Emerging Gauge Theories in 2D Rydberg Arrays

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High-energy physics at ultra-cold temperatures, ECT* 12/06/2019

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IQI

arXiv:1906.xxxx

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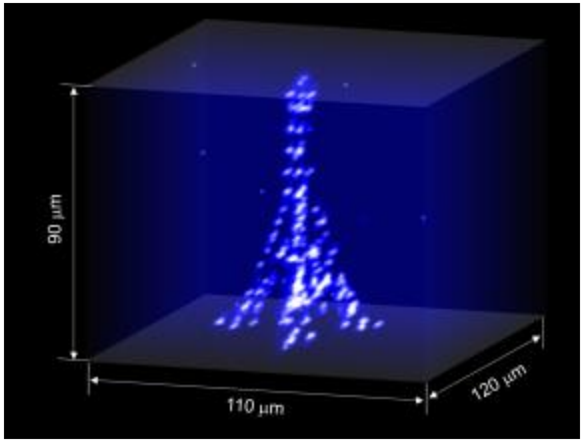
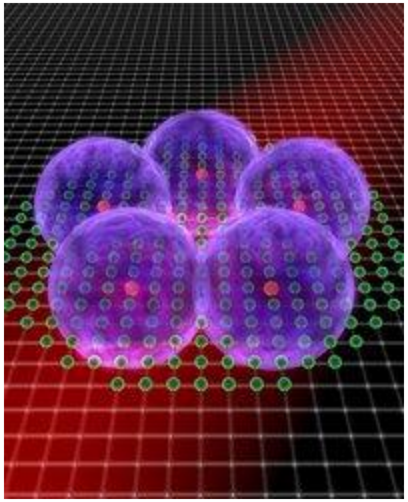
Rydberg atoms

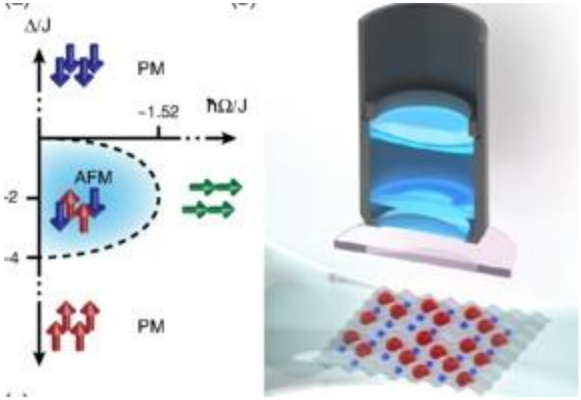
Arrays of Rydberg atoms: perfect to simulate spin models



Paris
Browaeys group

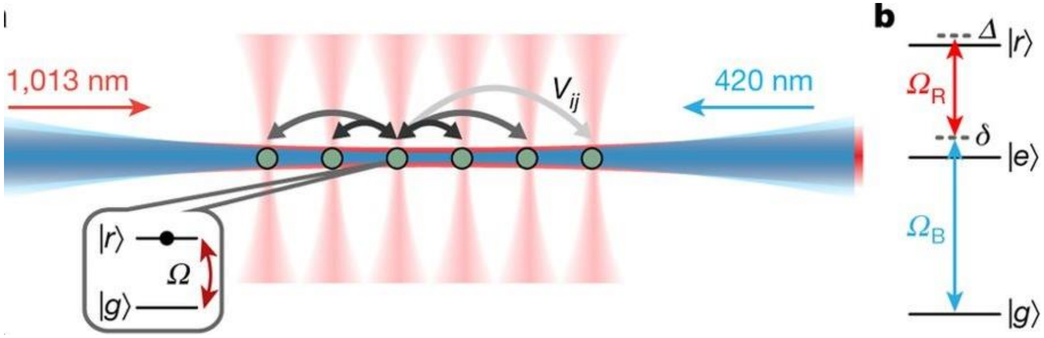


Munich
Bloch group



Princeton
Bakr group

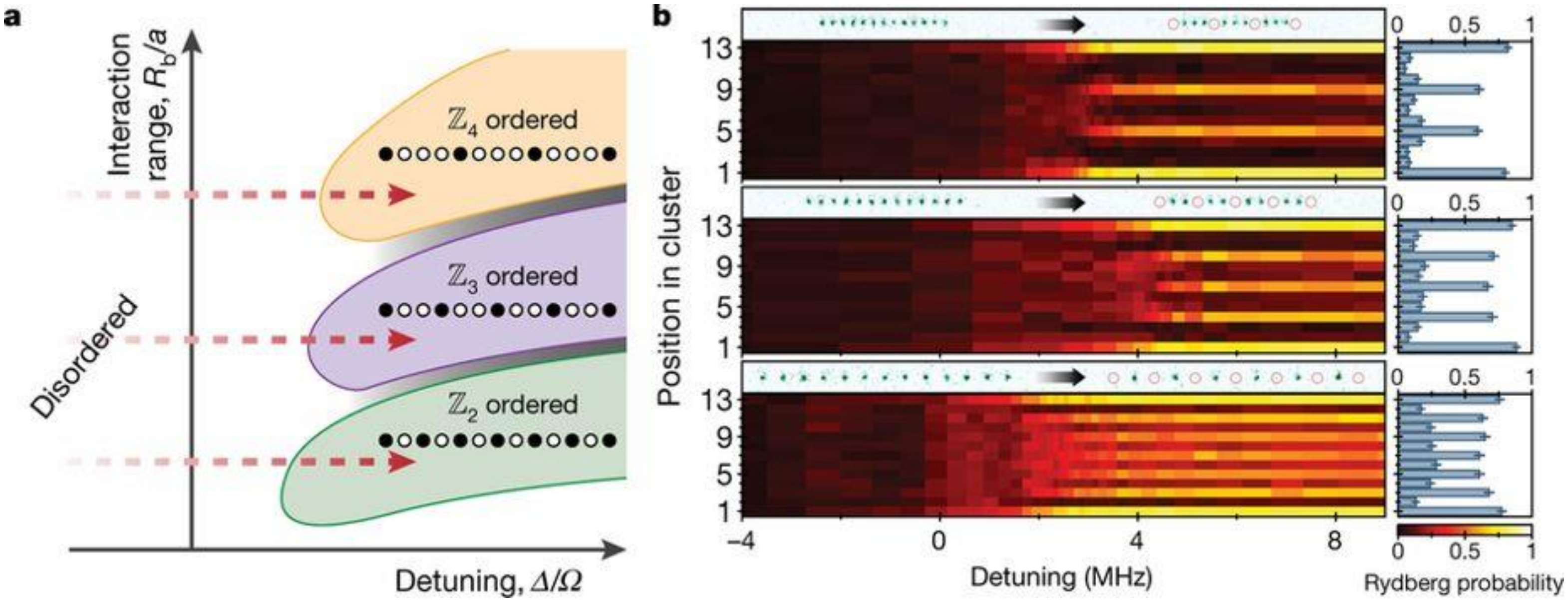
Harvard
Lukin group



Rydberg atoms: Blockade

Rydberg blockade: *PXP* dynamics!

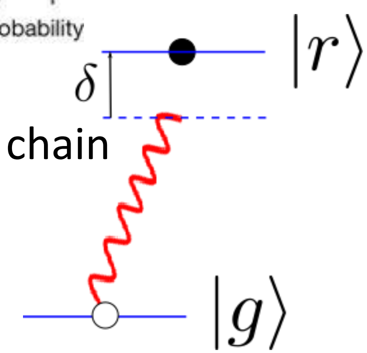
[Bernier et al., Nature 551, 579 (2017)]



$$H_{Ryd} = \sum_i \left[-\Omega\big(|r\rangle_i\langle g| + |g\rangle_i\langle r|\big) + \delta|r\rangle_i\langle r| + \sum_{k>0} V_k |r\rangle_i\langle r| \otimes |r\rangle_{i+k}\langle r| \right]$$

$$\overset{\delta\sim 0}{\approx} \sum_i \left[-\Omega |g\rangle_{i-1}\langle g| \big(|r\rangle_i\langle g| + |g\rangle_i\langle r|\big) |g\rangle_{i+1}\langle g| + \sum_{k>1} V_k |r\rangle_i\langle r| \otimes |r\rangle_{i+k}\langle r| \right].$$

1D Rydberg chain



Kibble-Zurek

Quantum scars, connection to graph theory

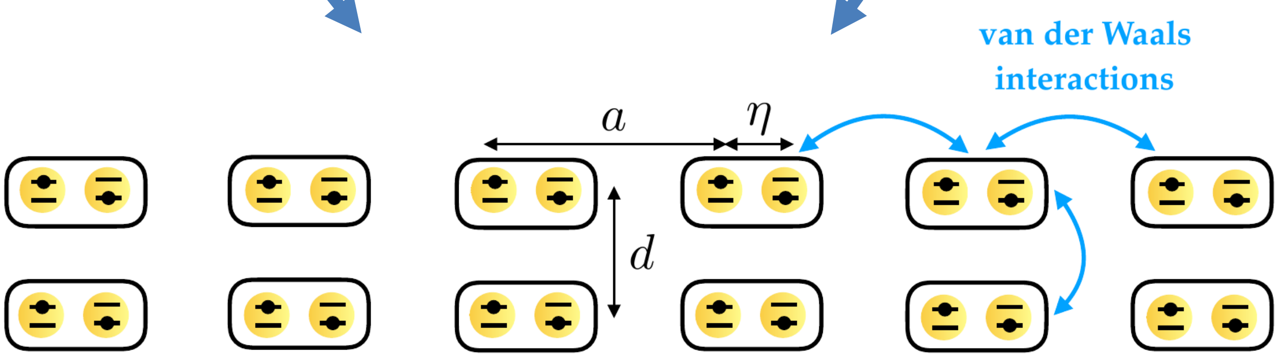
[Keesling et al., arXiv:1809.05540]

[Turner et al., Nature Phys. 14, 745 (2018)]

Take home message

Controllable 2D geometries of Rydberg arrays

Suitable encoding of gauge degrees of freedom



Emerging 2D lattice gauge theory

Outline

I. Motivations and tutorial

From static to dynamical gauge theories
The Rokhsar-Kivelson model
Implementation: experimental challenges

II. Suitable encoding
Converting Ring exchange to blockade

III. Rydberg implementation and examples

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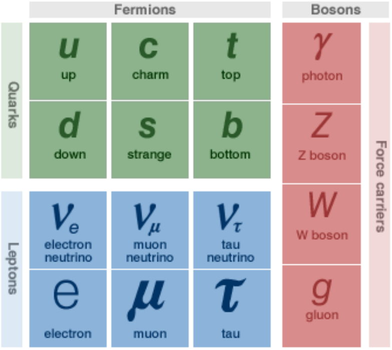
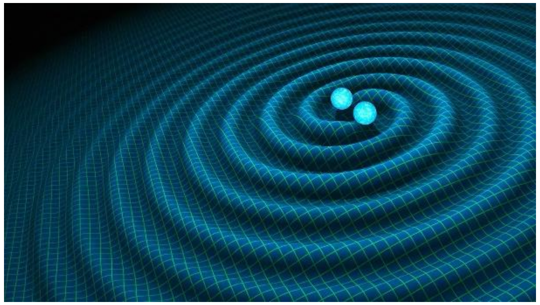
I.1 Why Gauge Theories?

Gauge theories appear everywhere!

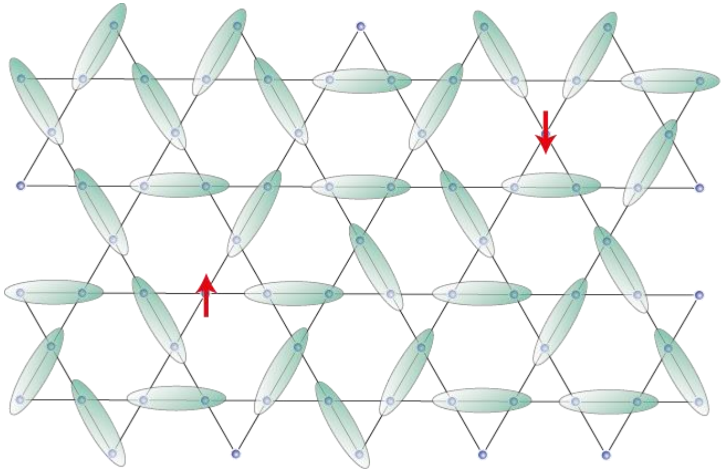
HEP: "All" fundamental interactions are gauge theories (even gravity)





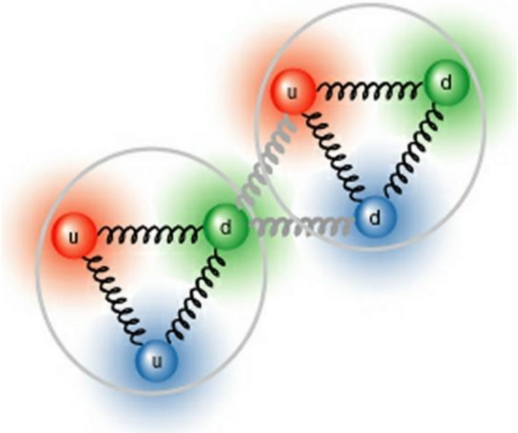
Condensed Matter: Emerging local symmetry

Quantum magnetism,
high-T_c superconductivity
& topological order



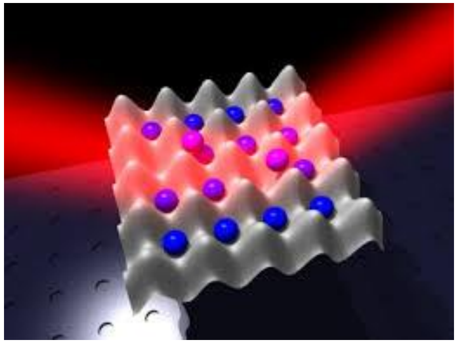
I.2 Why Lattice Gauge Theories?

Wilson'74: Lattice formulation to study QCD
by Quantum MonteCarlo



Success: Static properties at low fermion density

Sign problems: Dynamics, phase diagram at high density



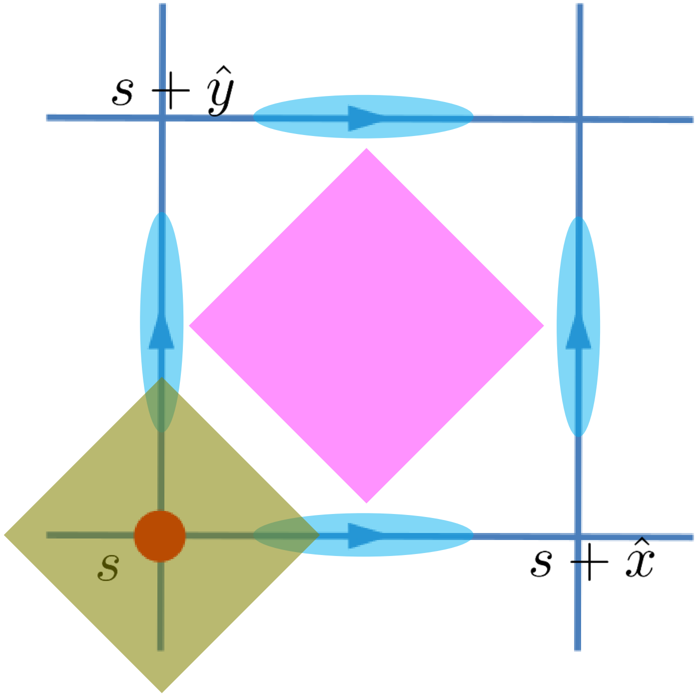
Perfect opportunity for tensor networks and
quantum simulation!

