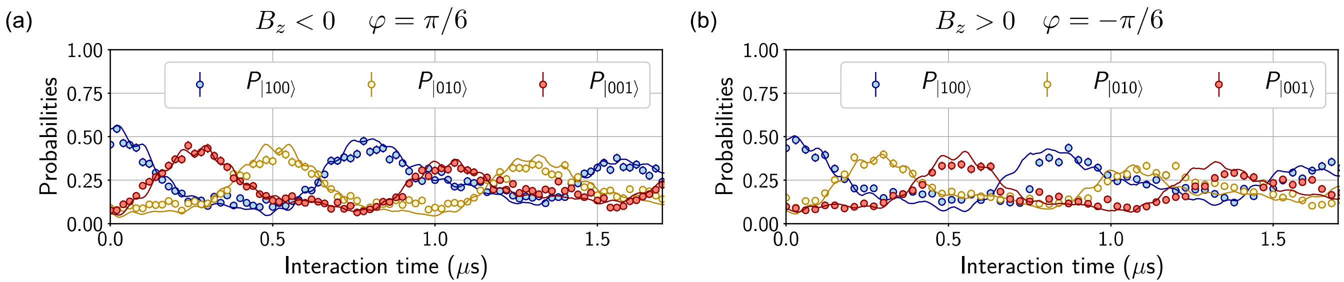
V. Lienhardt *et al.* Phys.Rev.X 10, 021031 (2020)

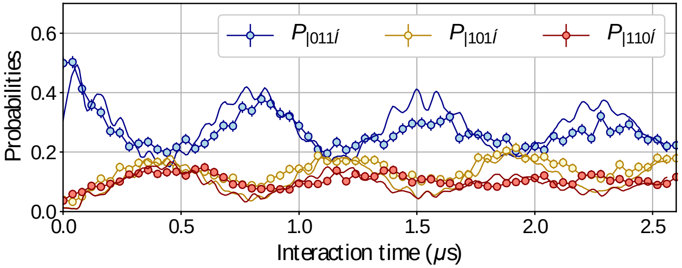
$$H = -J \sum_{\langle ij \rangle} \hat{b}_i^\dagger \hat{b}_j - 2gJ \sum_{\langle\langle ij \rangle\rangle} \hat{b}_i^\dagger \hat{b}_j e^{2i\phi_{ij}} (1 - \hat{n}_{\langle ij \rangle}) + \cdots$$





$$\vec{B} = B_z \, \vec{e}_z$$





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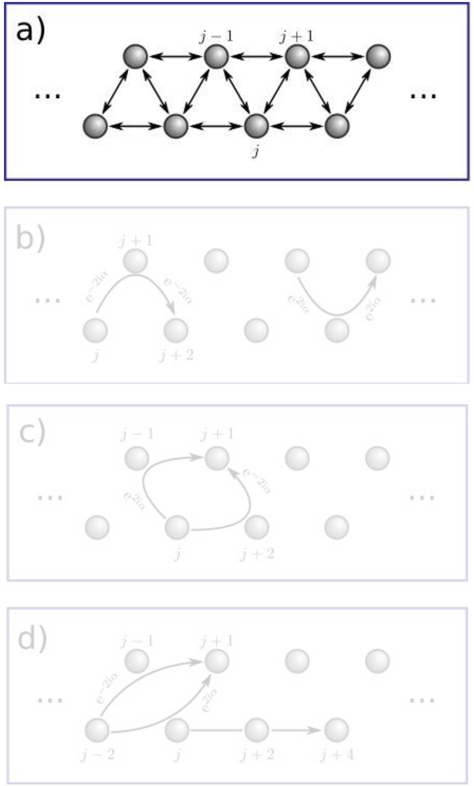
Emerging gauge fields in zig-zag ladder

Zig-zag ladder



$$\hat{H} = -J\sum_j \hat{b}^\dagger_{j+1}\hat{b}_j\left[1 + 2g\left(e^{\mp\frac{2\pi i}{3}}(1-\hat{n}_{j-1}) + e^{\pm\frac{2\pi i}{3}}(1-\hat{n}_{j+2})\right)\right] + h.a.$$

$$-J\sum_j \hat{b}^\dagger_{j+2}\hat{b}_j\left[1 + 2g\, e^{\pm\frac{4\pi i}{3}}(1-\hat{n}_{j+1})\right] + h.a.$$

$$-J\sum_j \hat{b}^\dagger_{j+3}\hat{b}_j\, 2g\left[e^{\mp\frac{2\pi i}{3}}(1-\hat{n}_{j+1}) + e^{\pm\frac{2\pi i}{3}}(1-\hat{n}_{j+2})\right] + h.a.$$

$$-J\sum_j \hat{b}^\dagger_{j+4}\hat{b}_j\, 2g(1-\hat{n}_{j+2}) + h.a.$$

$$-J\sum_j \hat{b}^\dagger_j\hat{b}_j\, 2g\eta\left[(1-\hat{n}_{j-1}) + (1-\hat{n}_{j+1}) + (1-\hat{n}_{j-2}) + (1-\hat{n}_{j+2})\right]$$

