Correlated phases of bosons in tilted lattices

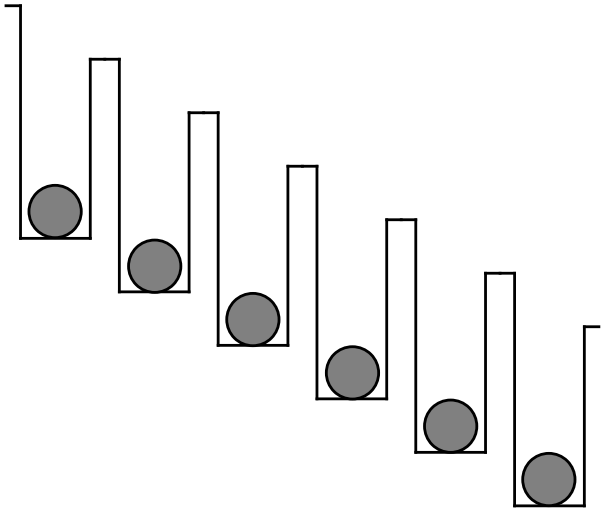
sachdev.physics.harvard.edu

Susanne Pielawa

Takuya Kitagawa

Erez Berg

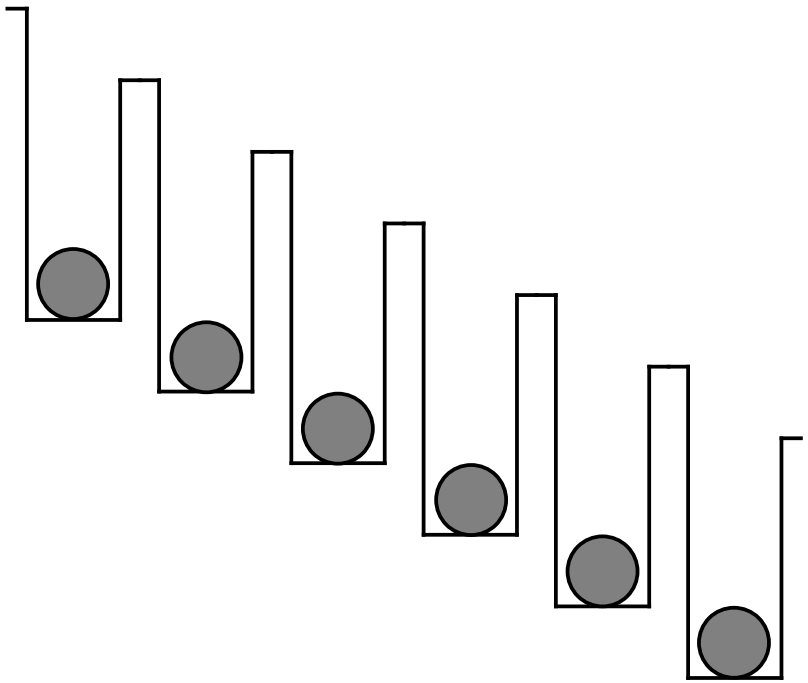
S. Sachdev, K. Sengupta, and S.M. Girvin, Phys. Rev. B **66**, 075128 (2002)
S. Pielawa, T. Kitagawa, E. Berg, S. Sachdev, Phys. Rev. B **83**, 205135 (2011)

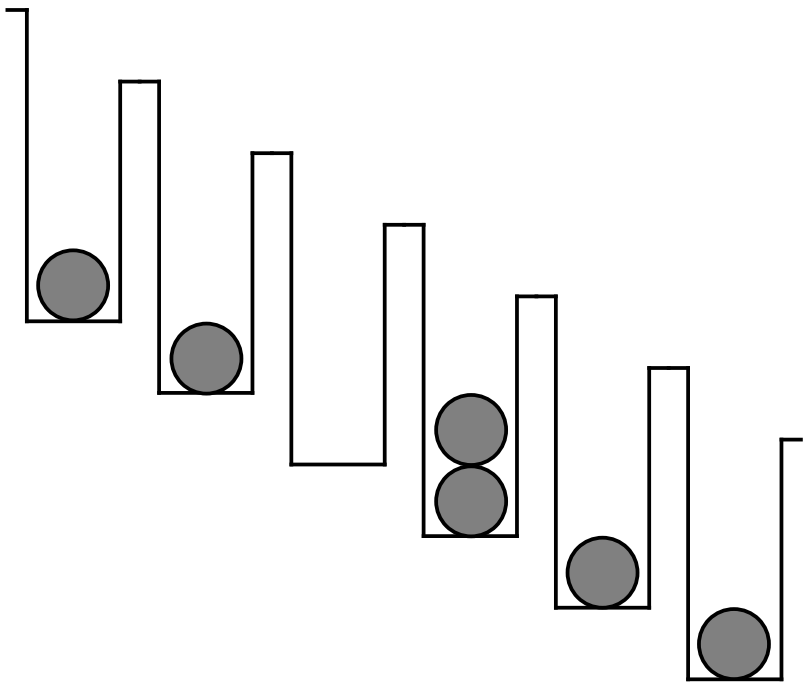


$$H = -t\sum_{\langle ij\rangle}\left(b_i^\dagger b_j + b_j^\dagger b_i\right) + \frac{U}{2}\sum_i n_i\left(n_i - 1\right) - \sum_i \boldsymbol{E}\cdot\boldsymbol{r}_i n_i$$