Hamiltonian approach: engineer an emergent gauge theory

I.3 Hamiltonian lattice gauge theory [Kogut,Susskind'75]

2D QED: Dynamical gauge field = operator on electro-magnetic quanta

$$[\hat{E}_{s,\mu}, \hat{U}_{s,\mu}] = -\hat{U}_{s,\mu}$$



+ Electro-magnetic energy

+ Gauss law U(1) gauge invariance

$$\hat{E}_{s,x} + \hat{E}_{s,y} - \hat{E}_{s-\hat{x},x} - \hat{E}_{s-\hat{y},y} = Q_s$$

$$H = -\sum_{s,\mu=x,y} g^2 \hat{E}^2_{s,\mu} - \frac{1}{g^2}(\hat{U}\hat{U}\hat{U}^\dagger\hat{U}^\dagger + H.c.)$$

I.3 Hamiltonian lattice gauge theory [Kogut,Susskind'75]

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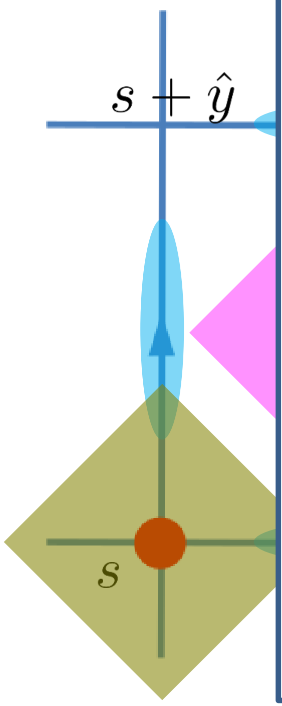
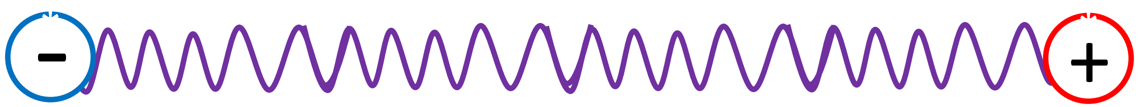


Static charges: **Confinement** probe



Scaling of potential energy with distance

gy

invariance

$\hat{E}_{s-\hat{y},y} = Q_s$

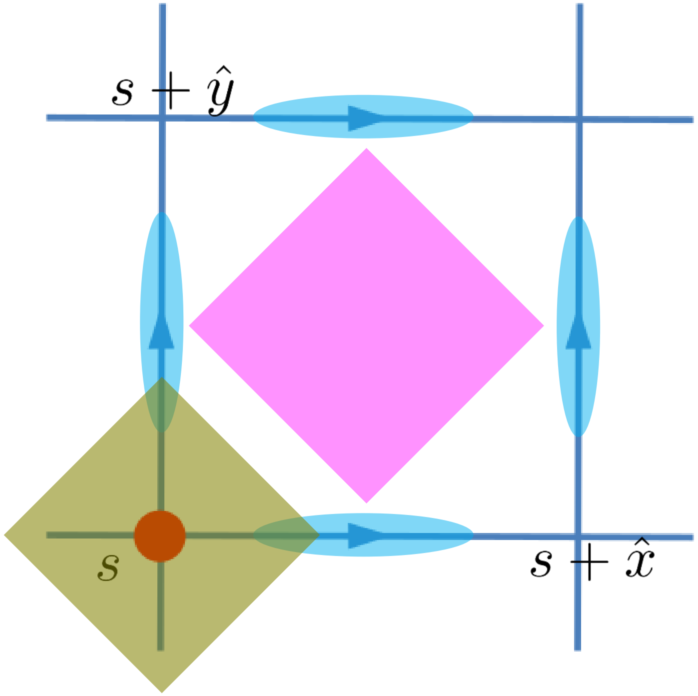
$$H = -\sum_{s,\mu=x,y} g^2 \hat{E}^2_{s,\mu} - \frac{1}{g^2}(\hat{U}\hat{U}\hat{U}^\dagger\hat{U}^\dagger + H.c.)$$

I.4 Spin gauge theory [Horn'81,Orland'90,Wiese'97…]

2D Spin QED: Electric truncated, 2S+1 states! (For QCD see Wiese)

Minimal choice: S=1/2

$$\hat{E}_{s,\mu} = \hat{S}^z_{s,\mu}, \quad \hat{U}_{s,\mu} = \hat{S}^-_{s,\mu} = \hat{S}^x_{s,\mu} + i\hat{S}^y_{s,\mu}$$



$$H = -J \sum_{s,\mu=x,y} (\hat{S}^-_{s,x}\hat{S}^-_{s+\hat{x},y}\hat{S}^+_{s+\hat{y},x}\hat{S}_{s,y} + H.c.)$$

$$= -J \sum_s \mathcal{S}_s + \mathcal{S}^+_s$$

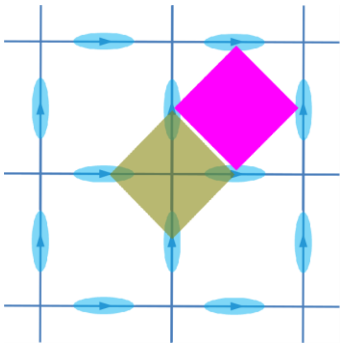
+ Gauss law U(1) gauge invariance

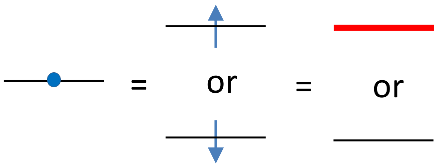
$$\hat{S}^z_{s,x} + \hat{S}^z_{s,y} - \hat{S}^z_{s-\hat{x},x} - \hat{S}^z_{s-\hat{y},y} = Q_s$$

Lattice gauge prototype! Emerging in condensed matter systems!

I.5 Spin gauge theory [Horn'81,Orland'90,Wiese'97...]

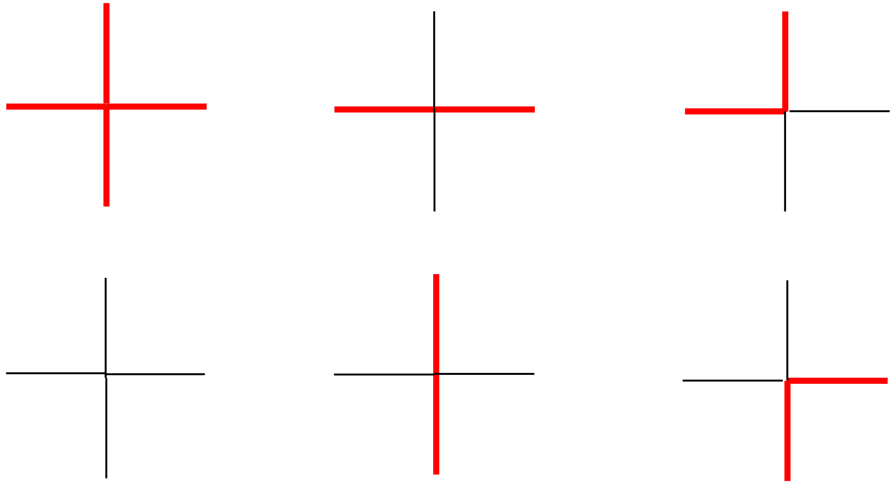
2D QED S=1/2: **Graphical notation**

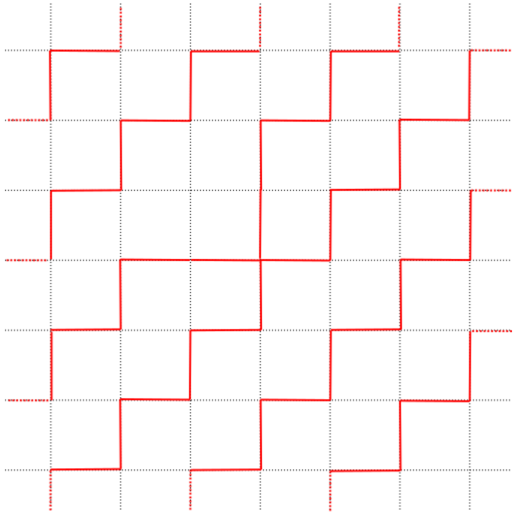




Gauss law no charges: 6 building blocks!

Equivalent to spin ice [Slater'41]

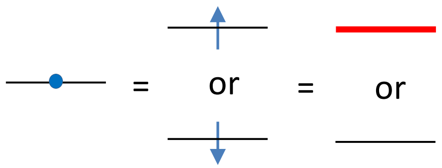


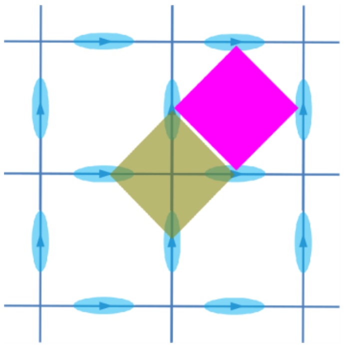


Physical states: strings going up & right

I.5 Spin gauge theory [Horn'81,Orland'90,Wiese'97...]

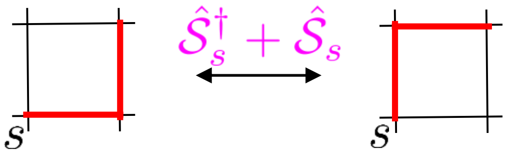
2D QED S=1/2: **Graphical notation**



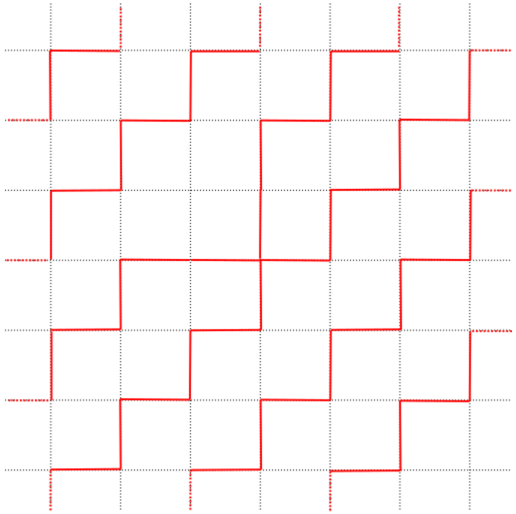


Plaquette operator: Kinetic term for strings

Flip



Map physical states into physical states



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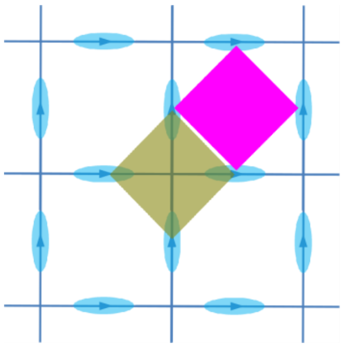

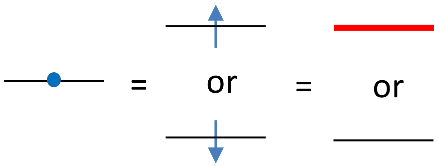

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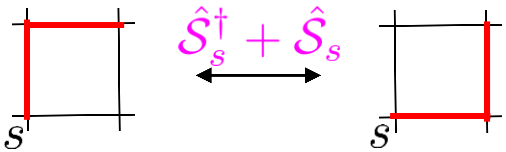

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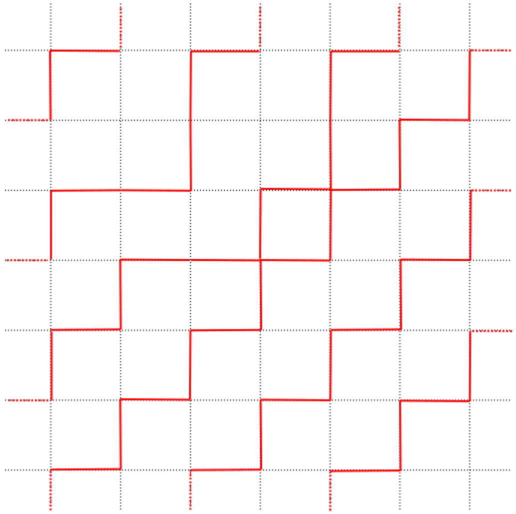

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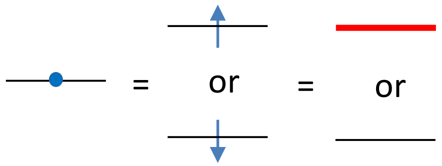

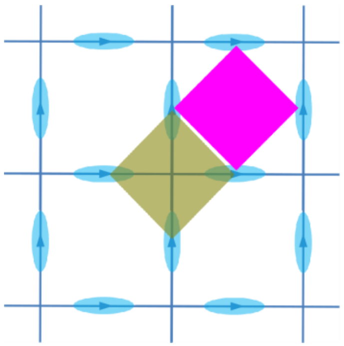

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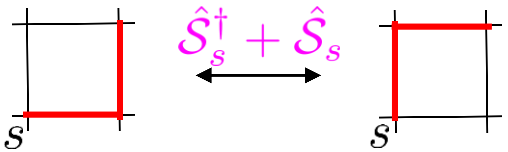

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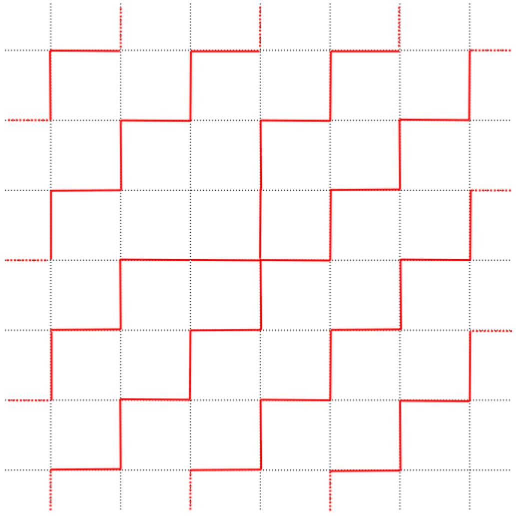

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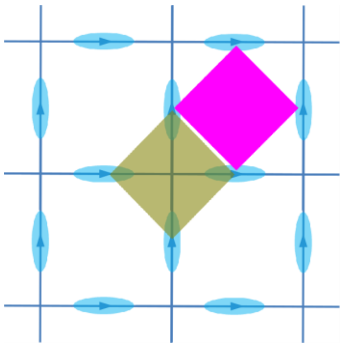