- ○ linear hopping
- ○ g nonlinear hopping
- ○ η density-density interaction

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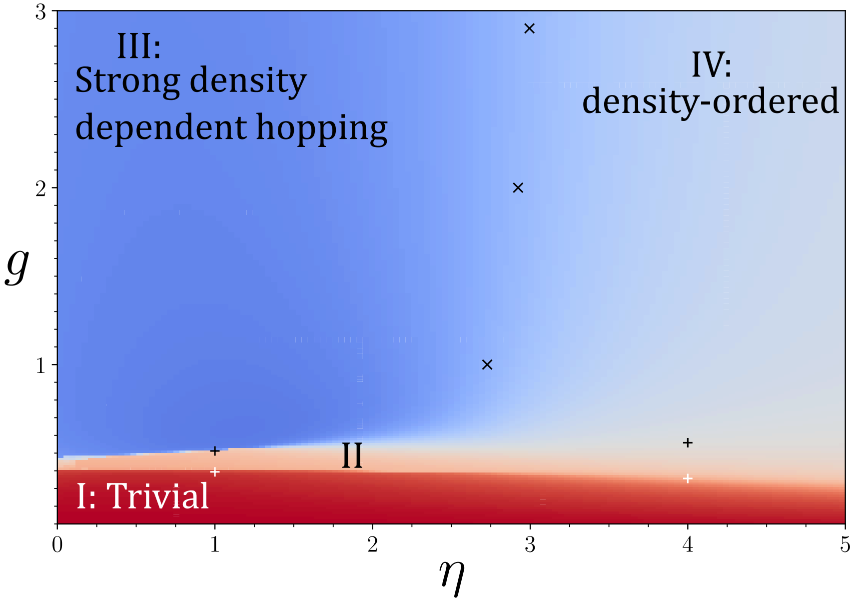
Phase diagram

- half filling



$$\mathrm{Re}[\langle \hat{b}_j^\dagger \hat{b}_{j+1} \rangle]$$

- ground-state fidelity

$$f(\lambda) = \frac{2}{N}\,\frac{1 - |\langle \Phi_0(\lambda) | \Phi_0(\lambda + \delta\lambda) \rangle|}{\delta\lambda^2}, \qquad \delta\lambda \to 0,$$

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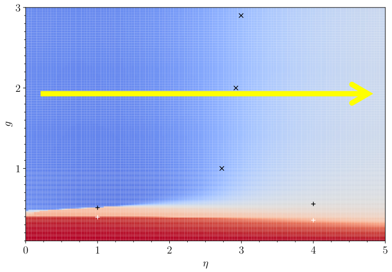
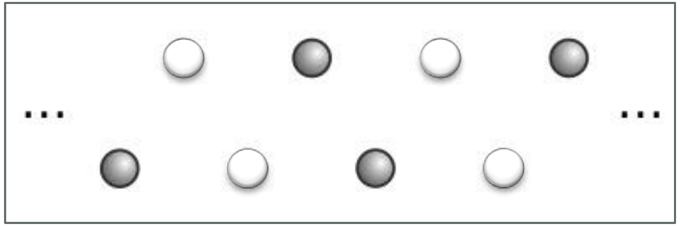
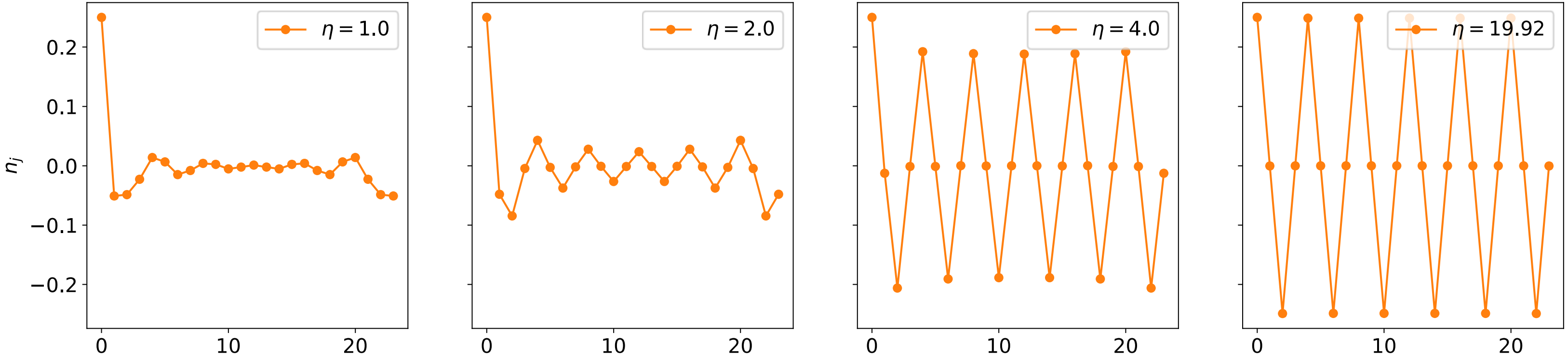
Liquid to density order