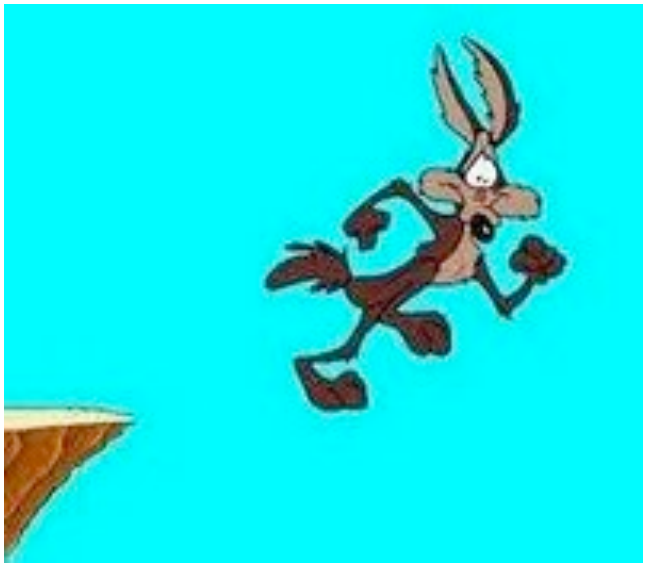
$$n_i = b_i^\dagger b_i$$

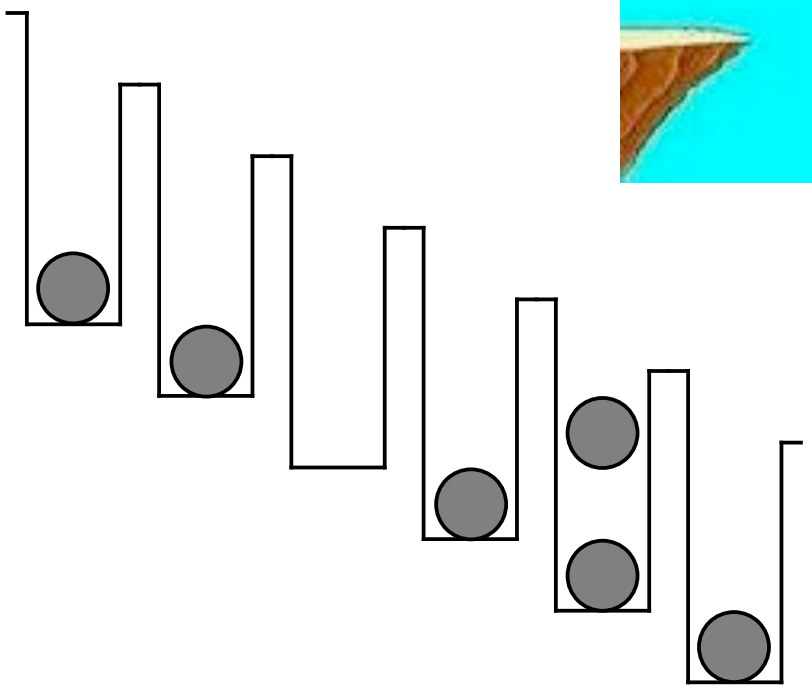
$$\left|U - E\right|, t \ll E, U$$



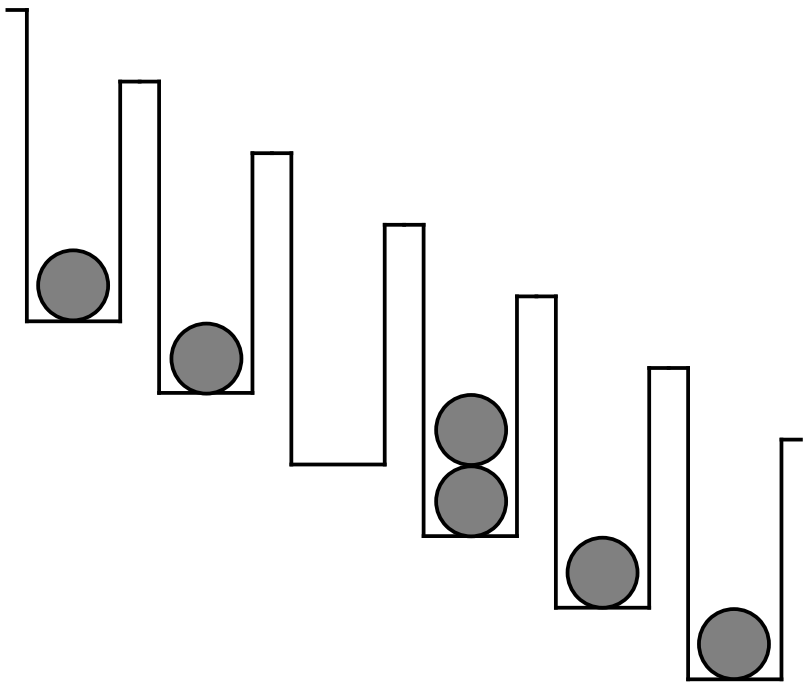


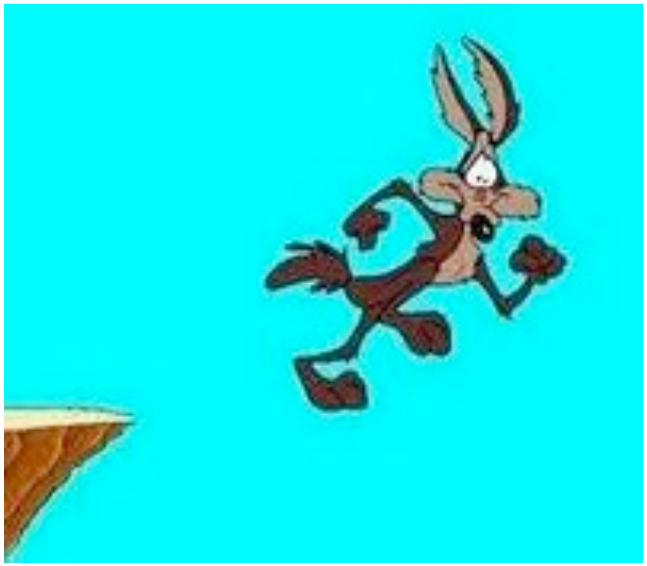
Resonant transition when $E \approx U$

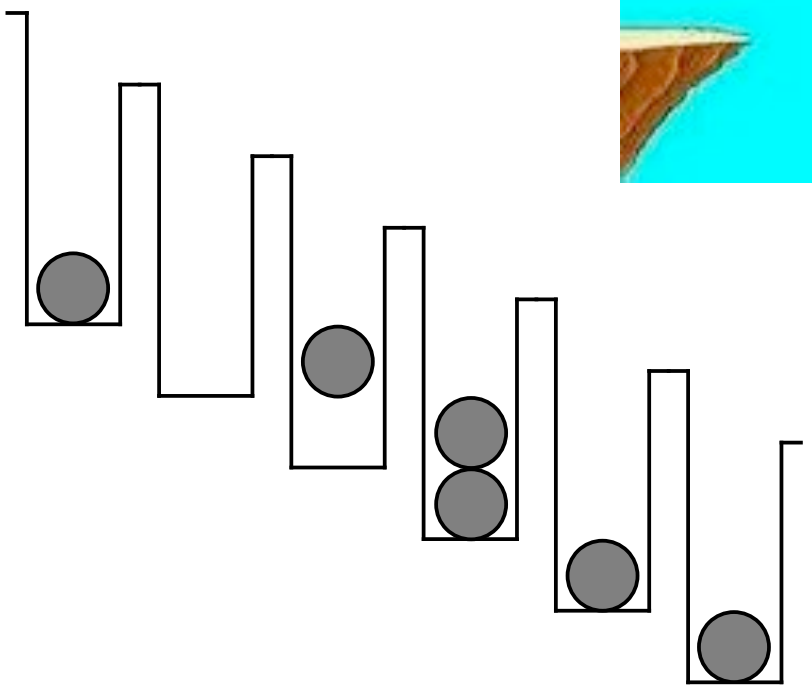




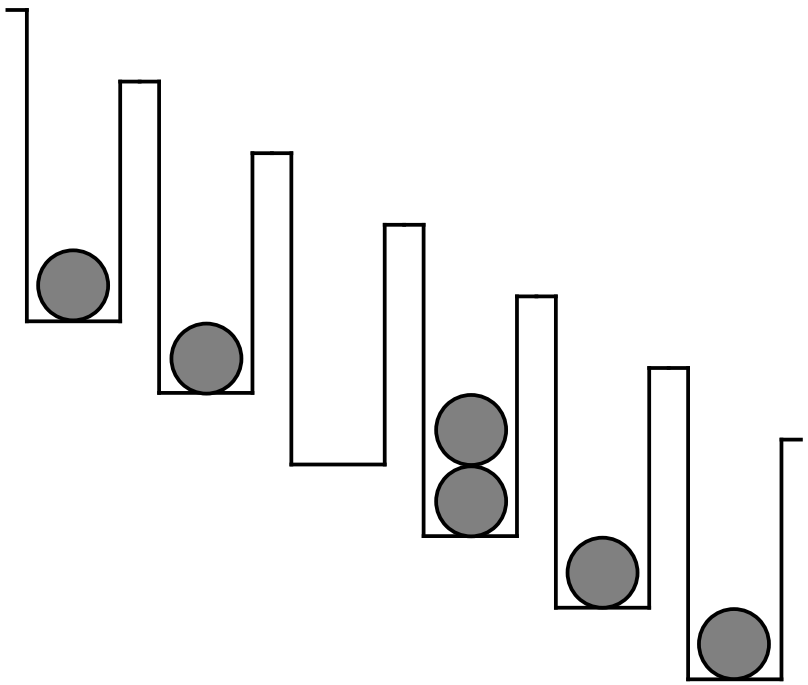
Virtual state

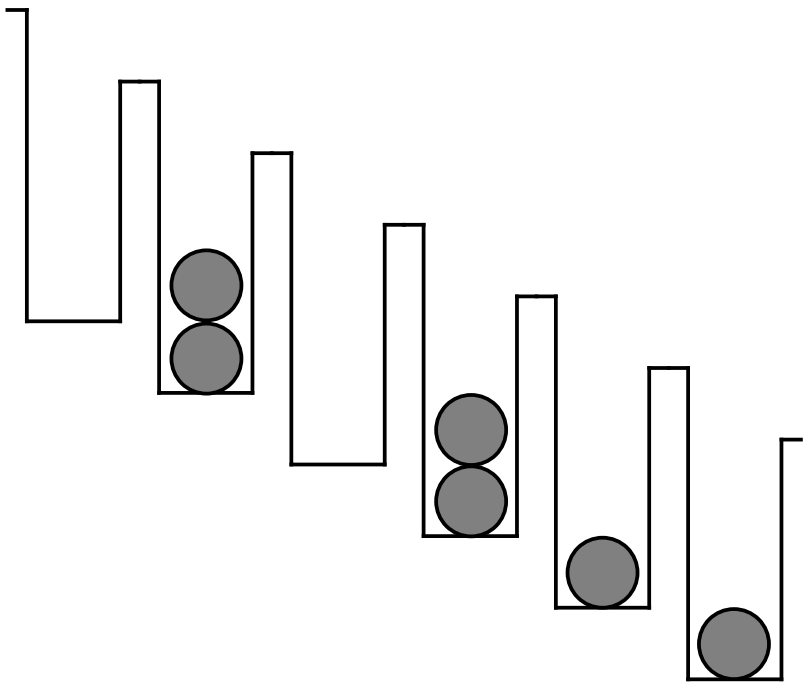




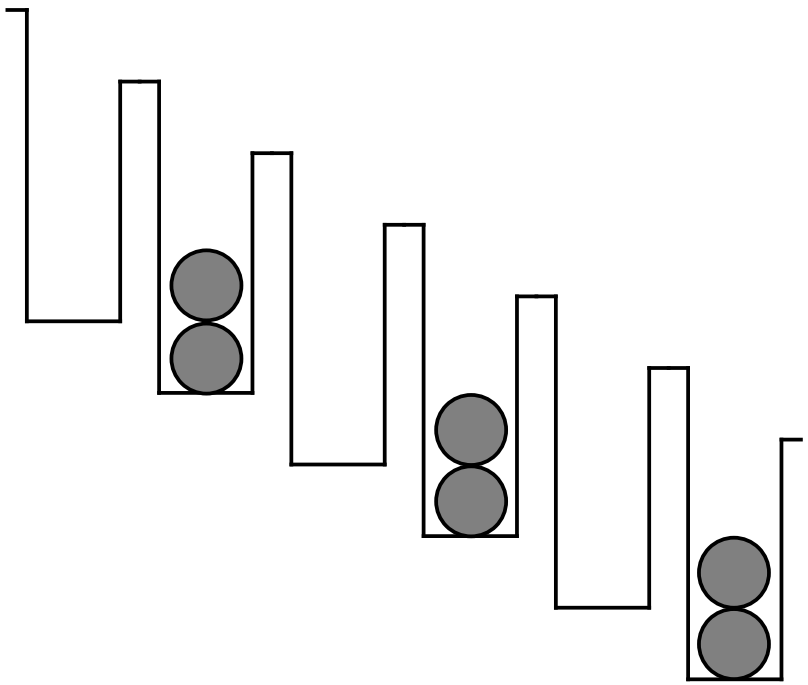


Virtual state

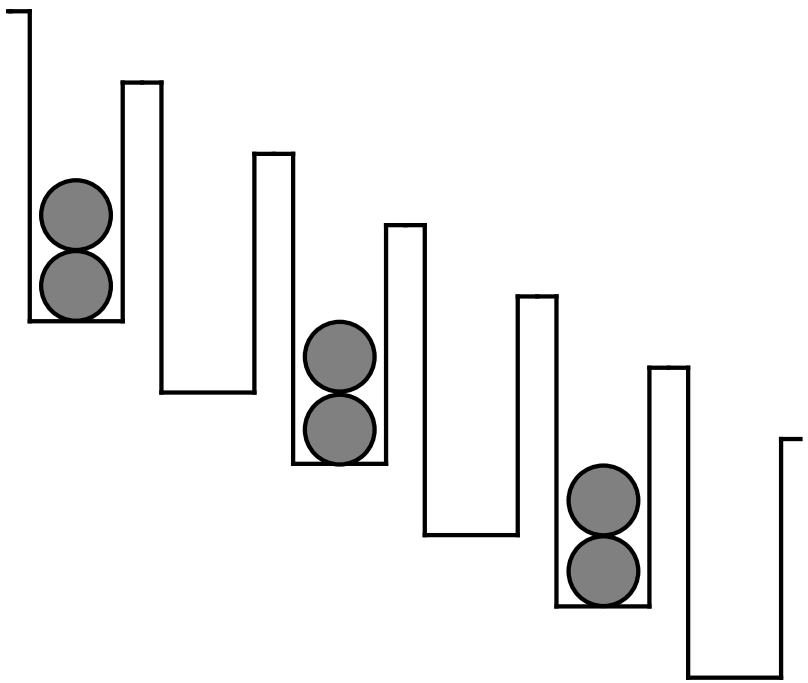