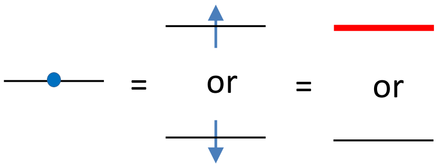

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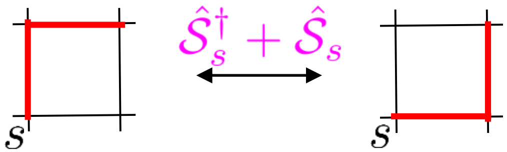

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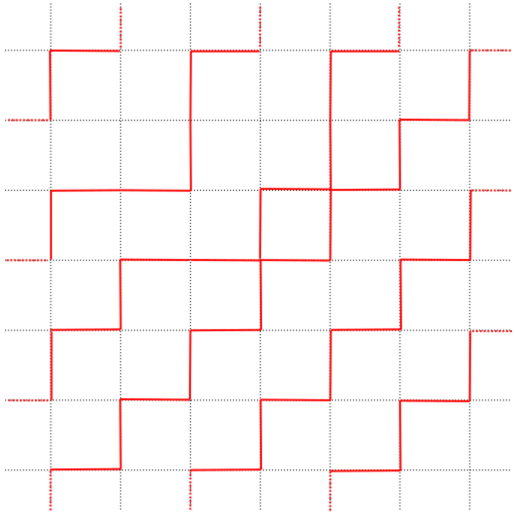

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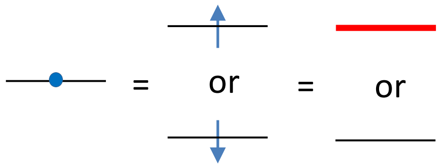

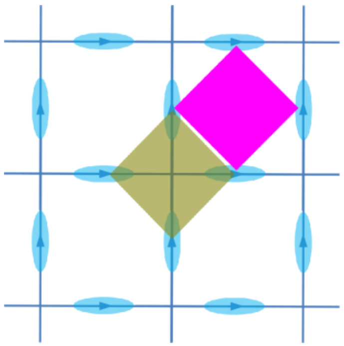

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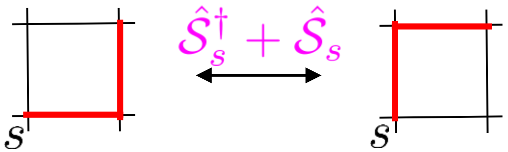

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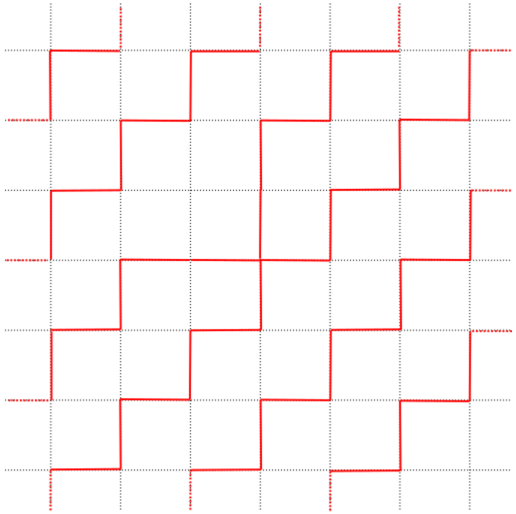
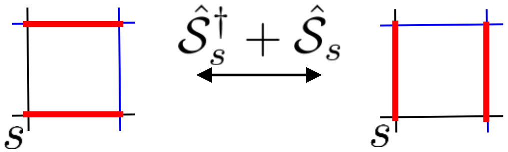


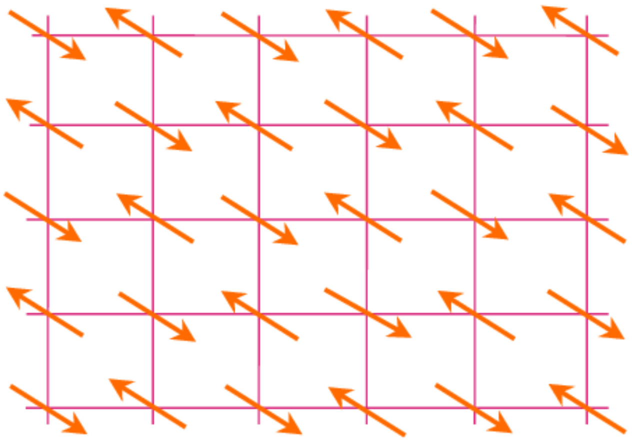
Equivalent to dimer move



up to spin redefinition

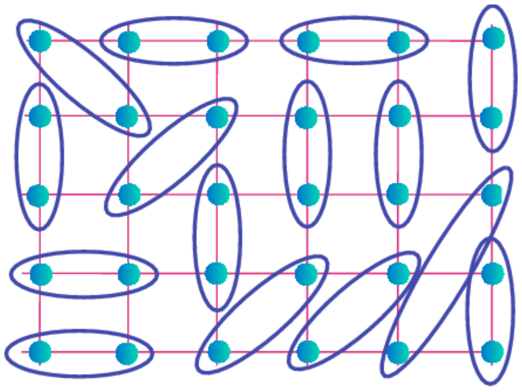
I.6 Quantum dimer model

Antiferromagnets



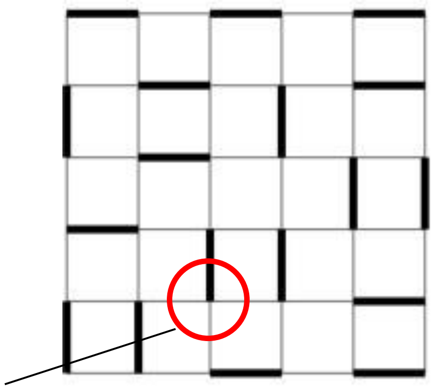
$\simeq$

Valence bond (VB) covering



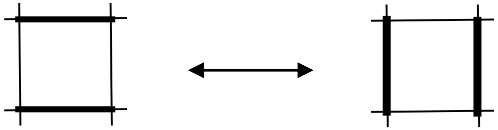
$\simeq$

Hard-core dimers



Hard core = Gauss law

Quantum fluctuations



Resonating valence bonds

[Anderson,Baskaran'87]

[Rokhsar,Kivelson'88]...

S=1/2 spin gauge theory

[Moessner,Sondhi,Fradkin'01]

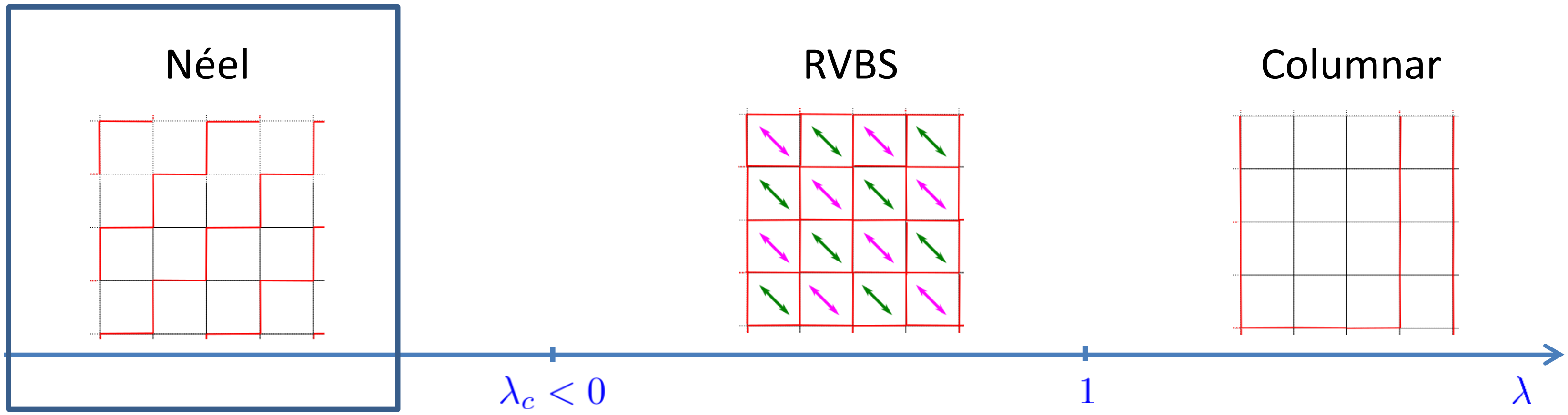
I.7 Rokhsar-Kivelson model [‘88]

$$H_{RK} = -J \sum_s \left[\left(\hat{\mathcal{S}}_s^\dagger + \hat{\mathcal{S}}_s \right) - \lambda \left(\hat{\mathcal{S}}_s^\dagger + \mathcal{S}_s \right)^2 \right]$$

Chemical potential for flippable plaquettes

ED [Shannon et al.’04]
QMC [Banerjee et al.’13]
DMRG [Tschirsich et al.’18]

Static phase diagram (no charges)



Flippable background
Order by disorder

I.7 Rokhsar-Kivelson model [‘88]

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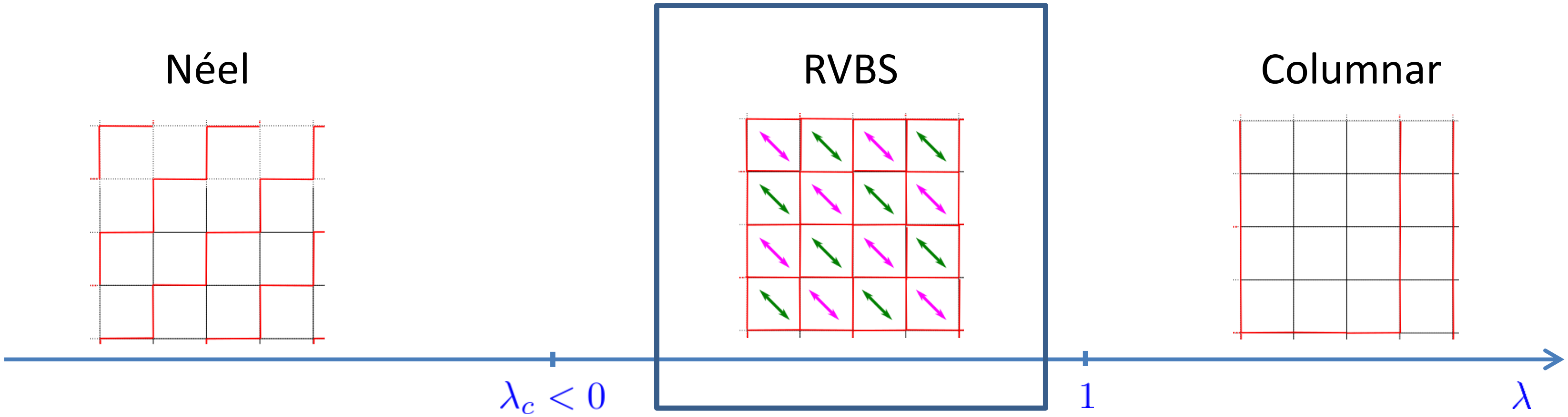

Resonating Valence Bond Solid: Correlations break translational invariance

I.7 Rokhsar-Kivelson model [‘88]

$$H_{RK} = -J \sum_s \left[\left(\hat{\mathcal{S}}_s^\dagger + \hat{\mathcal{S}}_s \right) - \lambda \left(\hat{\mathcal{S}}_s^\dagger + \mathcal{S}_s \right)^2 \right]$$

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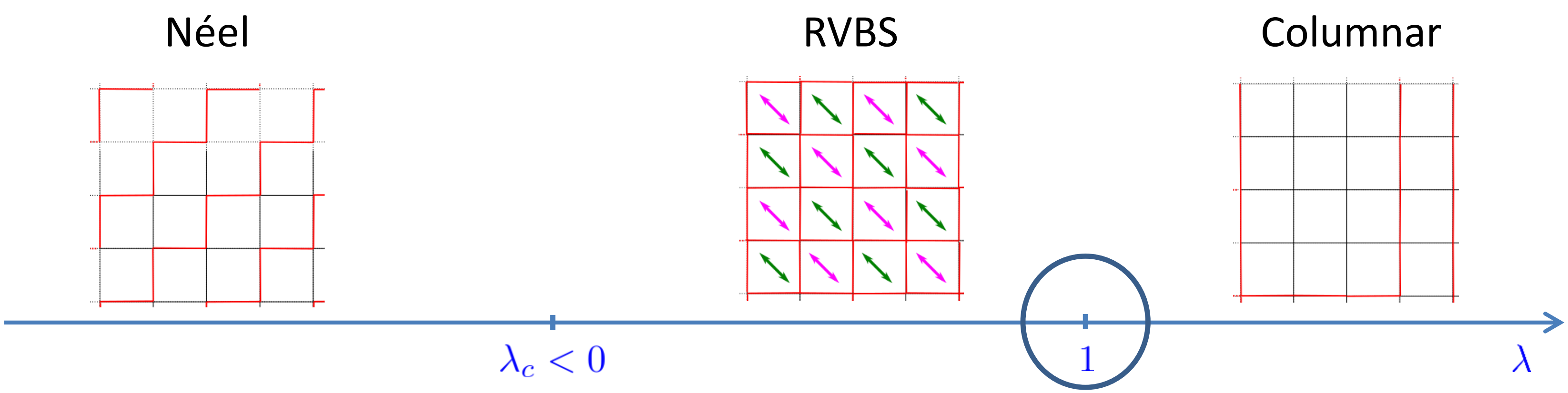

$$\lambda = 1$$

Integrable: superposition all physical states, short-range Resonating Valence bond

I.7 Rokhsar-Kivelson model [‘88]

$$H_{RK} = -J \sum_s \left[\left(\hat{\mathcal{S}}_s^\dagger + \hat{\mathcal{S}}_s \right) - \lambda \left(\hat{\mathcal{S}}_s^\dagger + \mathcal{S}_s \right)^2 \right]$$