- density with OBC







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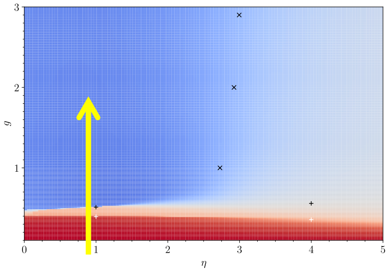
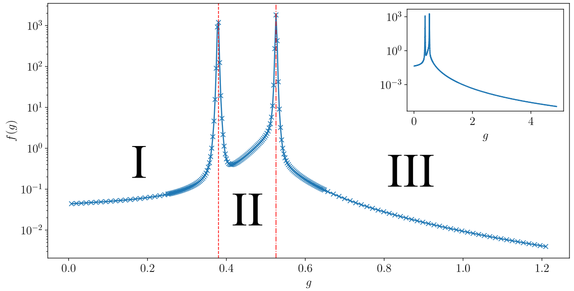
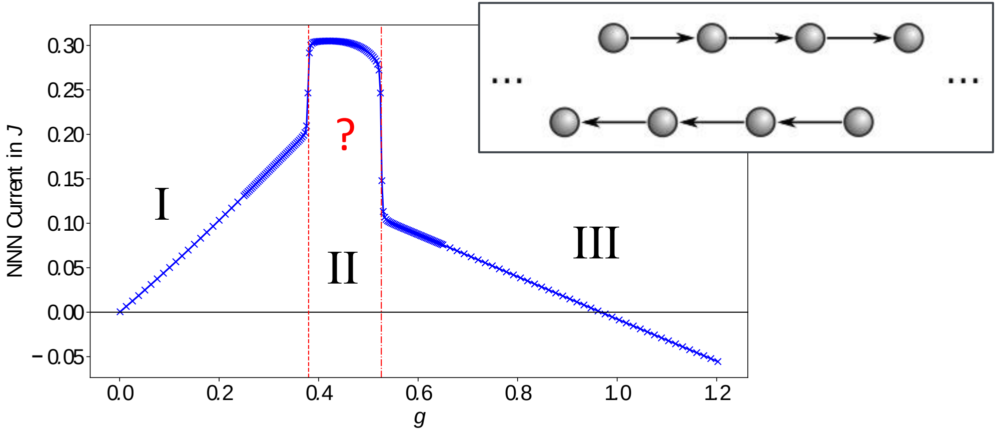
Liquid phases ?



- ground-state findelity:



- average current along sub-chains:



- fermion mean-field Hamiltonian:

$$\hat{H}_{MF} = -J\sum_j \hat{c}^\dagger_{j+1}\hat{c}_j(1-g) - J\sum_j \hat{c}^\dagger_{j+2}\hat{c}_j\, g e^{\pm\frac{4\pi i}{3}} + h.a.$$

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Current vortices

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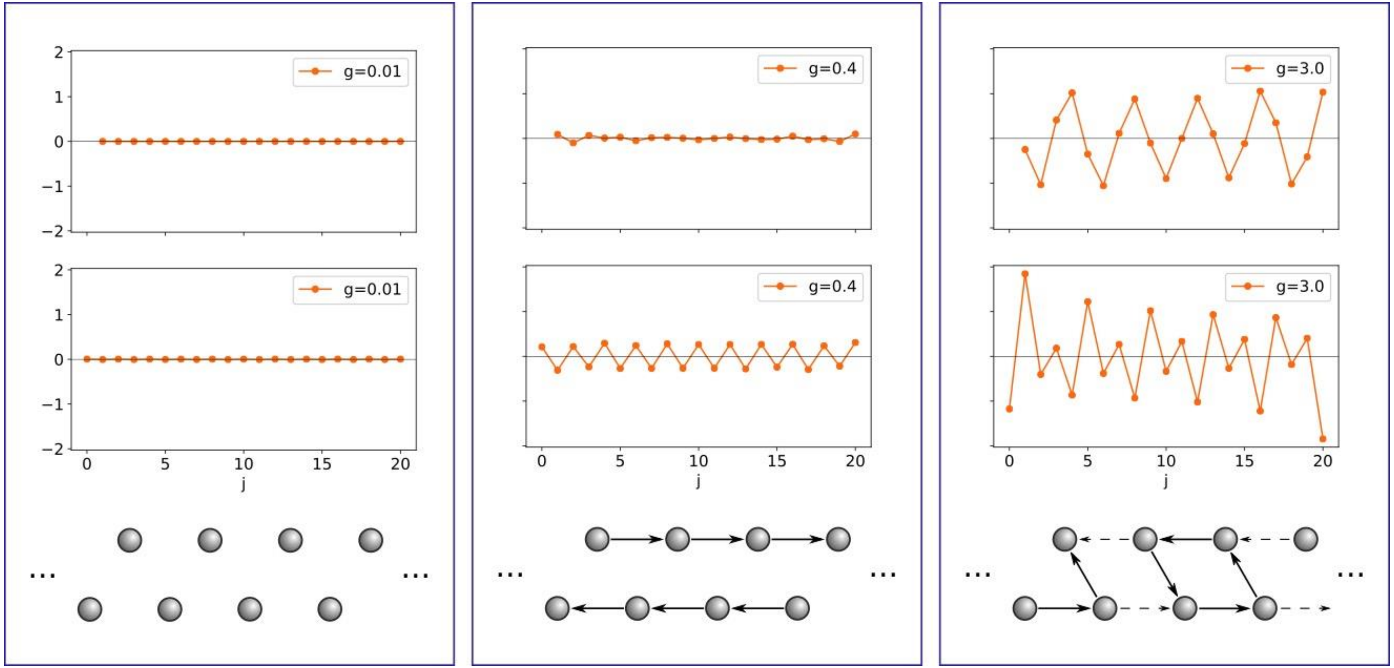
- open boundary conditions