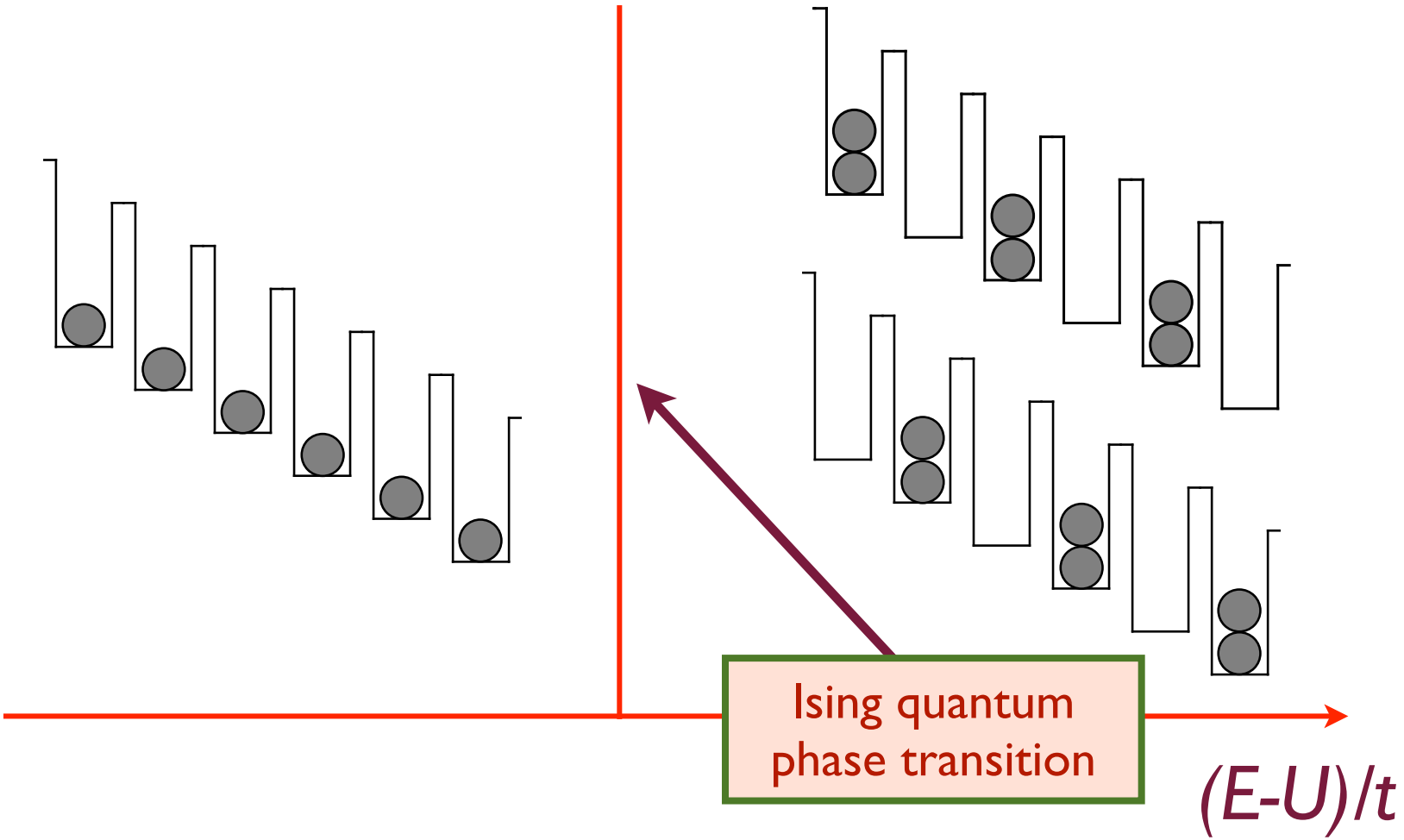
Resonant transition when $E \approx U$



Resonant transition when $E \approx U$



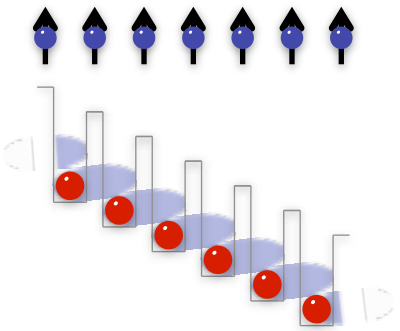
Phase diagram in one dimension

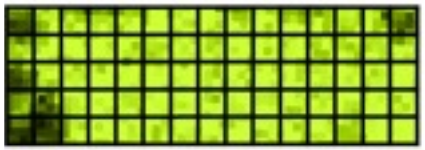


S. Sachdev, K. Sengupta, and S.M. Girvin, Phys. Rev. B 66, 075128 (2002)

Bakr *et al.*, Nature 462, 74 (2009)
Bakr *et al.*, Science.1192368 (June 2010)

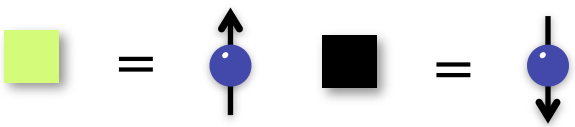
Adiabatic transition to the AF state





• High magnetic field: spins align with field