Chemical potential for flippable plaquettes

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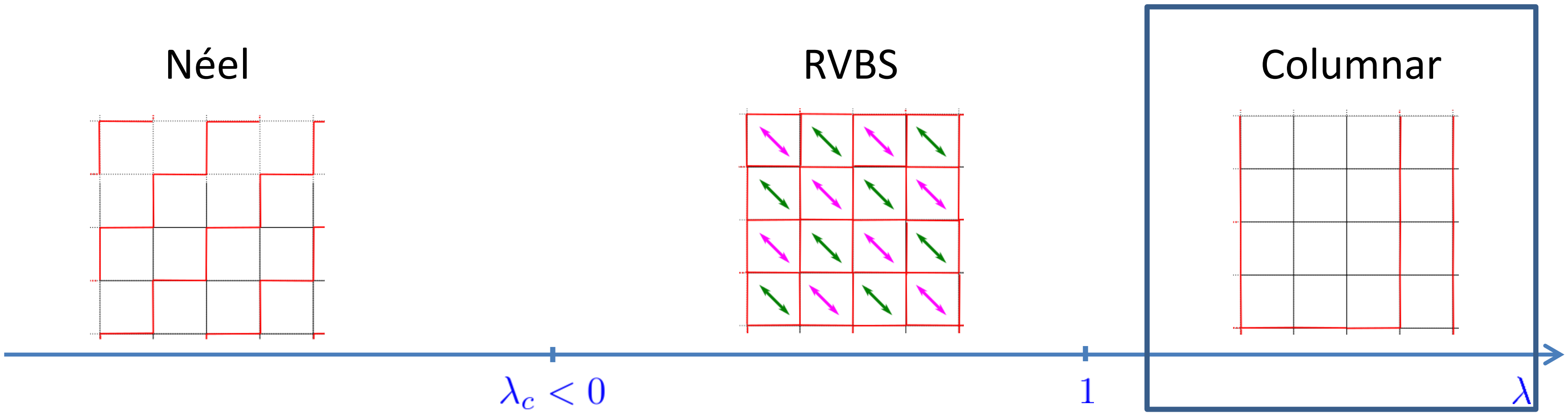
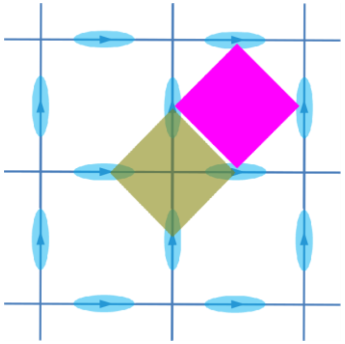


Unflippable background

I.8 Challenge in simulating spin gauge theories

$$H = -J\sum_s \left(\hat{S}^+_{s,x}\hat{S}^+_{s+\hat{x},y}\hat{S}^-_{s+\hat{y},x}\hat{S}^-_{s,y} + H.c.\right) = -J\sum_s \left(\hat{\mathcal{S}}^\dagger_s + \hat{\mathcal{S}}_s\right)$$



Plaquette interaction hard to implement

Existing proposal to simulate Gauss law and dynamics

- Analogue approach: Gauss law from energy penalty
  plaquette interactions perturbatively

[Büchler *et al*'05, Glaetzle *et al*'14]

- Digital simulation with Rydberg gates:
  Gauss law by dissipation
  plaquette interactions from sequential operations

[Weimer *et al*'10]
[Tagliacozzo,AC *et al*'13]

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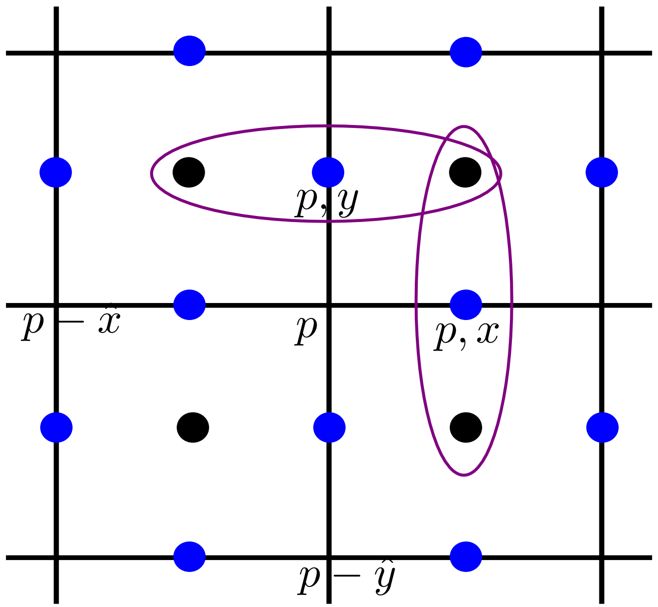
III. Rydberg implementation and examples

Dual formulation of spin gauge theory [AC *et al*, to appear]

$$H = -J \sum_p \left(\hat{S}^+_{p,x} \hat{S}^+_{p+\hat{x},y} \hat{S}^-_{p+\hat{y},x} \hat{S}^-_{p,y} + H.c. \right) = -J \sum_p \left(\hat{\mathcal{S}}^\dagger_p + \hat{\mathcal{S}}_p \right)$$



$$\hat{S}^z_{p,x} = -2(-1)^p \hat{\mathcal{S}}^z_p \hat{\mathcal{S}}^z_{p-\hat{y}}$$

$$\hat{S}^z_{p,y} = 2(-1)^p \hat{\mathcal{S}}^z_p \hat{\mathcal{S}}^z_{p-\hat{x}}$$

$$H_d = -2J \sum_p \left(P_p^{\uparrow\uparrow\uparrow\uparrow} + P_p^{\downarrow\downarrow\downarrow\downarrow} \right) \hat{\mathcal{S}}^x_p$$

Dual formulation of spin gauge theory [AC *et al*, to appear]

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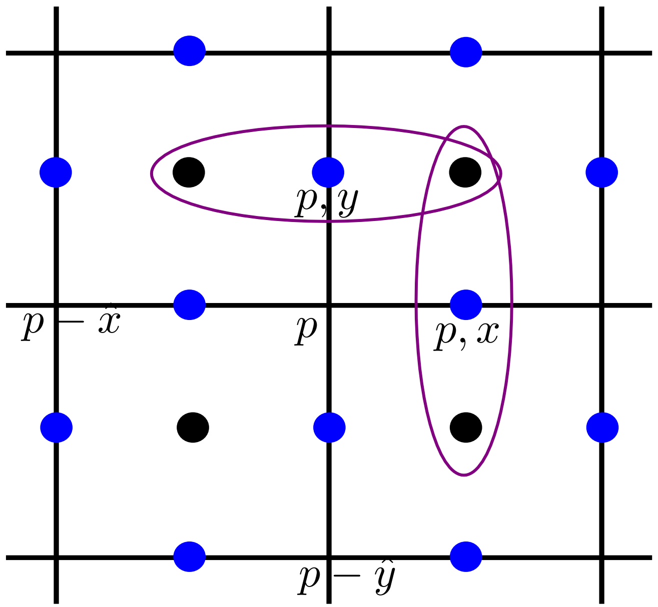

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$$\hat{S}^z_{p,y} = 2(-1)^p\hat{\mathcal{S}}^z_p\hat{\mathcal{S}}^z_{p-\hat{x}}$$

Spin version of height construction

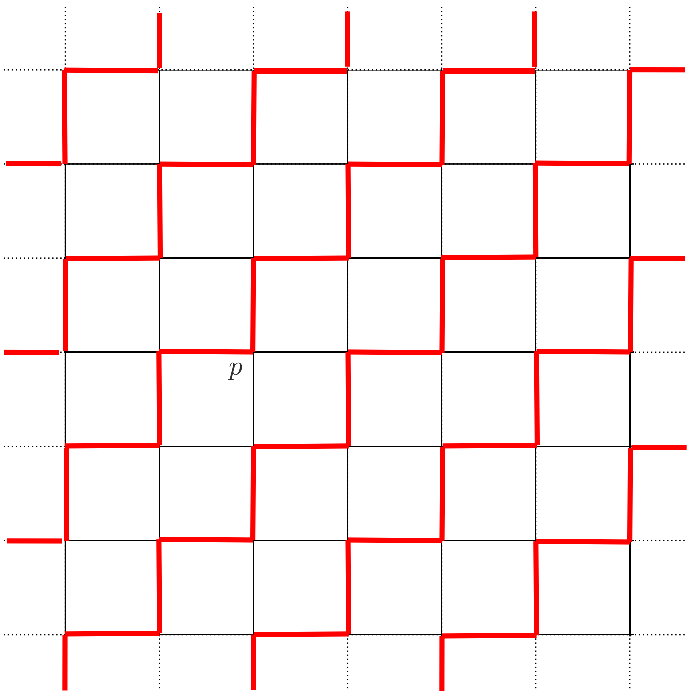
$$H_d = -2J\sum_p\left(P^{\uparrow\uparrow\uparrow\uparrow}_p + P^{\downarrow\downarrow\downarrow\downarrow}_p\right)\hat{\mathcal{S}}^x_p$$

cf. duality in KS U(1), [*J. Zhang et al* PRL **121**, 223201 (2018)]

Dual formulation of spin gauge theory [AC *et al*, to appear]

All plaquettes flippable

Ferro state



$$\hat{S}^z_{p,x} = -2(-1)^p \hat{S}^z_p \hat{S}^z_{p-\hat{y}}$$

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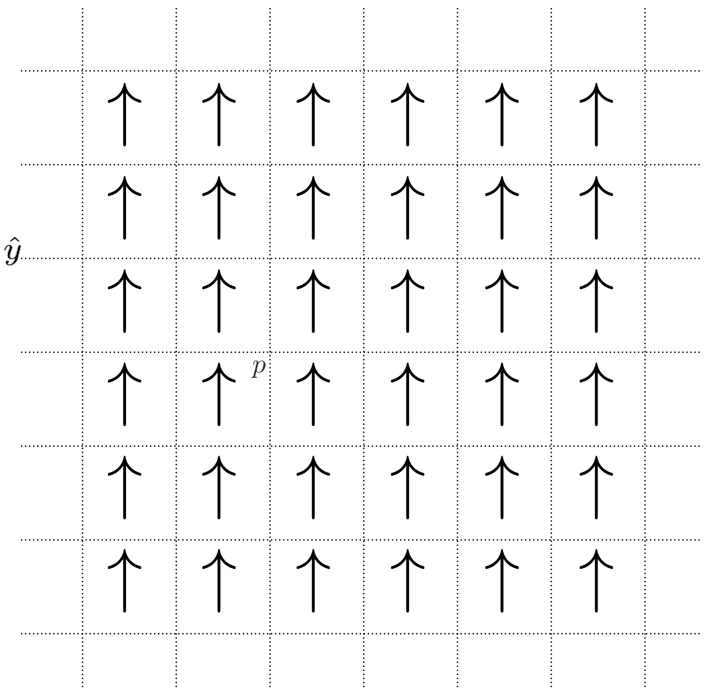
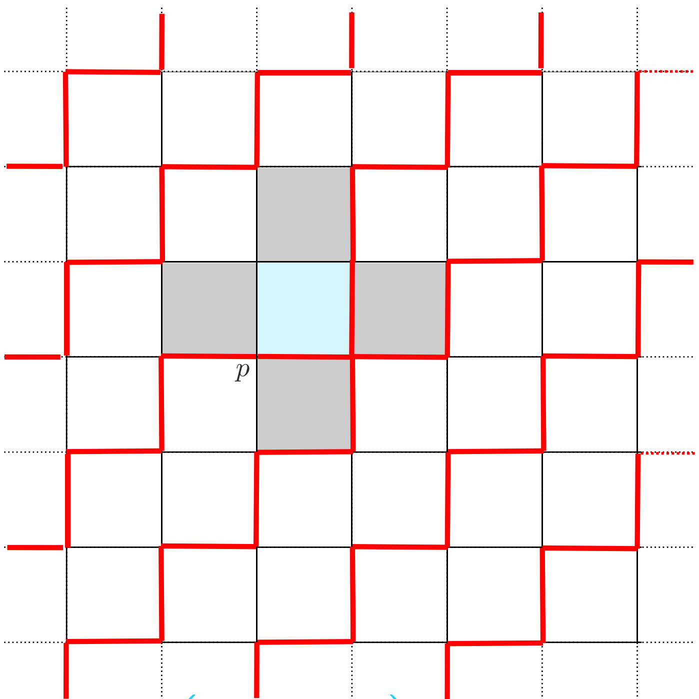


$|\Omega\rangle$

$|\Omega\rangle$

Dual formulation of spin gauge theory [AC *et al*, to appear]

Plaquette action: flip and blockade



$$\left(\hat{\mathcal{S}}_p + \hat{\mathcal{S}}_p^\dagger\right)|\Omega\rangle$$

$$\hat{S}^z_{p,x} = -2(-1)^p \hat{S}^z_p \hat{S}^z_{p-\hat{y}}$$

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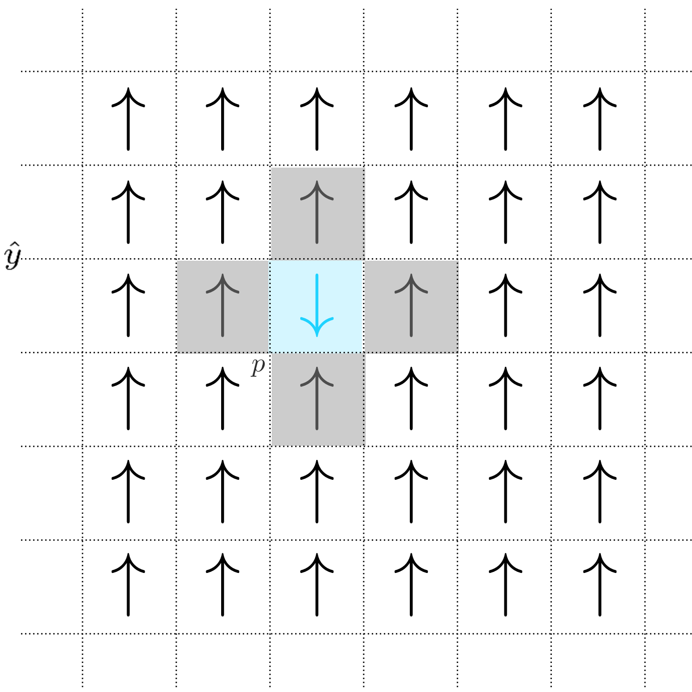
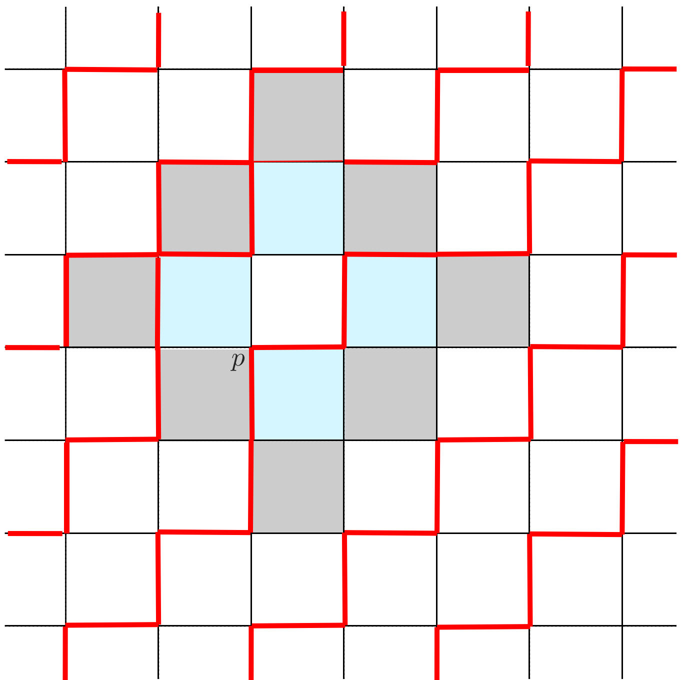


$$\left(\hat{\mathcal{S}}_p + \hat{\mathcal{S}}_p^\dagger\right)|\Omega\rangle$$

Dual formulation of spin gauge theory [AC *et al*, to appear]