$\eta = 2$



current vortices

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Current vortices

- fermion Hamiltonian

$$\hat H = -J\sum_j \hat c^\dagger_{j+1}\hat c_j \left[1 + 2g\hat U_{j+1,j}(1-\hat n_{j-1}\hat n_{j+2})\right] + h.a.$$

$$-J\sum_j \hat c^\dagger_{j+2}\hat c_j \left[(1-2\hat n_{j+1}) + 2g\hat U_{j+2,j}(1-\hat n_{j+1})\right] + h.a.$$

$$+J\sum_j \hat c^\dagger_{j+3}\hat c_j\, 2g\hat U_{j+3,j}(1-\hat n_{j+1}\hat n_{j+2}) + h.a.$$

$$-J\sum_j \hat c^\dagger_{j+4}\hat c_j\, 2g\hat U_{j+4,j}(1-\hat n_{j+2}) + h.a.$$

$$+\eta\, \hat H_{\text{density-density}}$$

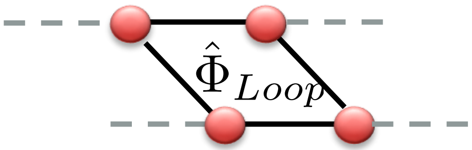
- unitary link operators

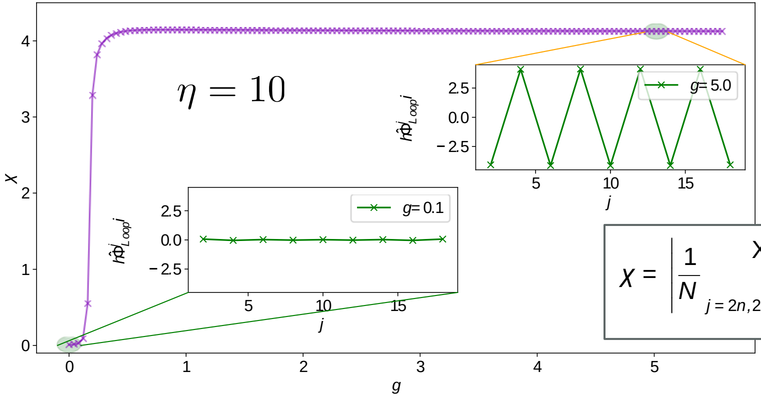
$$\hat U_{j+1,j} = \exp\left(i\hat A_{j+1,j}\right) = \exp\left(\mp\frac{\pi}{3}(\hat n_{j-1}-\hat n_{j+2})\right)$$

$$\hat U_{j+2,j} = \exp\left(iA_{j+2,j}\right) = \exp\left(\mp\frac{2\pi i}{3}\right),$$

$$\hat U_{j+3,j} = \exp\left(i\hat A_{j+3,j}\right) = \exp\left(\pm\frac{2\pi i}{3}(\hat n_{j+1}-\hat n_{j+2})\right).$$

$$\hat U_{j+4,j} = \exp\left(i\hat A_{j+4,j}\right) = \exp\left(\pm i\pi(\hat n_{j+1}-\hat n_{j+3})\right).$$





$$\chi = \left|\frac{1}{N}\sum_{j=2n,\,2<n<L-4}(-1)^n\left\langle\hat\Phi^{(j)}_{Loop}\right\rangle\right|$$