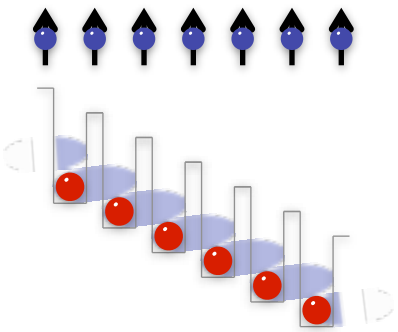
Modulation spectroscopy: turn double occupancy into single occupancy

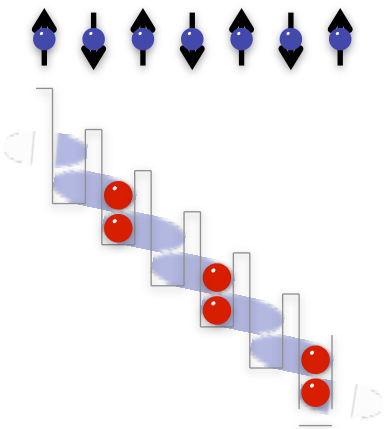


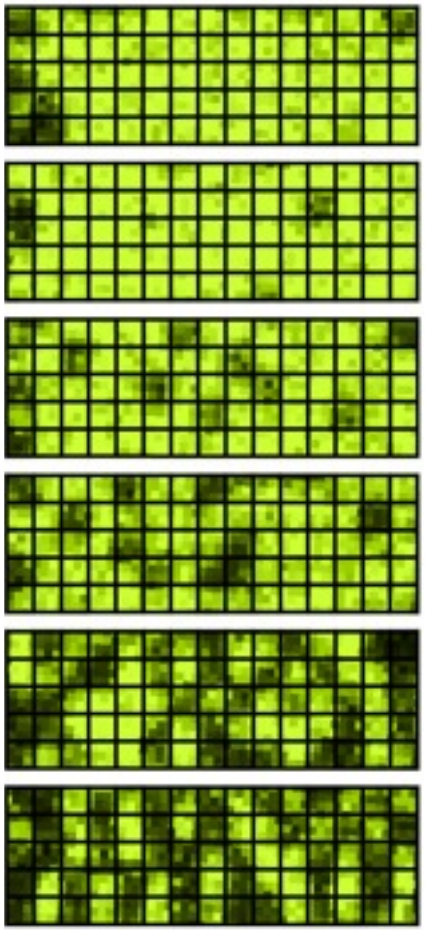
Direct spin imaging preliminary

Bakr *et al.*, Nature 462, 74 (2009)
Bakr *et al.*, Science.1192368 (June 2010)

Adiabatic transition to the AF state



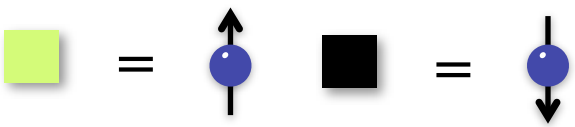




- High magnetic field: spins align with field

- Low magnetic field: antiferromagnetic interactions dominate, producing Neel order