Plaquette action: also antiblockade



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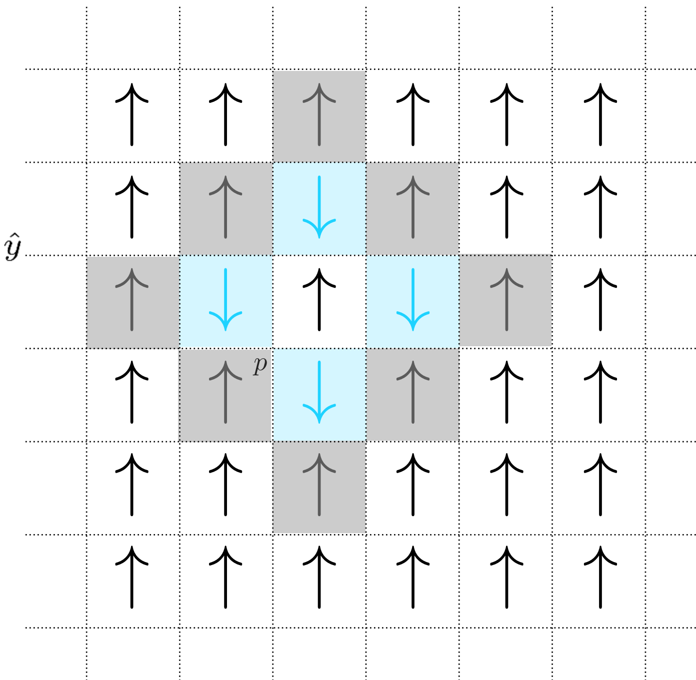

$$\prod_{p' \in <p>} \left(\hat{\mathcal{S}}_p + \hat{\mathcal{S}}_p^\dagger\right)|\Omega\rangle$$

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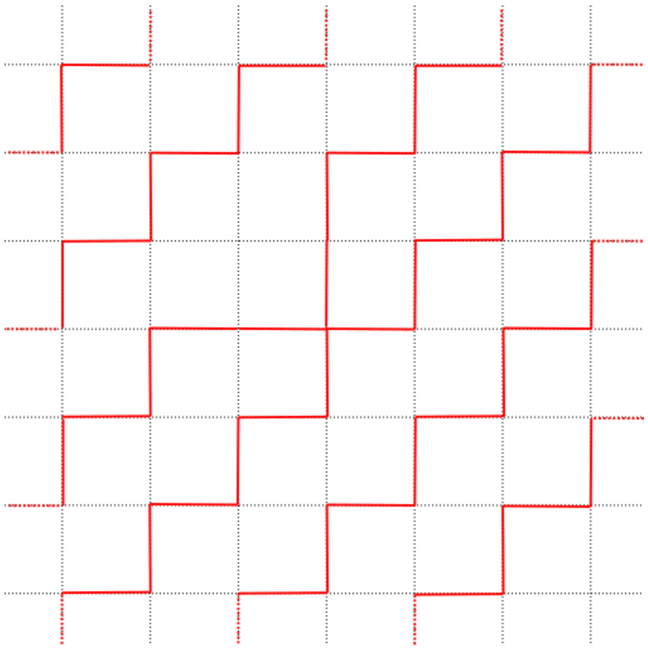
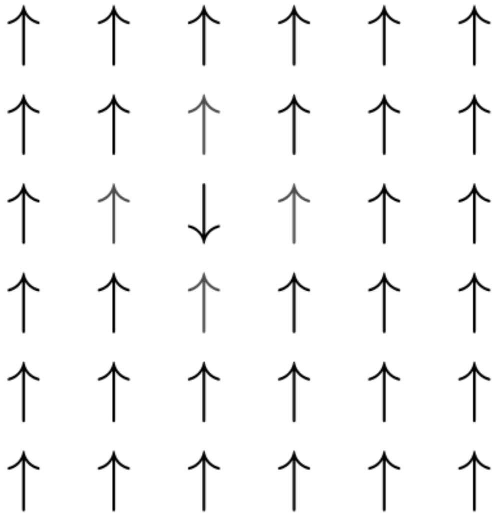
Dual formulation of spin gauge theory [AC *et al*, to appear]

Original string states



Dual plaquette spins



$$H = -J \sum_p \left(\hat{S}_p^\dagger + \hat{S}_p \right) \quad \Longleftrightarrow \quad H_d = -2J \sum_p \left(\hat{P}_p^{\uparrow\uparrow\uparrow\uparrow} + \hat{P}_p^{\downarrow\downarrow\downarrow\downarrow} \right) \hat{S}_p^x$$

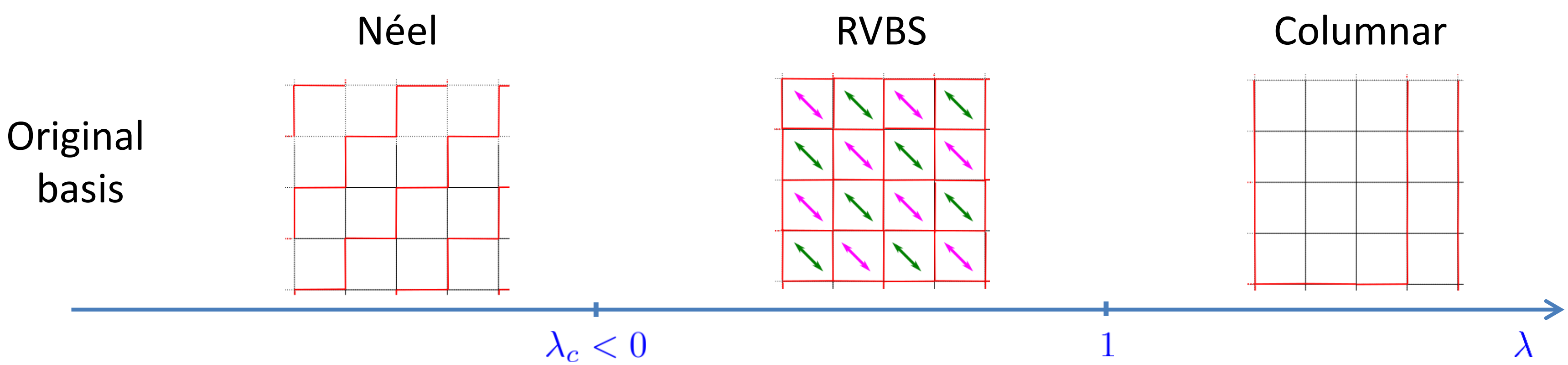
Valid for other lattices and background charges

Dual Rokhsar-Kivelson Hamiltonian [AC *et al*, to appear]

The map trivially extends to the Rokhsar-Kivelson term

$$H_{RK} = -J \sum_s \left(\left(\hat{\mathcal{S}}_s^\dagger + \hat{\mathcal{S}}_s \right) - \lambda \left(\hat{\mathcal{S}}_s^\dagger + \hat{\mathcal{S}}_s \right)^2 \right) \quad \Longleftrightarrow \quad H_{dRK} = -J \sum_s \left(P_s^{\uparrow\uparrow\uparrow\uparrow} + P_s^{\downarrow\downarrow\downarrow\downarrow} \right) \left(2\hat{S}_s^x - \lambda \right)$$

Phase diagram



Dual Rokhsar-Kivelson Hamiltonian [AC *et al*, to appear]

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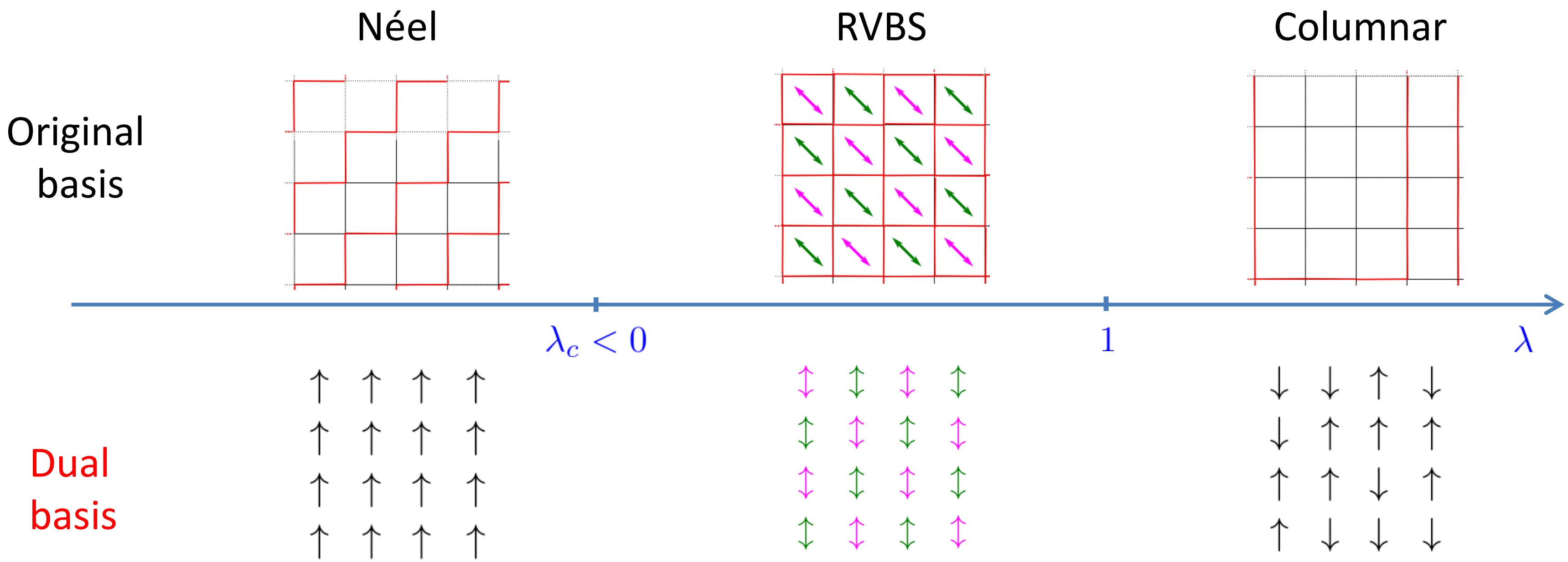

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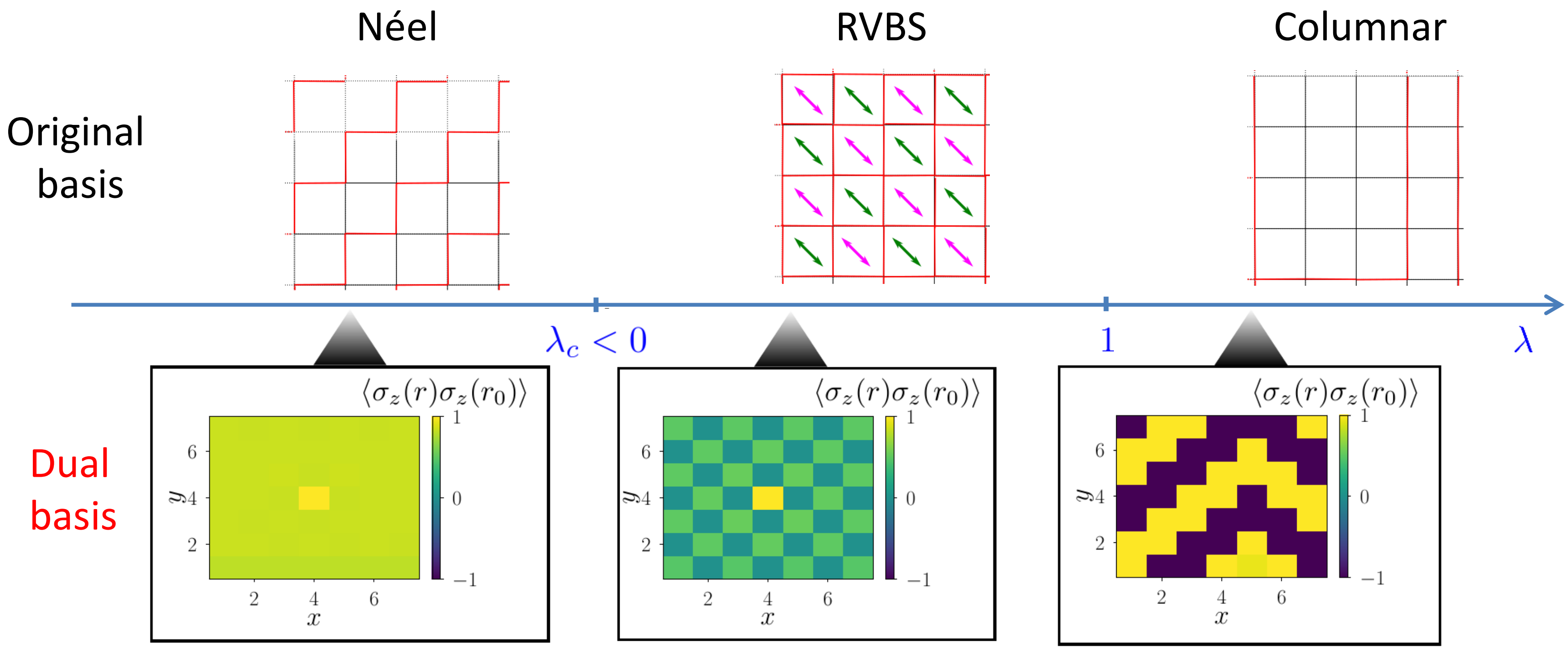
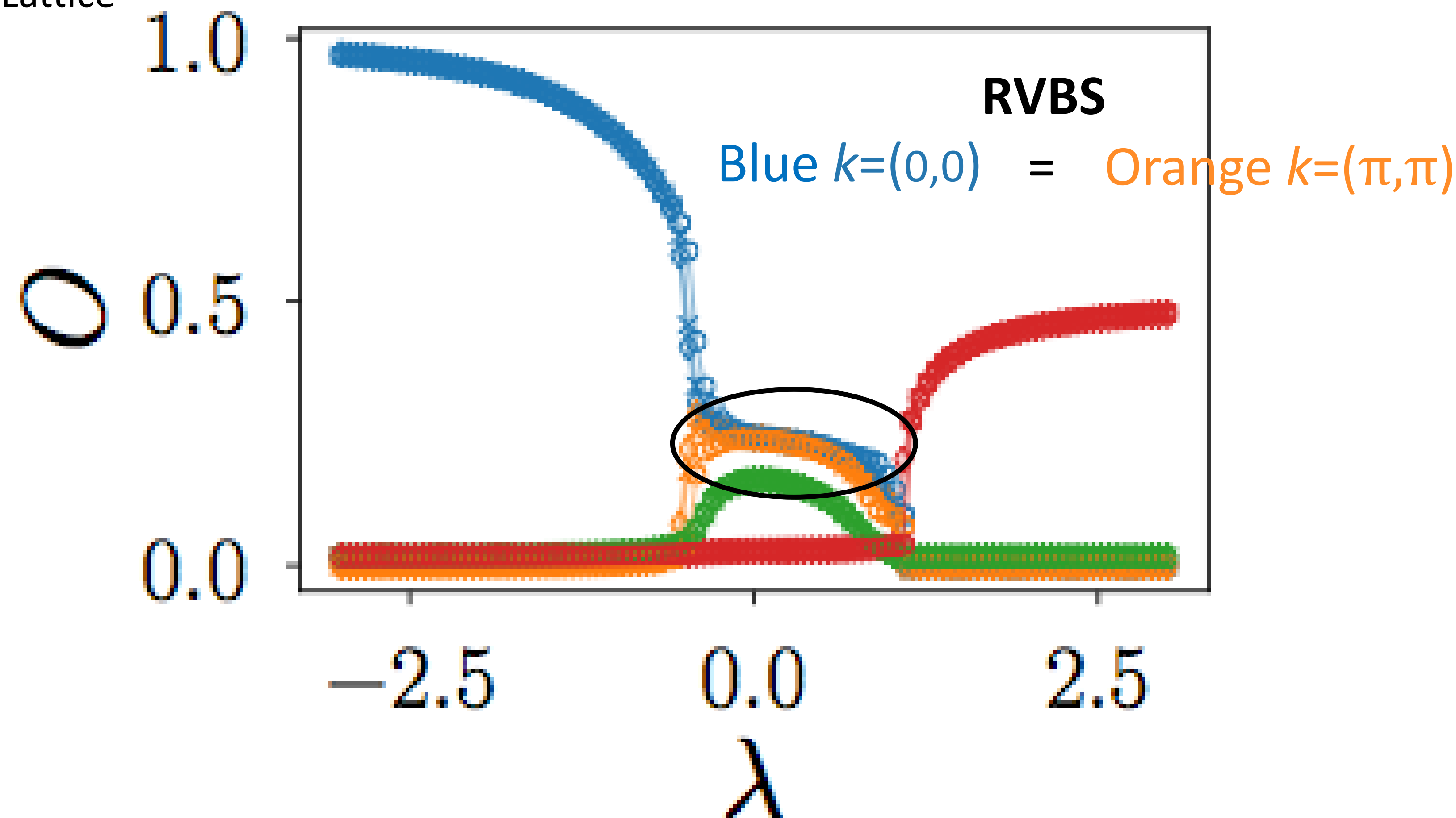
Phase diagram