flux lattice induced by density order

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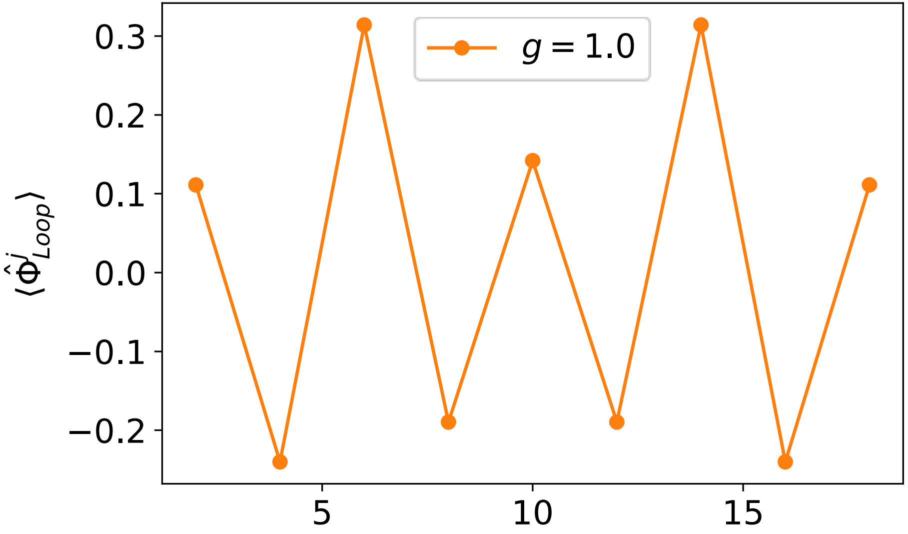
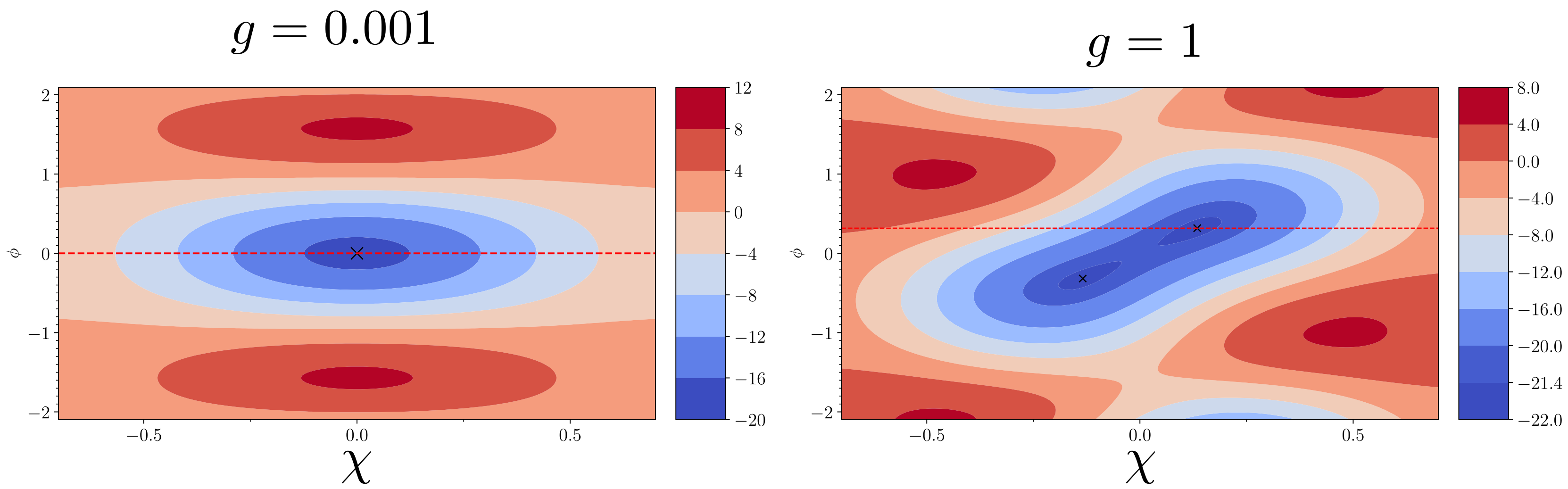
Spontaneous gauge field creation

- What happens at $\eta = 0$??



→ still liquid-like flux correlations

Variational approach



→ Emerging gauge field minimizes energy despite formation of density wave

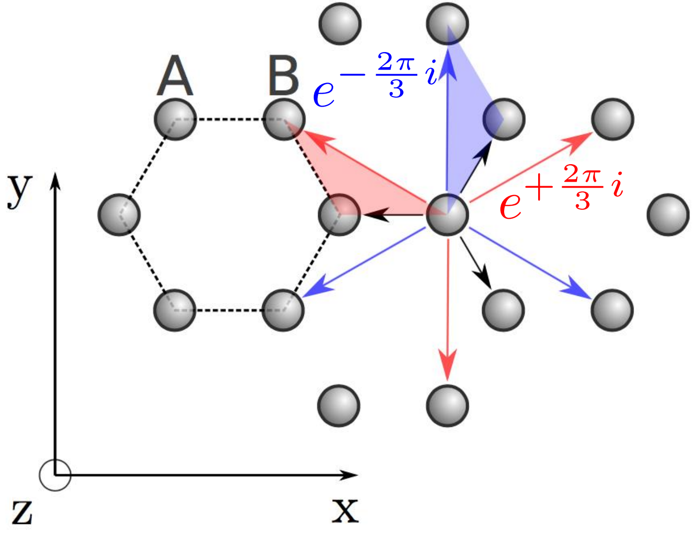
Rydberg Haldane model

Honeycomb lattice

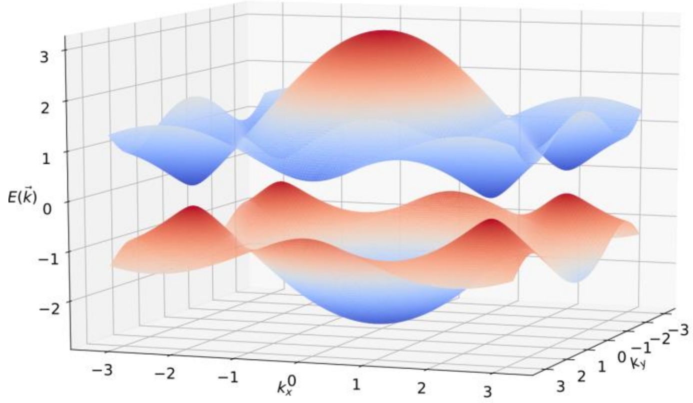
- Hamiltonian

$$\hat{H} = -J\sum_{\langle i,j\rangle} \hat{b}_j^\dagger \hat{b}_i + \text{H.c.} - 2gJ \sum_{\langle\langle i,j\rangle\rangle} \hat{b}_j^\dagger \hat{b}_i \mathrm{e}^{\pm\frac{2\pi}{3}\mathrm{i}} (1 - \hat{n}_{ij}) + \text{H.c.}$$