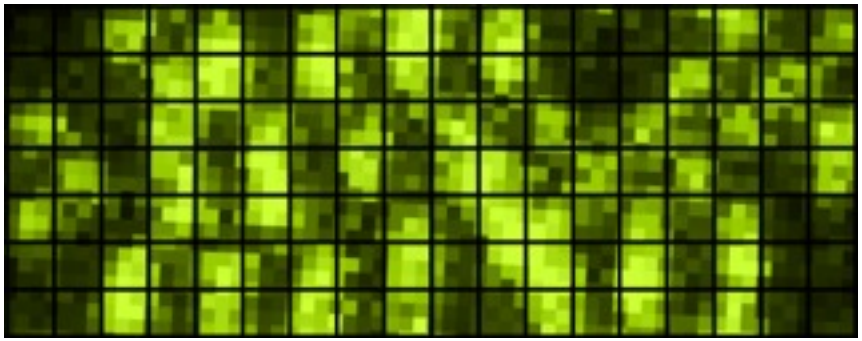
Modulation spectroscopy: turn double occupancy into single occupancy

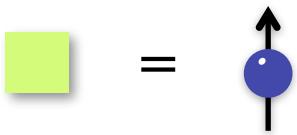


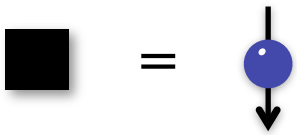
Direct spin imaging preliminary

Direct detection of AF order

Modulation spectroscopy: turn double occupancy into single occupancy

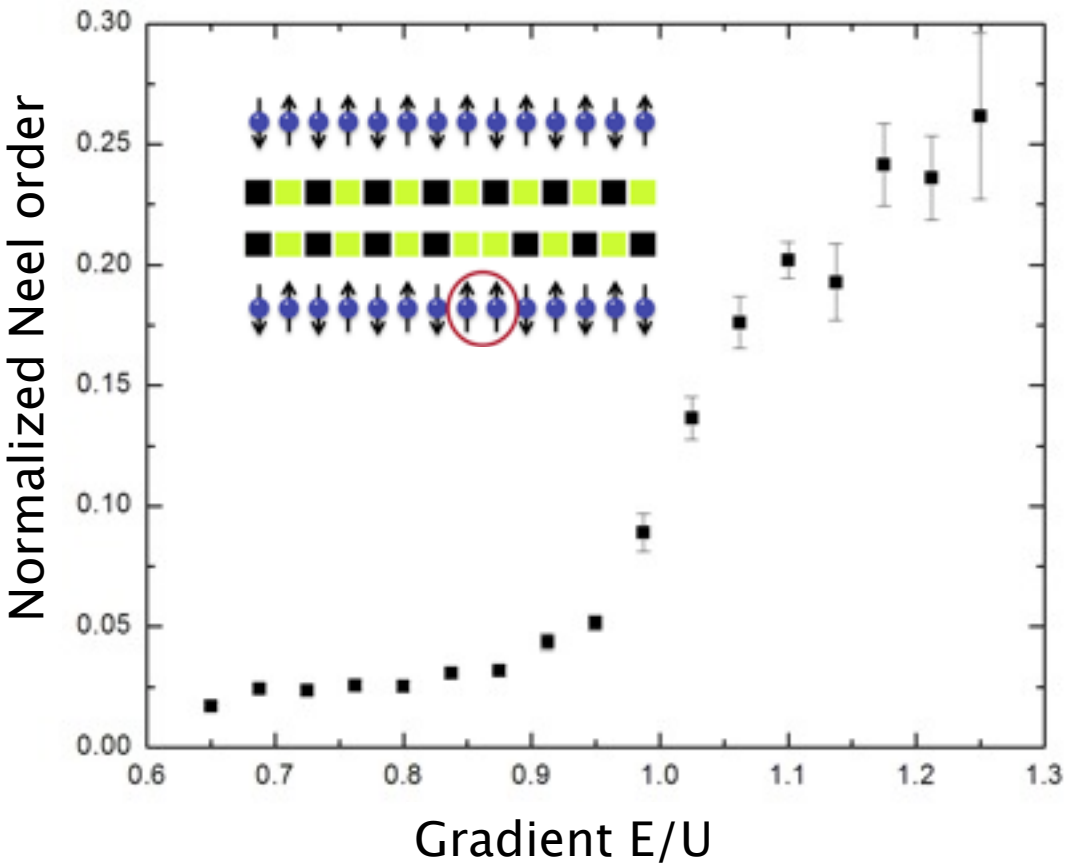






Bakr et al., arXiv:1105.5834

Direct measurement of Neel order parameter

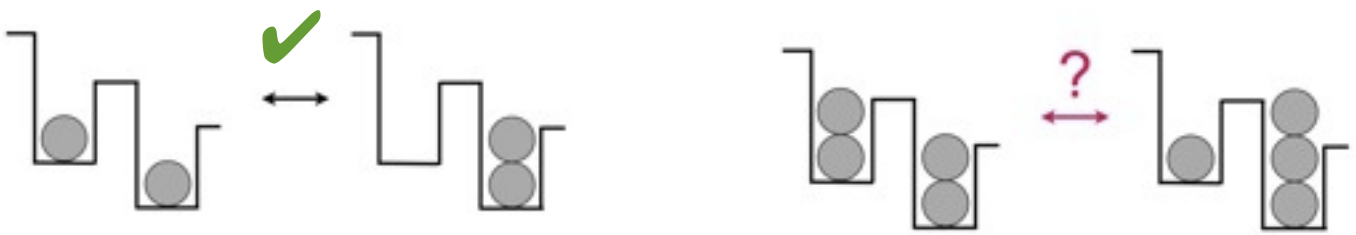


Bakr et al., arXiv:1105.5834

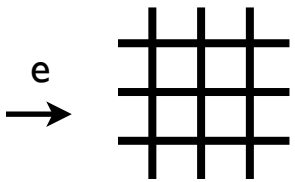
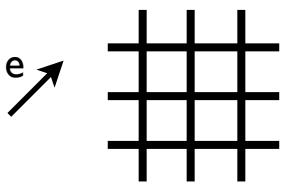
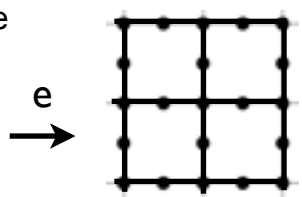
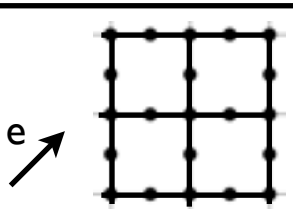
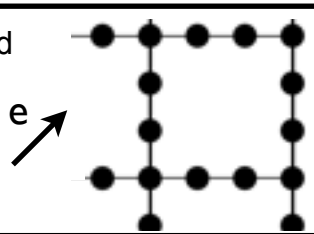
HARVARD UNIVERSITY ᵥ MIT
CENTER FOR ULTRACOLD ATOMS

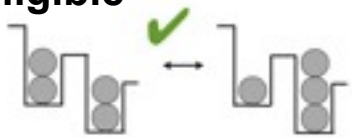
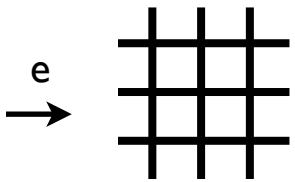
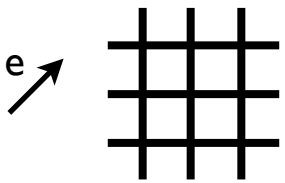
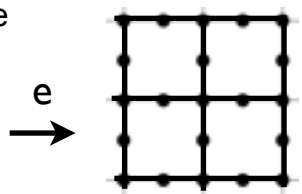
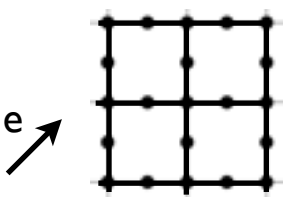
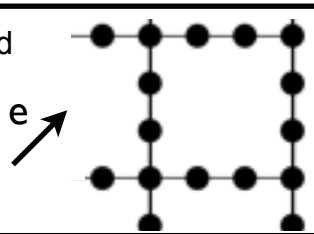
2d: phases, degeneracy and excitations depend on:

- lattice geometry
- tilt direction
- effective three-body interaction negligible?