Dual Rokhsar-Kivelson Hamiltonian [AC *et al*, to appear]

Structure factors and potential energy: good order parameters

DMRG 8x8 Lattice



$$S_k[z] = \sum_s e^{i(s-s')\cdot k} \langle \hat{S}_s^z \hat{S}_{s'}^z \rangle$$

Dual Rokhsar-Kivelson Hamiltonian [AC *et al*, to appear]

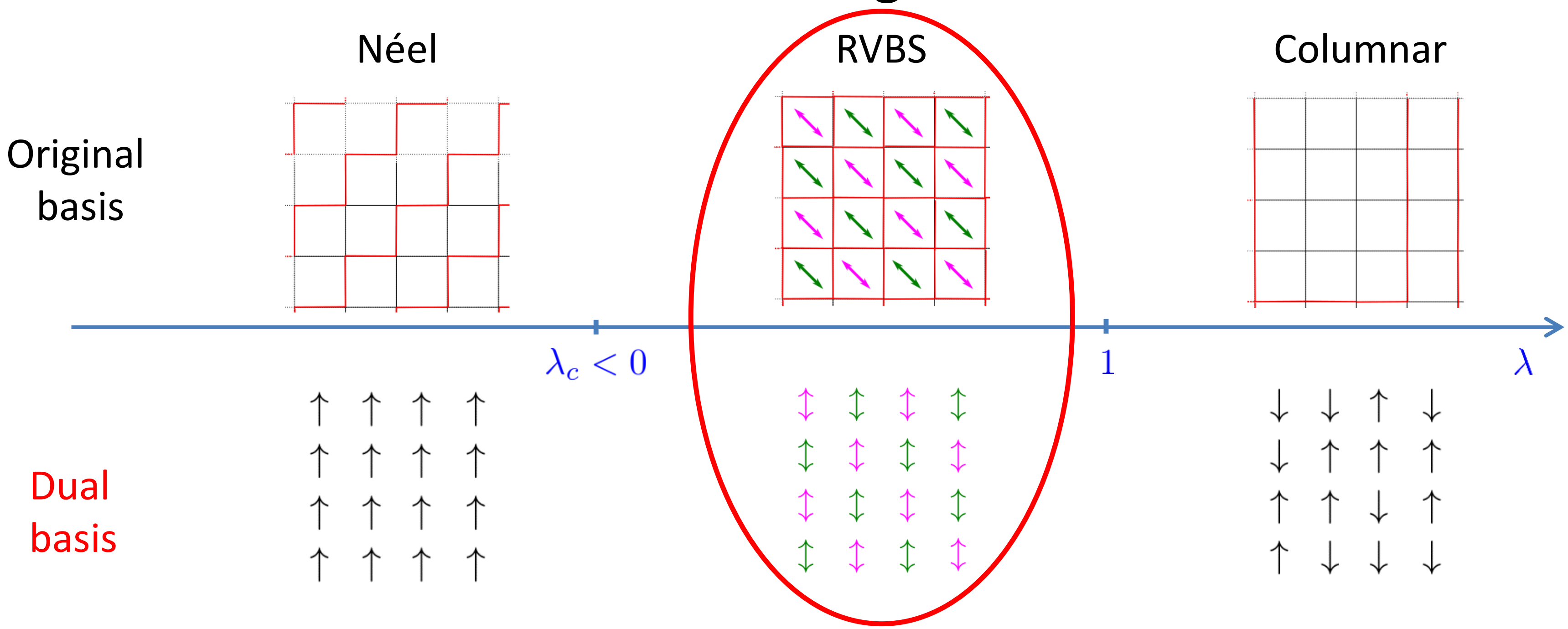
The map trivially extends to the Rokhsar-Kivelson term

$$H_{RK} = -J \sum_s \left(\left(\hat{\mathcal{S}}_s^\dagger + \hat{\mathcal{S}}_s \right) - \lambda \left(\hat{\mathcal{S}}_s^\dagger + \hat{\mathcal{S}}_s \right)^2 \right) \quad \Longleftrightarrow \quad H_{dRK} = -J \sum_s \left(P_s^{\uparrow\uparrow\uparrow\uparrow} + P_s^{\downarrow\downarrow\downarrow\downarrow} \right) \left(2\hat{S}_s^x - \lambda \right)$$

Anti-blockade term restores charge conjugation

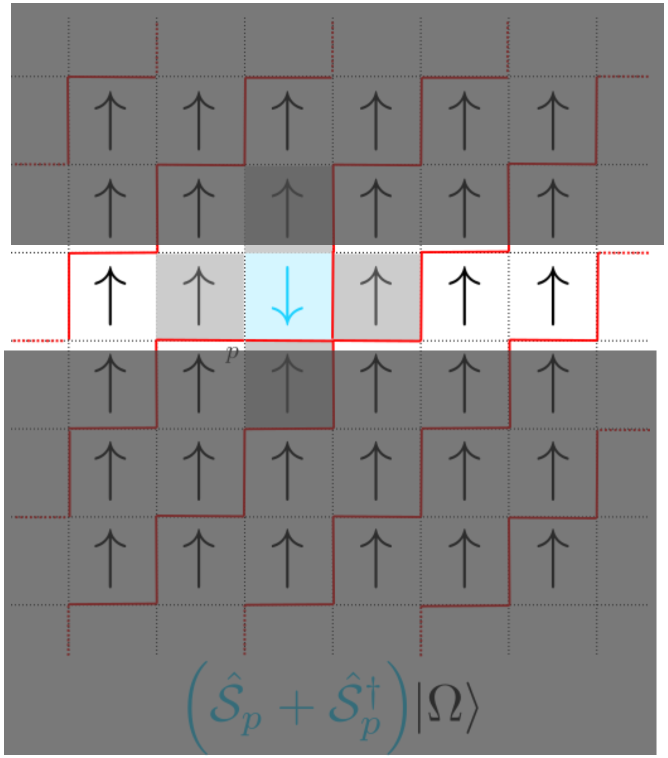
Crucial to achieve the RVBS phase

Phase diagram



Special case.1 RK on a ladder [AC *et al*, to appear]

Minimalist instance: just blockade!



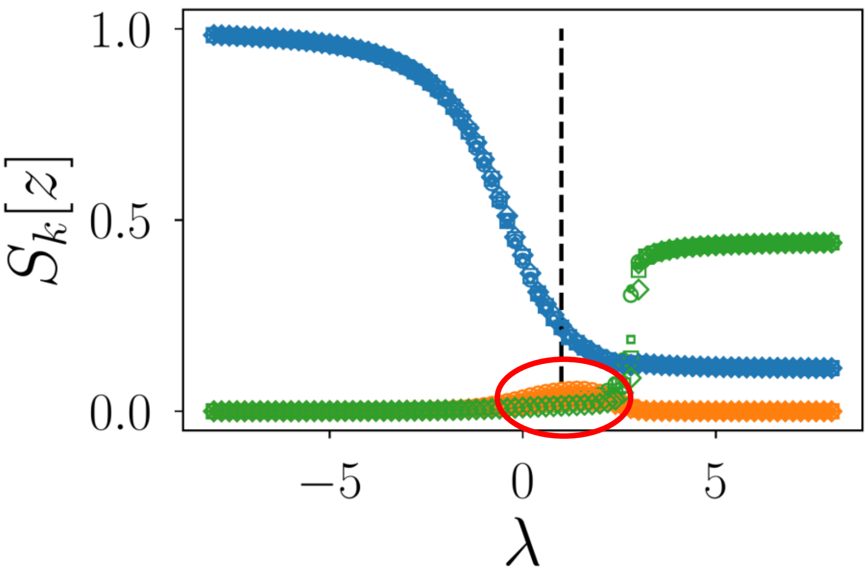
[Moessner,Sondhi'01]

$$H_{dRK} \to -J \sum_s P_s^{\uparrow\uparrow} \left(2\hat{S}_s^x - \lambda\right)$$

$$= PXP + \text{detuning}$$

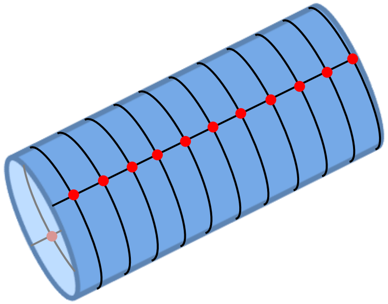
Realized by a Rydberg chain!

RVBS replaced by a disorder phase



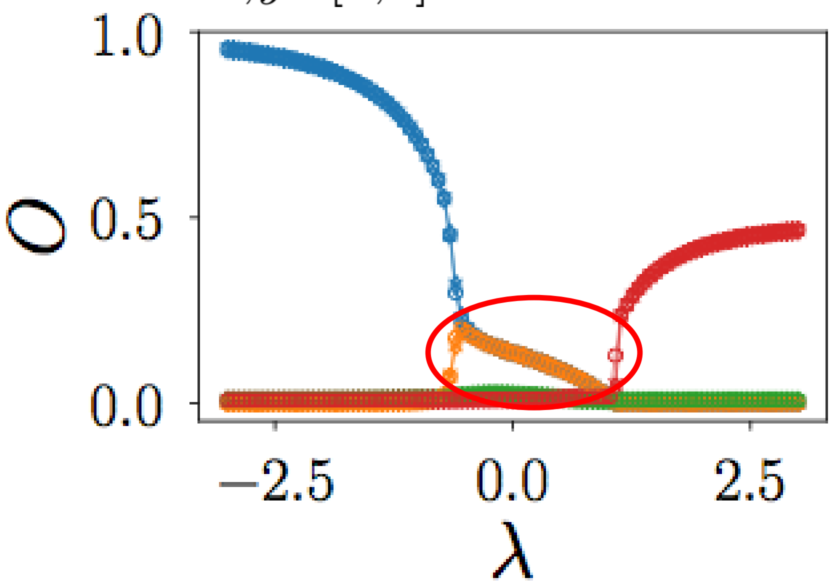
No free lunch:
we need antiblockade!

Special case.2 RK on a periodic ladder [AC *et al*, to appear]



Periodic ladder: simplest cylinder
Bulk plaquettes have all neighbors, 3 independent

$$H_{dRK} \to -J \sum_{x,y=[0,1]} \left(P_{x,y}^{\uparrow\uparrow\uparrow} + P_{x,y}^{\downarrow\downarrow\downarrow}\right)\left(2\hat{S}_{x,y}^{x} - \lambda\right)$$



DMRG 64x2

Minimal geometry hosting a RVBS phase

Outline

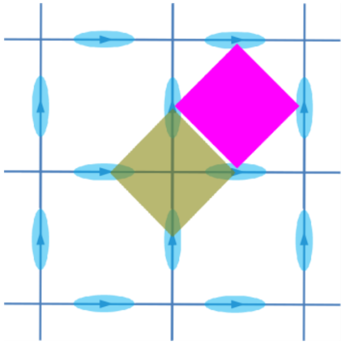
I. Motivations and tutorial

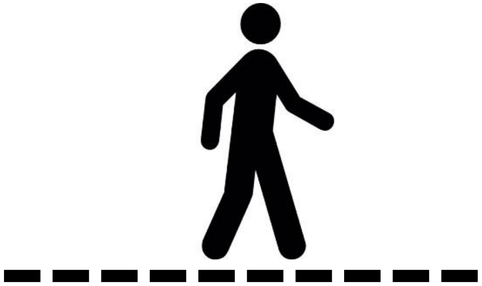
From static to dynamical gauge theories
The Rokhsar-Kivelson model
Implementation: experimental challenges

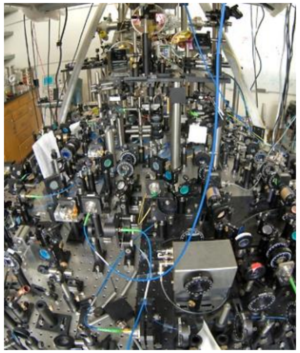
II. Suitable encoding
Converting Ring exchange to blockade

III. Rydberg implementation and examples

Engineering the dual Rokhsar-Kivelson model [AC *et al*, to appear]

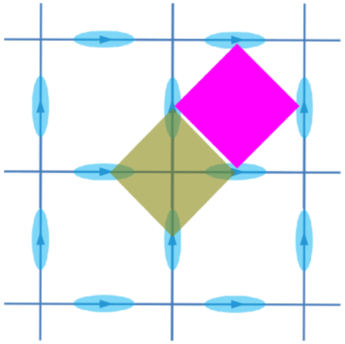


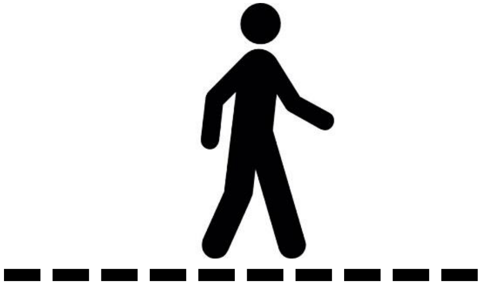


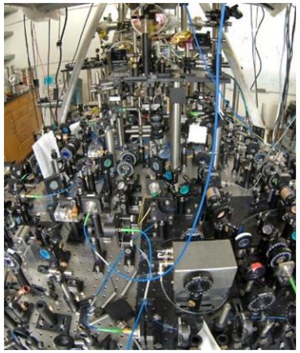


$$H_{RK} \to H_{dRK} \to -J \sum_{s} \left(P_s^{\uparrow\uparrow\uparrow\uparrow} + P_s^{\downarrow\downarrow\downarrow\downarrow}\right) \left(2\hat{S}_s^x - \lambda\right)$$