$$+ 2gJ \sum_{\langle i,j\rangle} \hat{n}_i \hat{n}_j ,$$



Haldane model



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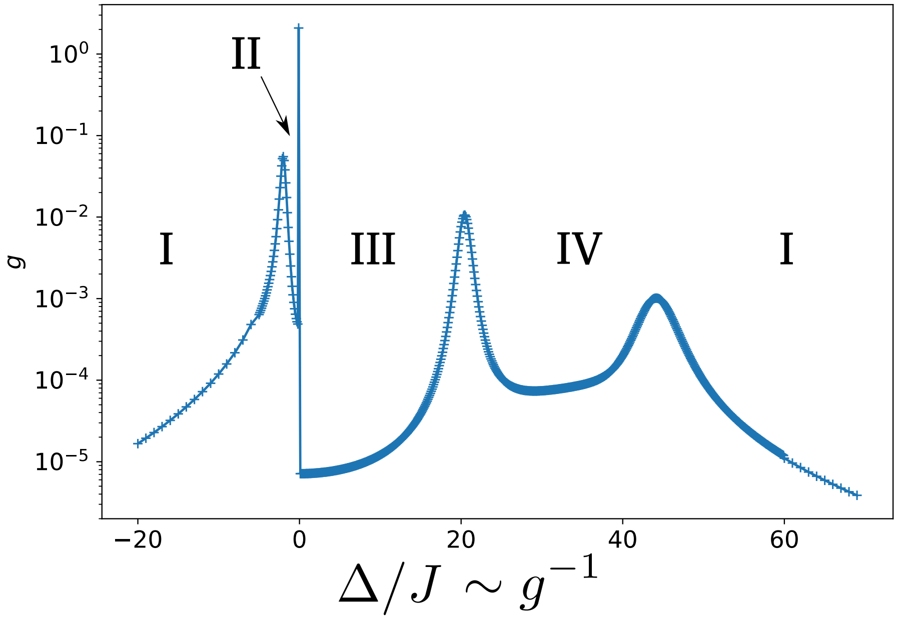
Phase diagram $\eta = 1$