Engineering the dual Rokhsar-Kivelson model [AC *et al*, to appear]





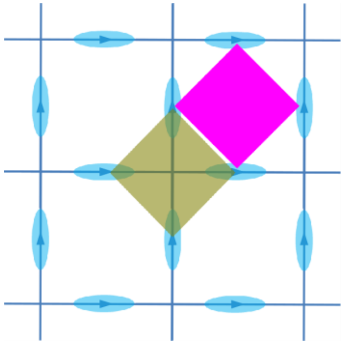


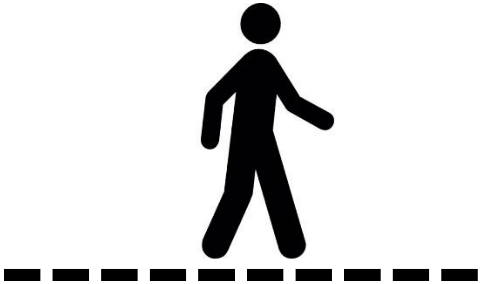
$$H_{RK} \to H_{dRK} \to -J \sum_s \left(P_s^{\uparrow\uparrow\uparrow\uparrow} + P_s^{\downarrow\downarrow\downarrow\downarrow}\right)\left(2\hat{S}_s^x - \lambda\right)$$

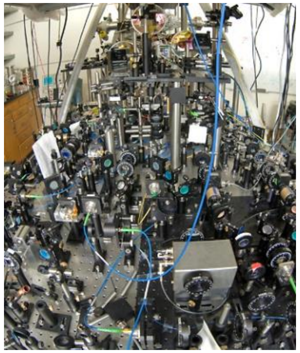
Lesson from blockade: projectors from nearest-neighbor interactions

$$\left(P_s^{\uparrow\uparrow\uparrow\uparrow} + P_s^{\downarrow\downarrow\downarrow\downarrow}\right)\hat{S}_s^x \sim \hat{S}_s^x + \sum_{s'=<s>} V_{ss'}\hat{S}_s^z\hat{S}_{s'}^z, \quad \text{if} \sum_{s'=<s>} V_{ss'} = 0 + \ldots$$

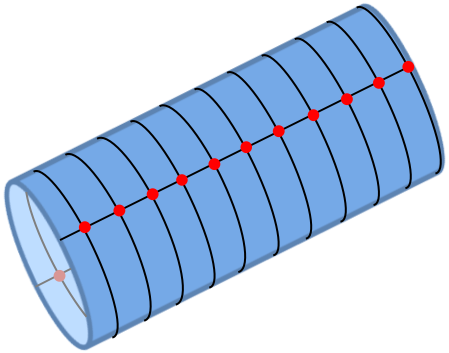
Engineering the dual Rokhsar-Kivelson model [AC *et al*, to appear]



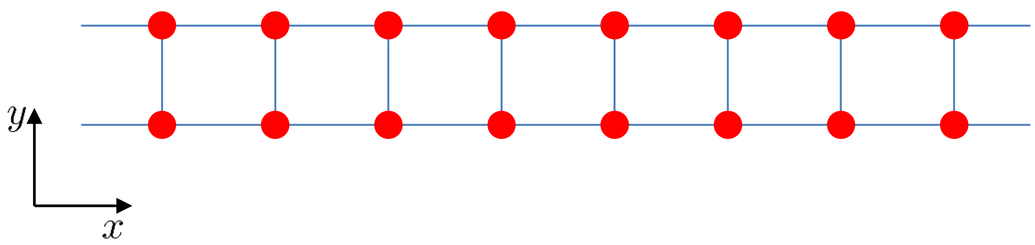




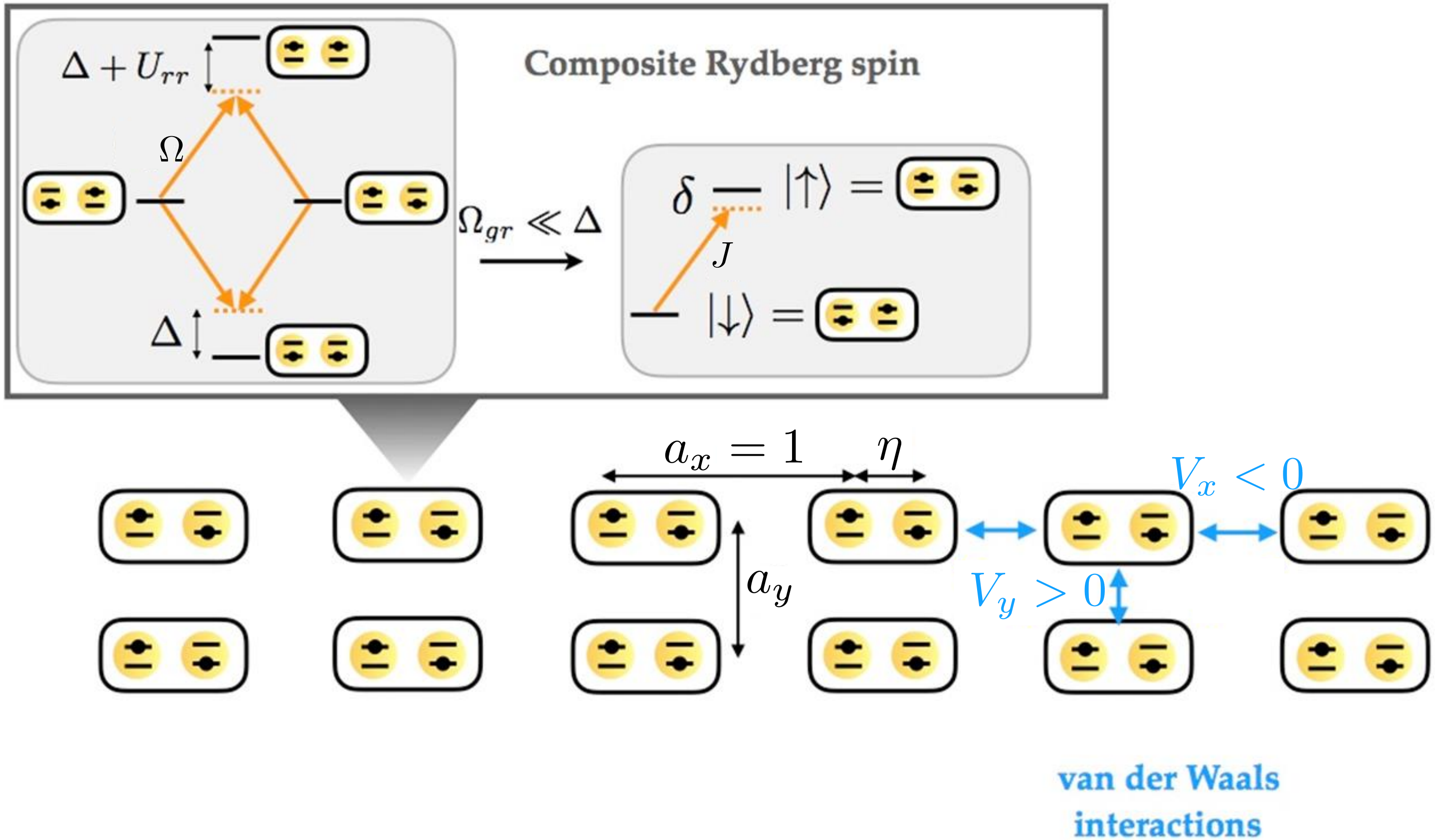
$$H_{RK} \rightarrow H_{dRK} \rightarrow -J \sum_{x,y=[0,1]} \left(P_{x,y}^{\uparrow\uparrow\uparrow} + P_{x,y}^{\downarrow\downarrow\downarrow}\right) \left(2\hat{S}_{x,y}^{x} - \lambda\right)$$



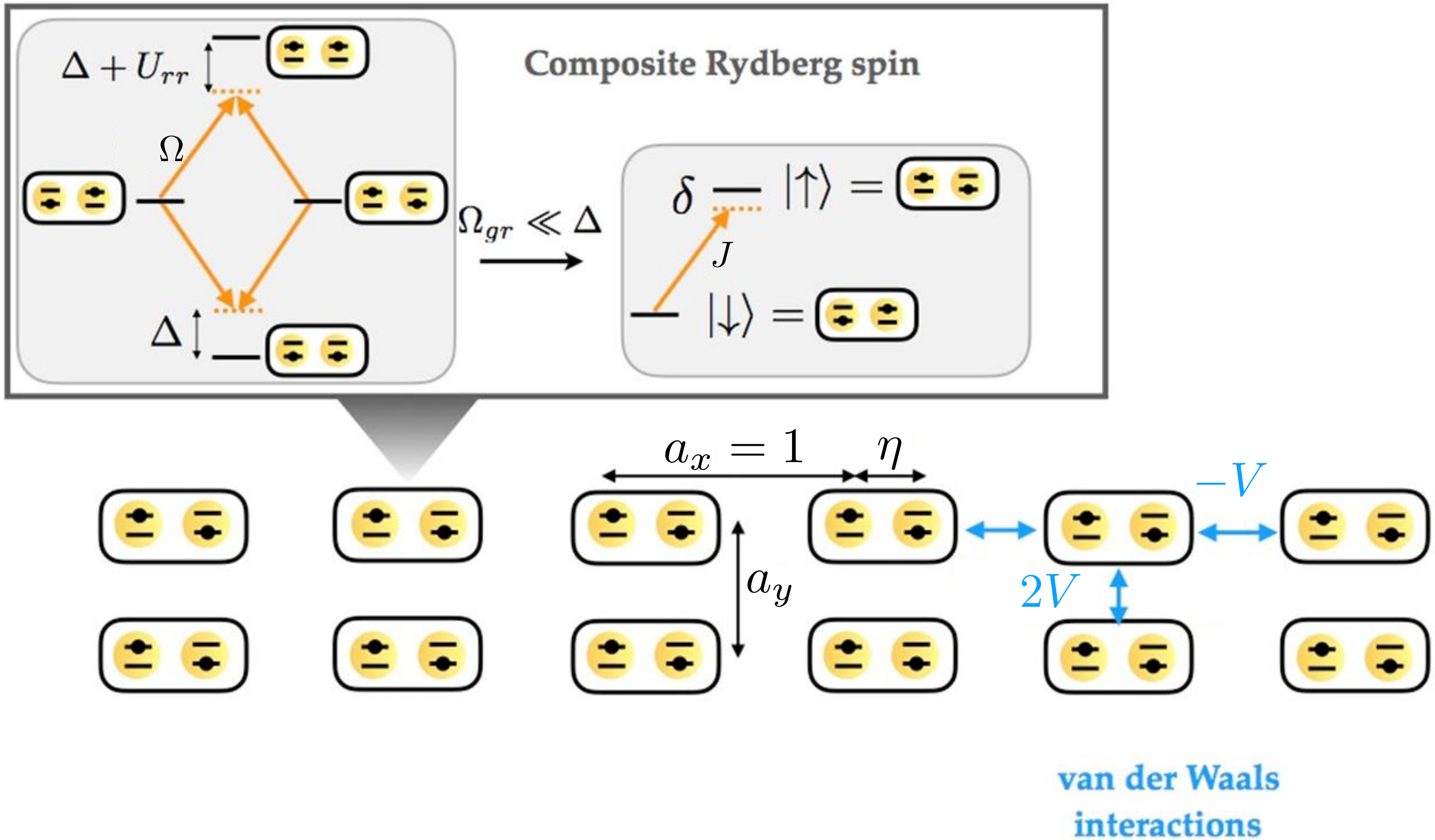
$\rightarrow$



Rokhsar-Kivelson on a periodic ladder [AC *et al*, to appear]



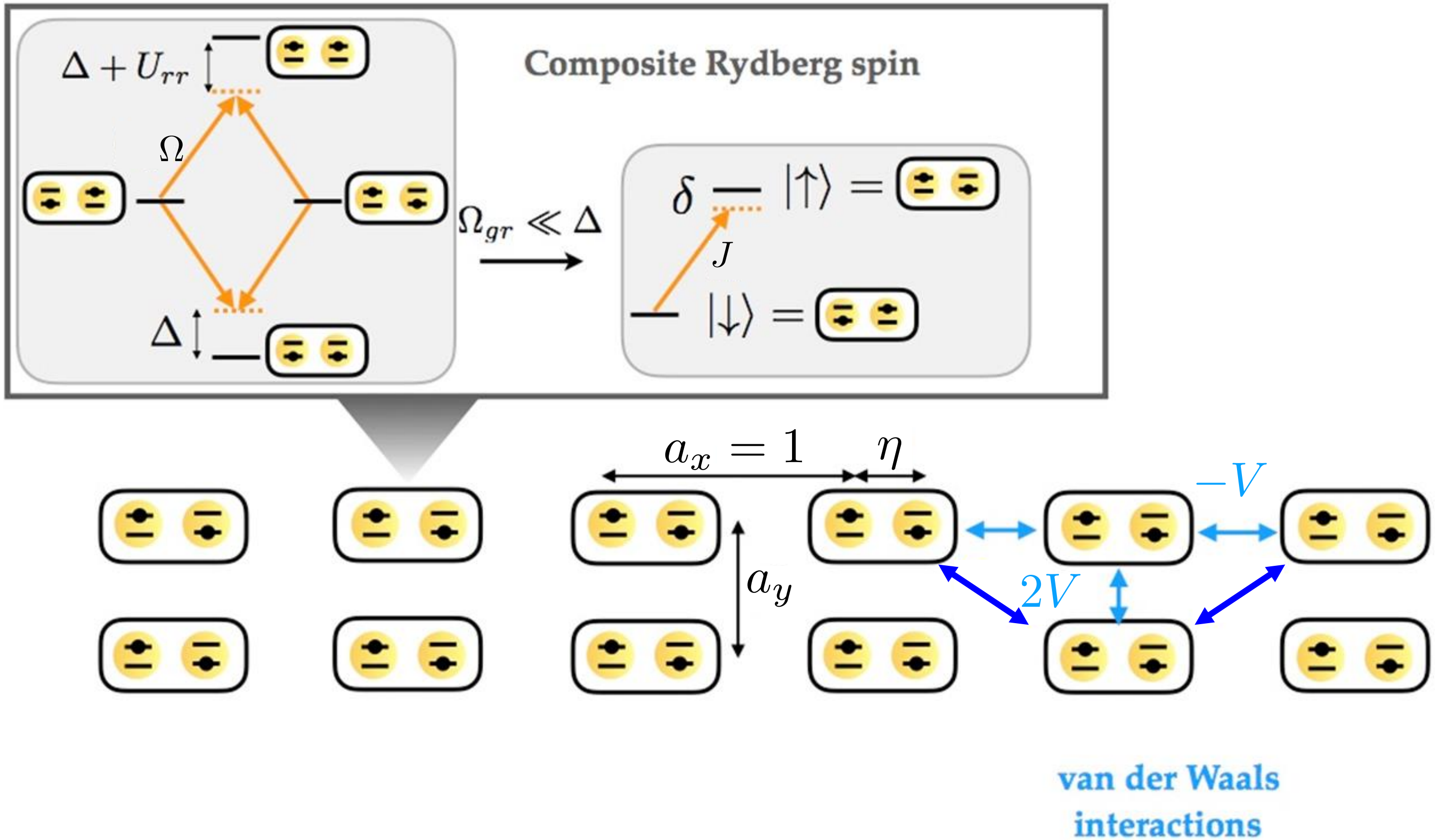
Rokhsar-Kivelson on a periodic ladder [AC *et al*, to appear]



$$H_{Ryd} = \sum_p \left[-2J\hat{S}^x_p - V\hat{S}^z_p \left(\hat{S}^z_{p+\hat{x}} + \hat{S}^z_{p-\hat{x}} - 2\hat{S}^z_{p+\hat{y}} \right) \right]$$

$$\sim -2J \sum_p \left(P^{\uparrow\uparrow\uparrow}_p + P^{\downarrow\downarrow\downarrow}_p \right) \hat{S}^x_p, \text{ for } J \ll V,$$