- half filling

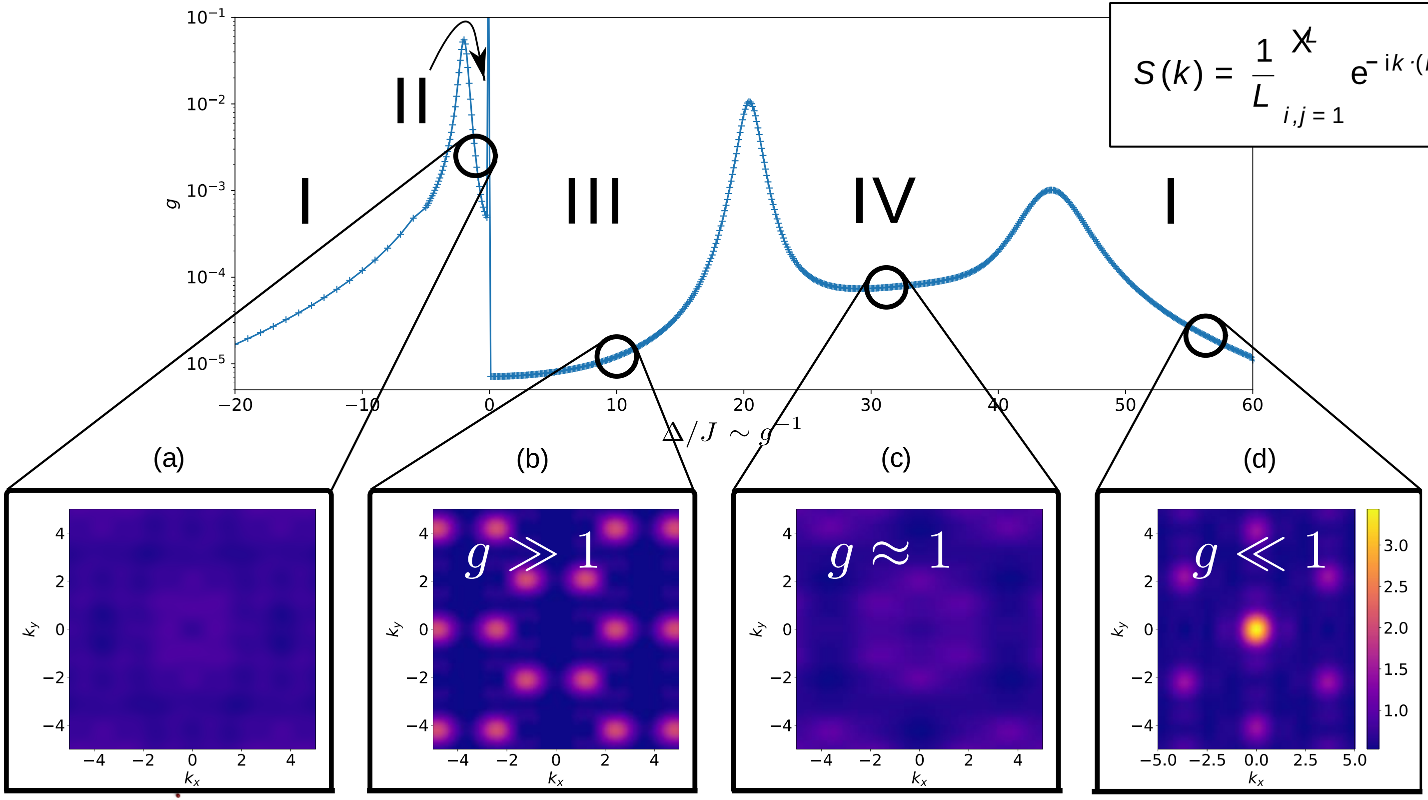


ground-state fidelity

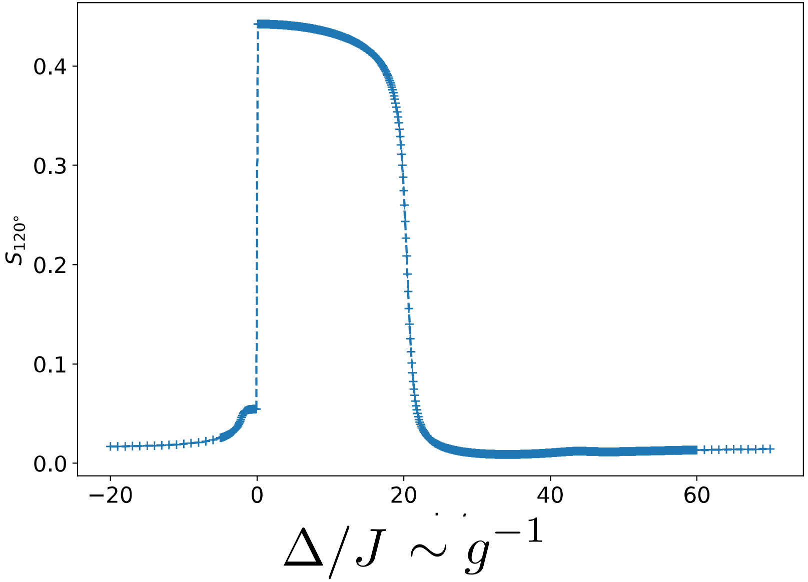
$$f(\lambda) = \frac{2}{N}\,\frac{1 - |\langle\Phi_0(\lambda)|\Phi_0(\lambda+\delta\lambda)\rangle|}{\delta\lambda^2}, \qquad \delta\lambda \to 0,$$

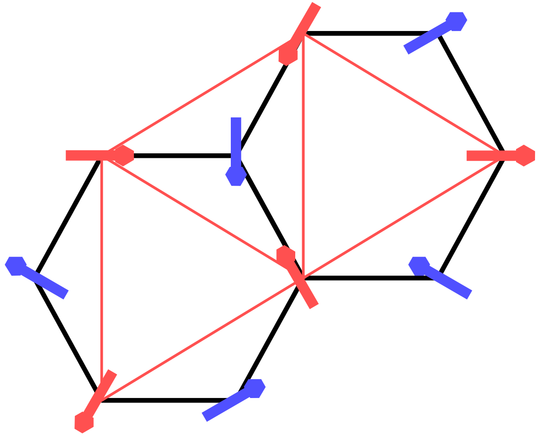
Spin structure factor

$$S(k) = \frac{1}{L} \sum_{i,j=1}^{L} e^{-ik\cdot(r_i - r_j)} \left\langle \hat{S}_i \cdot \hat{S}_j \right\rangle$$