Rokhsar-Kivelson on a periodic ladder [AC *et al*, to appear]



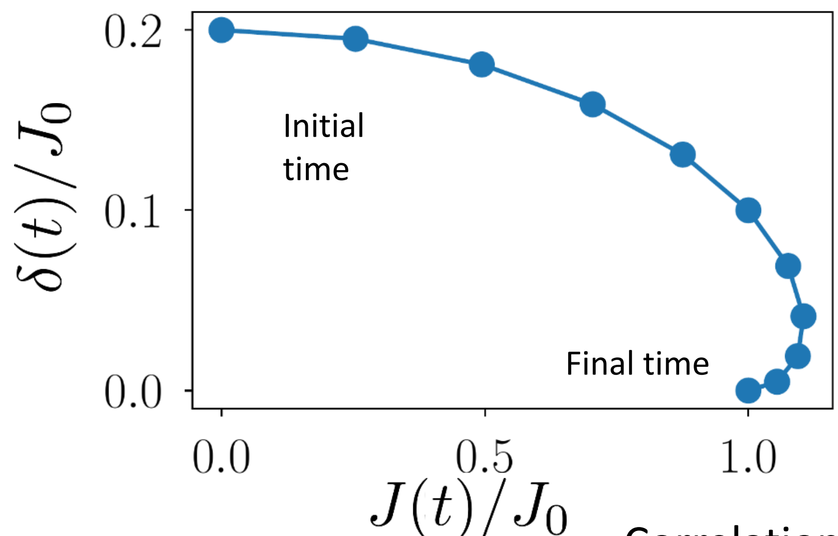
$$H_{Ryd} = \sum_p \left[-2J\hat{S}^x_p - V\hat{S}^z_p \left(\hat{S}^z_{p+\hat{x}} + \hat{S}^z_{p-\hat{x}} - 2\hat{S}^z_{p+\hat{y}} \right) \right] + V^{(2)}$$

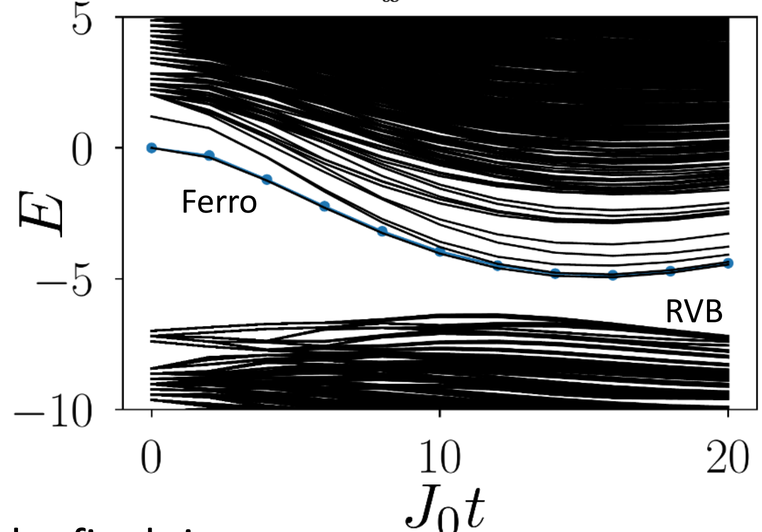
$$\sim -2J \sum_p \left(P_p^{\uparrow\uparrow\uparrow} + P_p^{\downarrow\downarrow\downarrow} \right) \hat{S}^x_p + \Lambda \left(P_p^{\uparrow\uparrow\uparrow} + P_p^{\downarrow\downarrow\downarrow} - P_p^{\uparrow\downarrow\uparrow} - P_p^{\downarrow\uparrow\downarrow} \right)$$

Rokhsar-Kivelson on a periodic ladder [AC *et al*, to appear]

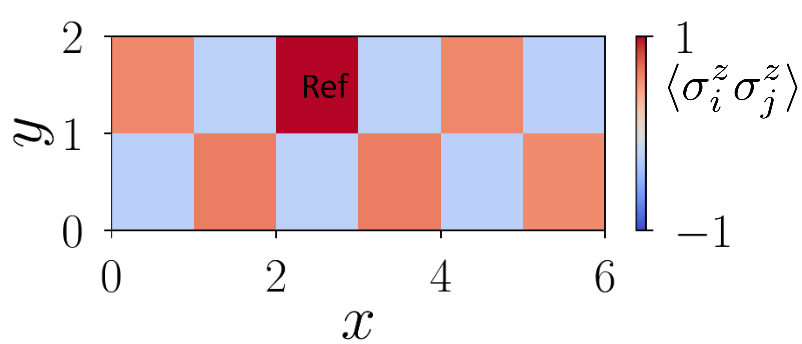
Adiabatic preparation of a RVBS state

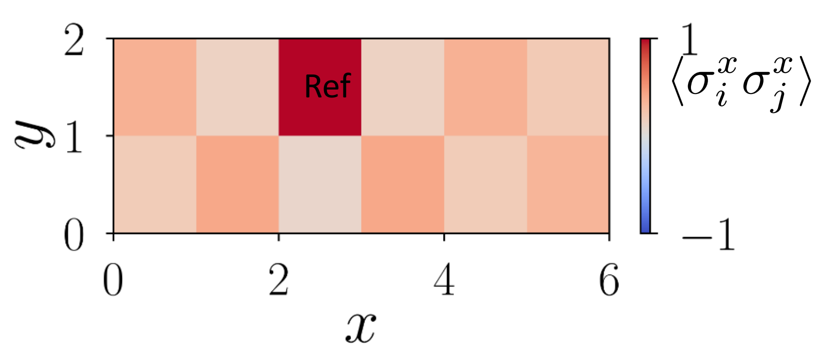
$$\Psi(t=0) = \downarrow \ldots \downarrow \qquad J_0 = \frac{C_6}{a_x^6}$$





Correlations at the final time

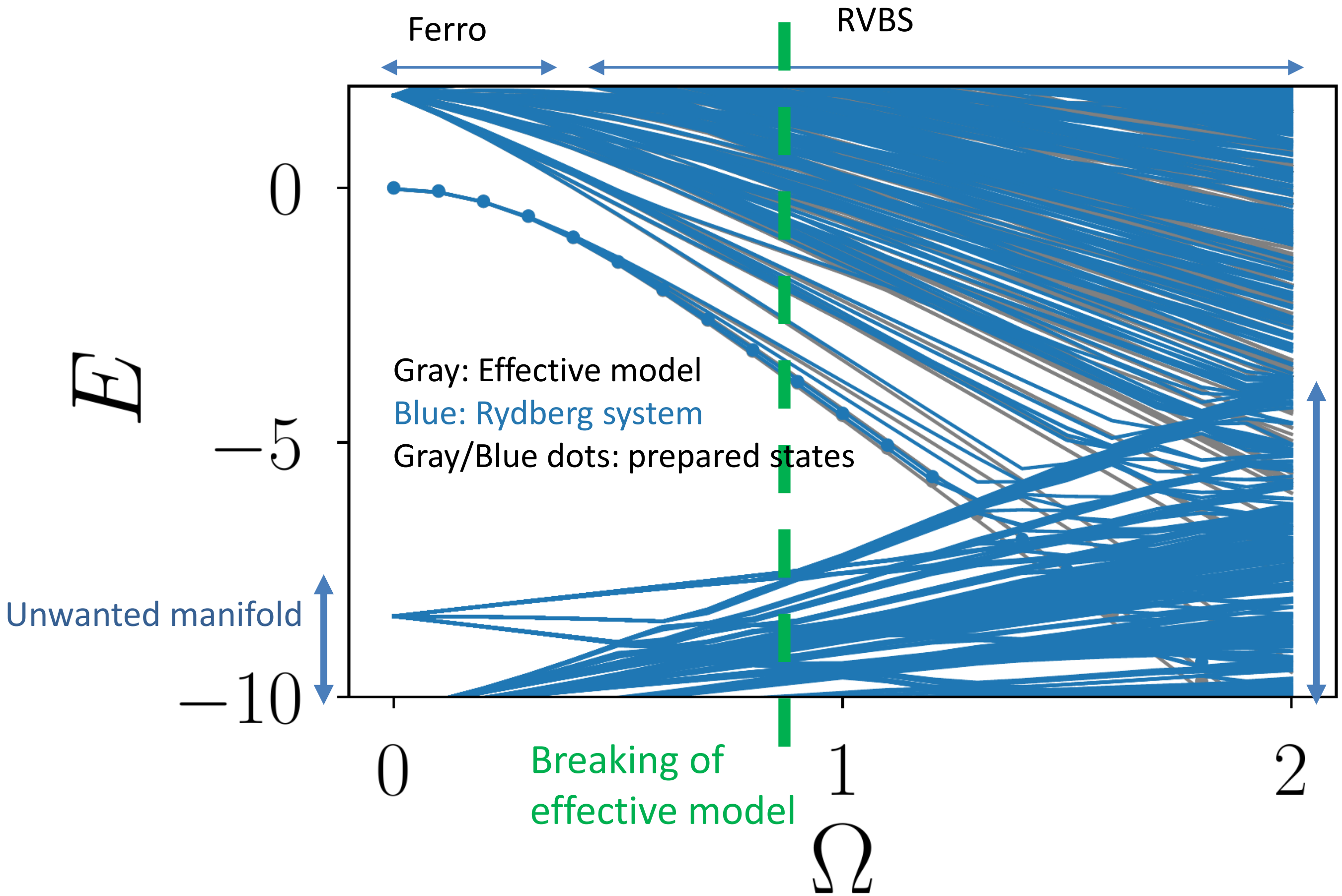




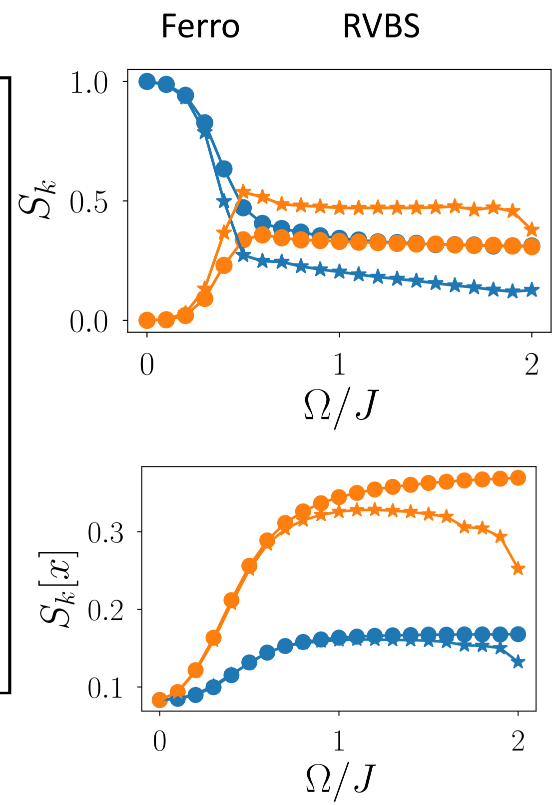
Full Rydberg Model 6x2 PBC $\quad \eta = 0.38 a_x \to a_y(\eta = 0.38 a_x) = 0.59 a_x, V = 15.8 J_0, \Lambda = -0.92 J_0$

Rokhsar-Kivelson on a periodic ladder [AC *et al*, to appear]

Checking the validity of the effective model



Structure Factor



Summary

Rydberg atoms "naturally" realize a 2D scalable U(1) lattice gauge theory

We can prepare and detect the RVBS phase in its dual formulation

B. Vermersch

P. Zoller

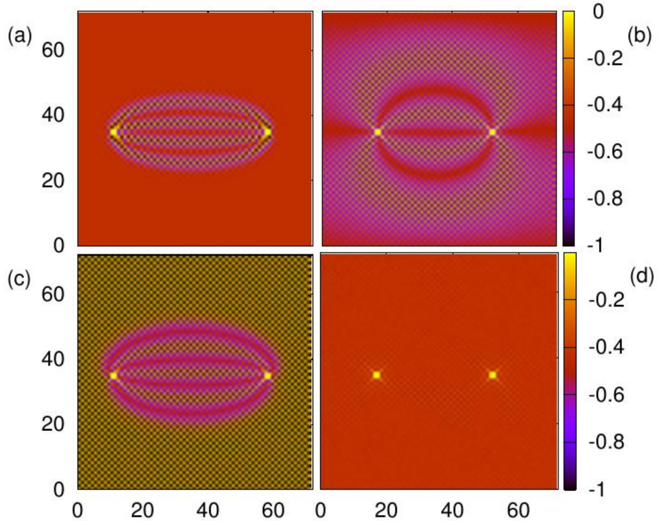
Probing confinement through static charges

Consider other charge distributions/boundary conditions e.g. dual formulation of quantum dimers

Dynamical charges (bosons) -> Higgs mechanism

M.Lukin

In progress



B. Vermersch

P. Zoller

Probing confinement through static charges

Consider other charge distributions/boundary conditions
e.g. dual formulation of quantum dimers

M.Lukin

Dynamical charges (bosons) -> Higgs mechanism

Prospects

HEP: First 2D lattice gauge theory soon in the lab!

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Condensed matter: new route to quantum magnetism

- Other geometries
- Charges and excitation (quantum probes)
- New mechanisms RVBS -> U(1) spin liquid?

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AMO physics: new family of models with entangled phases

- Anisotropic tunable coupling
- Larger spin from macro-atoms

Rokhsar-Kivelson on the square lattice [AC *et al*, to appear]