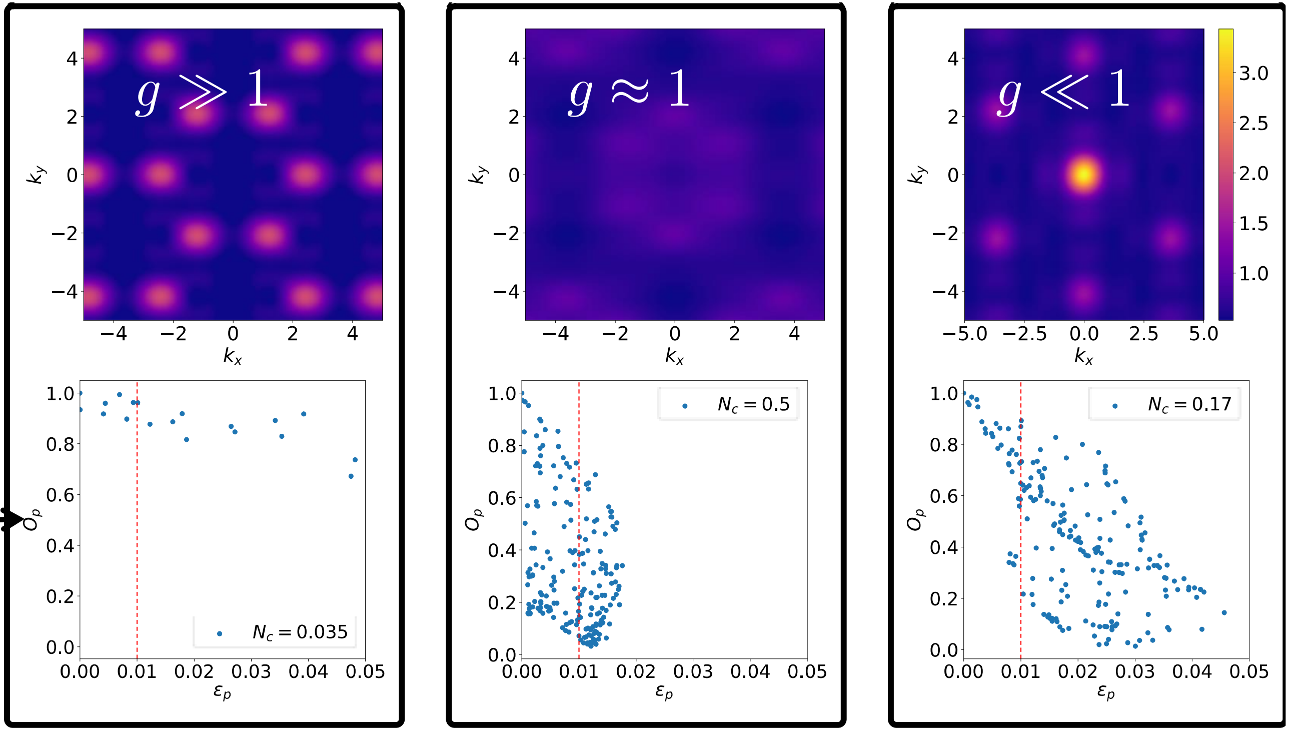
120° spin order $g \gg 1$





$$S_{120^\circ} = \left\langle \hat{S}^{(5)}_{2\pi/3} \hat{S}^{(10)}_{4\pi/3} \hat{S}^{(13)}_{0} \hat{S}^{(18)}_{2\pi/3} \right\rangle$$

Randomly twisted BC

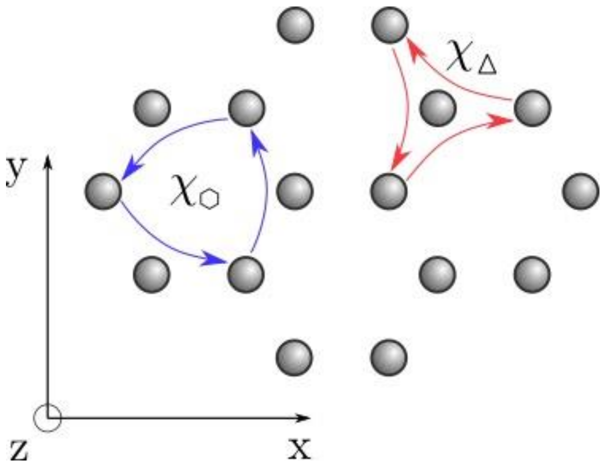


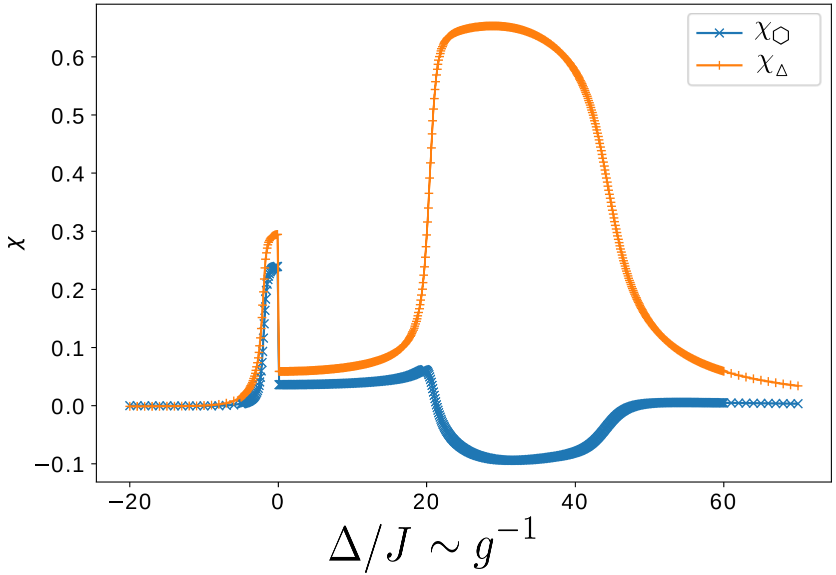
Overlap with optimum ground state

→ disordered

Spin chirality

$$\chi_S = \left\langle \hat{\boldsymbol{S}}_i \cdot \left(\hat{\boldsymbol{S}}_j \times \hat{\boldsymbol{S}}_k \right) \right\rangle$$





→ chiral spin liquid ??

Summary

Rydberg-excitations transport

- Density-dependent complex hopping
- Experimental verification for triangle

Zig-zag ladder

- Vortex and Flux lattice induced by density-density interaction
- Self-generated gauge field

Honeycomb lattice

- Potential chiral spin liquid

Other

- Z_2 lattice-gauge theory
- Anyon Hubbard model