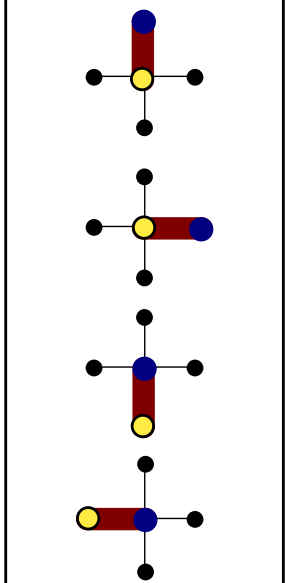
- filling of parent Mott insulator

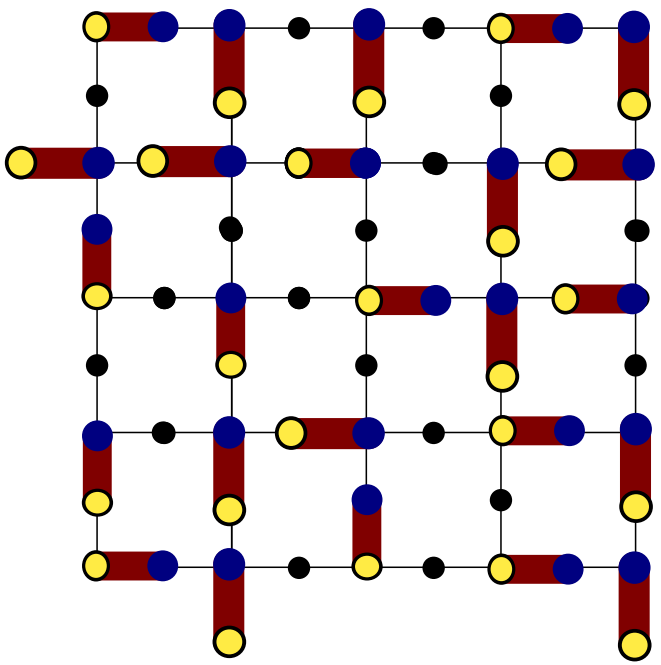
Lattice and tilt configuration	U_3 important	U_3 negligible
square lattice tilted along principal lattice direction 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
square lattice diagonal tilt 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
decorated square tilt along lattice direction 	decoupled 1D systems	"Tetris-Runaway-Instability" ?
decorated square diagonal tilt 	quantum liquid state	$n_0 = 1$: quantum dimer model $n_0 > 1$: density wave order
doubly decorated square diagonal tilt 	quantum dimer model	Susanne Pielawa

Lattice and tilt configuration	U_3 important	U_3 negligible 
square lattice tilted along principal lattice direction e 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
square lattice diagonal tilt e 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
decorated square tilt along lattice direction e 	decoupled 1D systems	"Tetris-Runaway-Instability" ?
decorated square diagonal tilt e 	quantum liquid state	$n_0 = 1$: quantum dimer model $n_0 > 1$: density wave order
doubly decorated square diagonal tilt e 	quantum dimer model	Susanne Pielawa

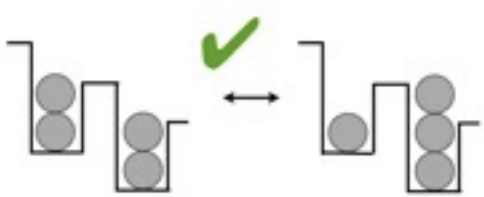
$n_0 = 1$

particle-hole pairs:





e

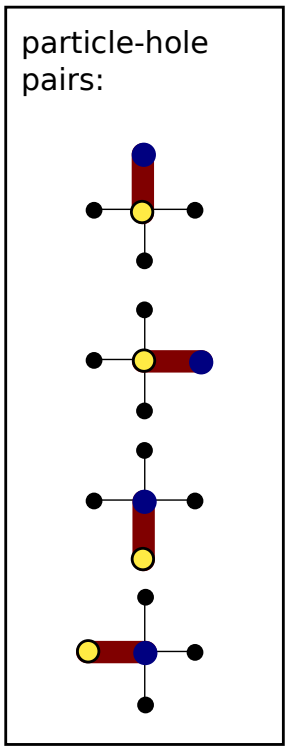


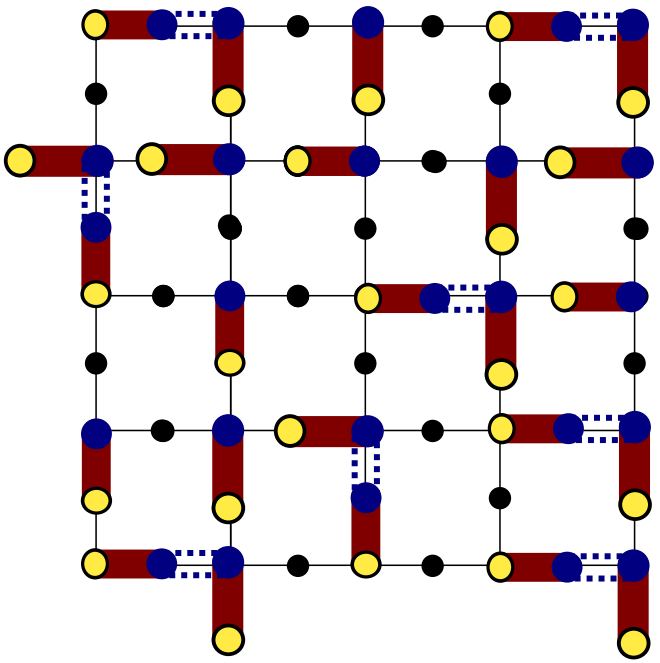
= = quasi-particle

= = hole

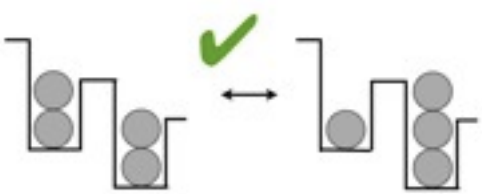
= quasi vacuum

$n_0 = 1$





e



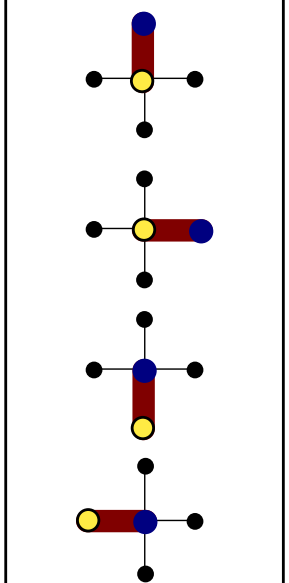
= = quasi-particle

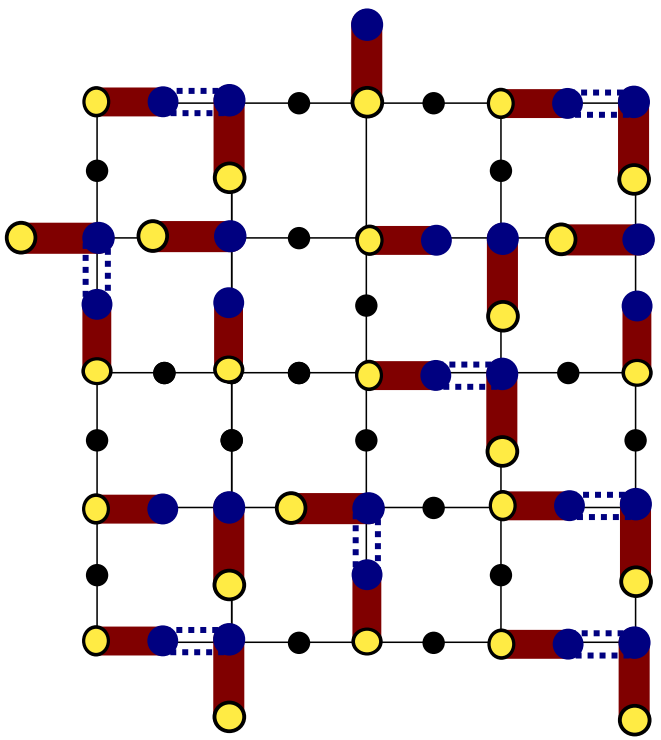
= = hole

= quasi vacuum

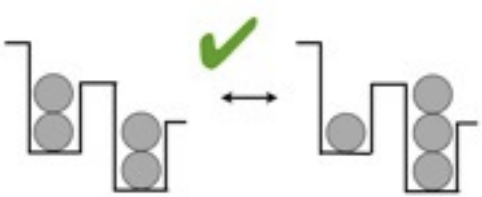
$n_0 = 1$

particle-hole pairs:





e



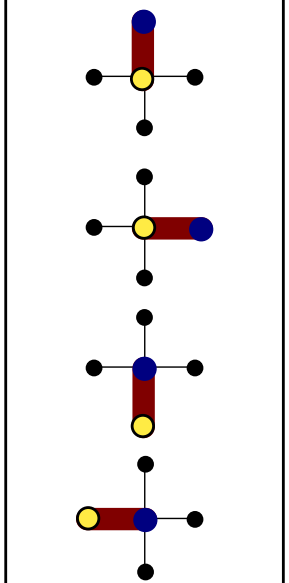
= = quasi-particle

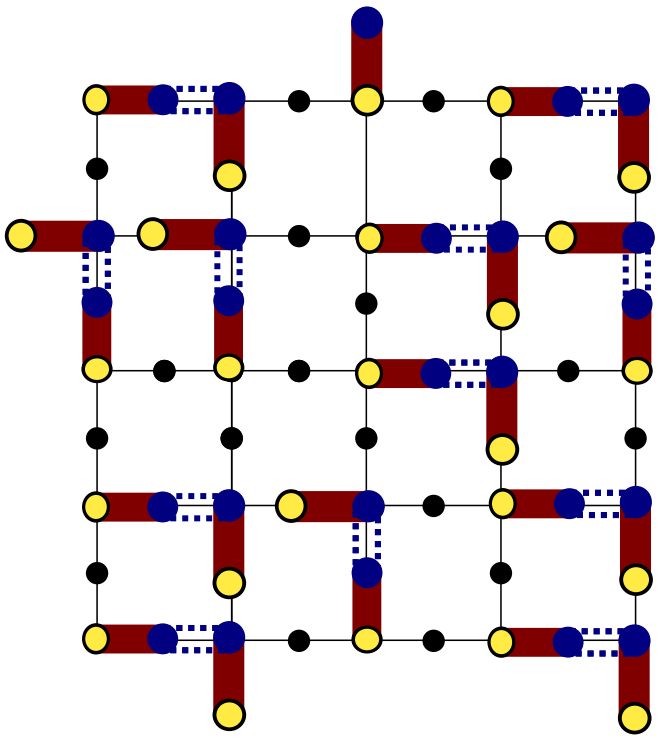
= = hole

= quasi vacuum

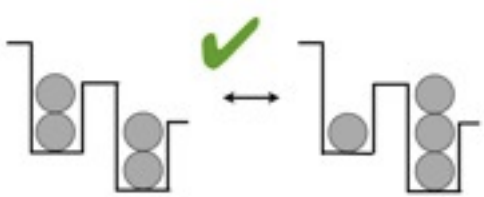
$n_0 = 1$

particle-hole pairs:





e

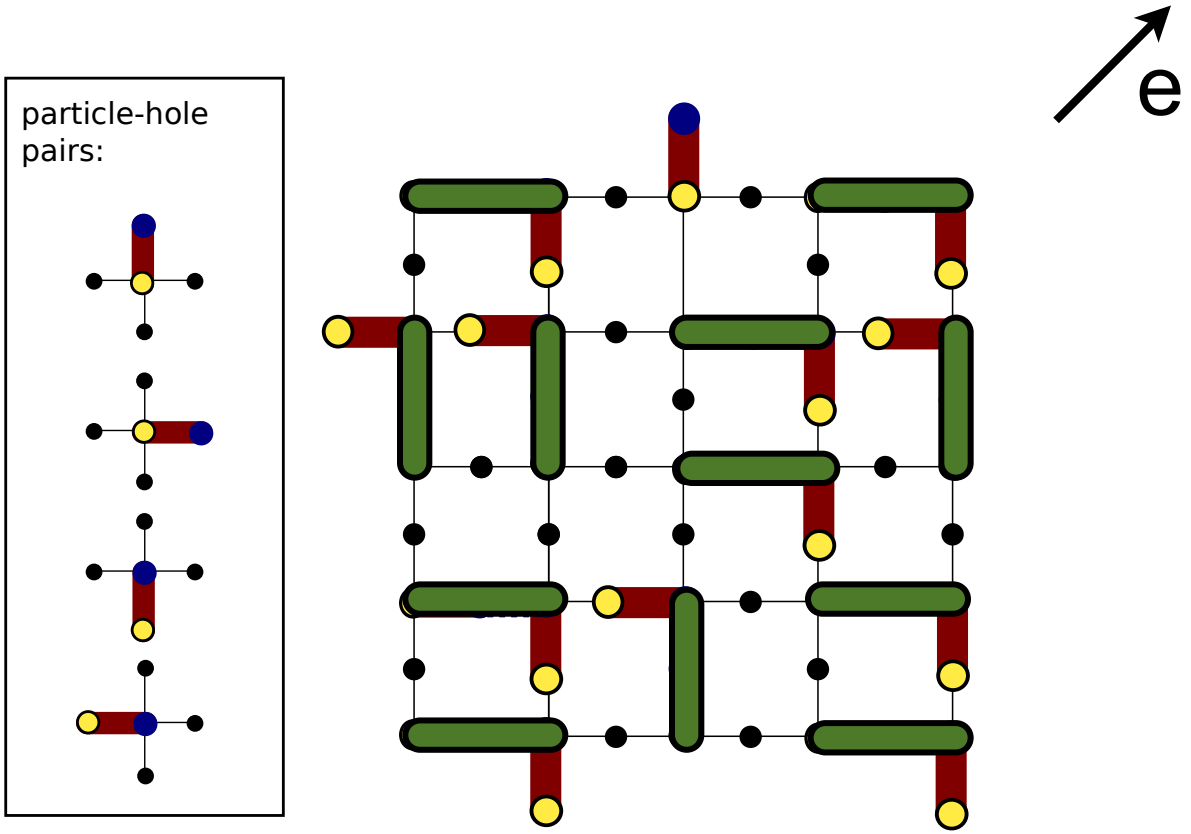


= = quasi-particle

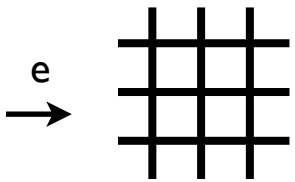
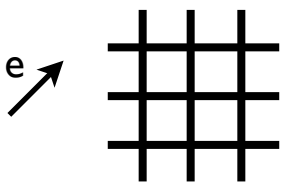
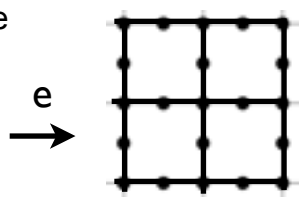
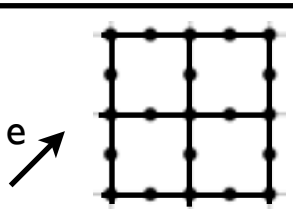
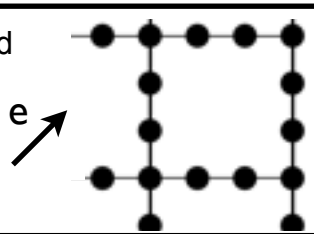
= = hole

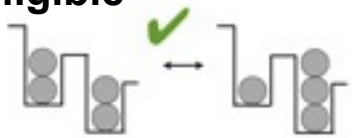
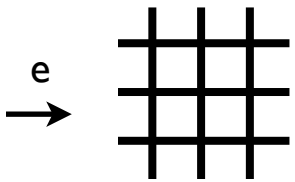
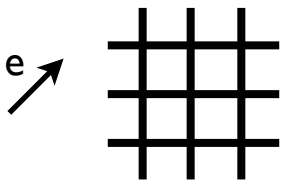
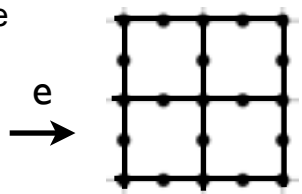
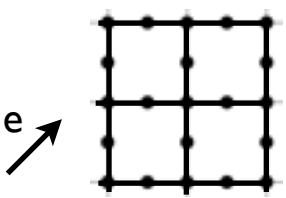
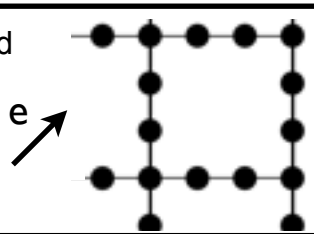
= quasi vacuum

$n_0 = 1$

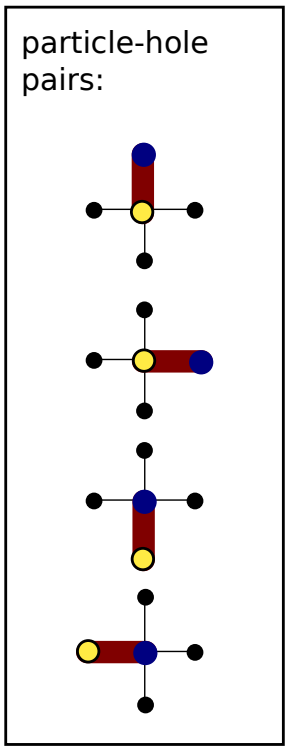


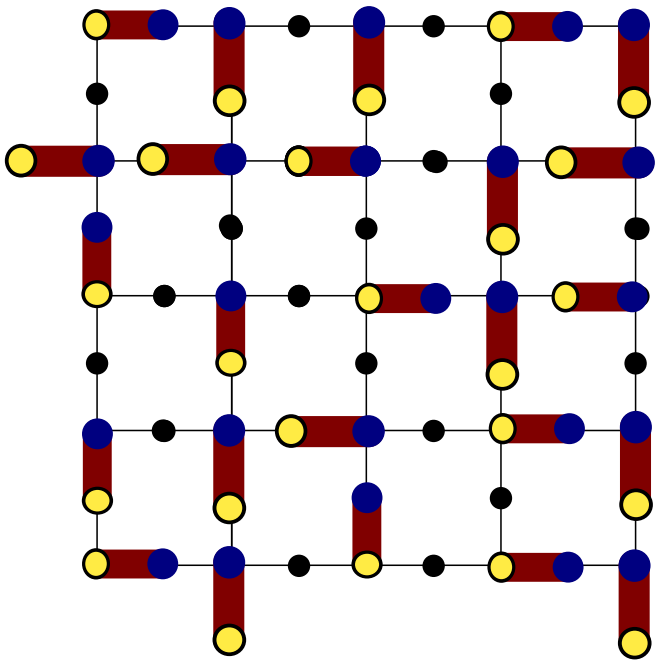
Hilbert space and effective Hamiltonian of quantum dimer model

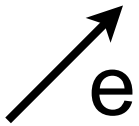
Lattice and tilt configuration	U_3 important	U_3 negligible
square lattice tilted along principal lattice direction 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
square lattice diagonal tilt 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
decorated square tilt along lattice direction 	decoupled 1D systems	"Tetris-Runaway-Instability" ?
decorated square diagonal tilt 	quantum liquid state	$n_0 = 1$: quantum dimer model $n_0 > 1$: density wave order
doubly decorated square diagonal tilt 	quantum dimer model	Susanne Pielawa

Lattice and tilt configuration	U_3 important	U_3 negligible 
square lattice tilted along principal lattice direction e 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
square lattice diagonal tilt e 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
decorated square tilt along lattice direction e 	decoupled 1D systems	"Tetris-Runaway-Instability" ?
decorated square diagonal tilt e 	quantum liquid state	$n_0 = 1$: quantum dimer model $n_0 > 1$: density wave order
doubly decorated square diagonal tilt e 	quantum dimer model	Susanne Pielawa

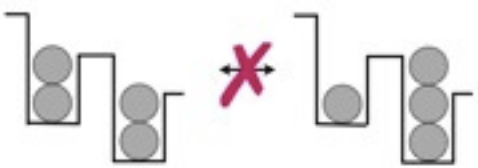
$n_0 = 1$

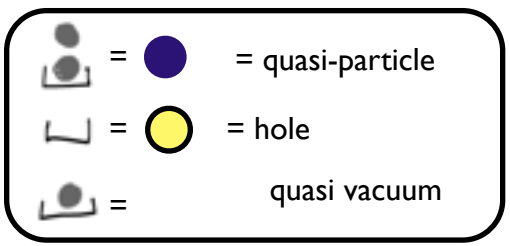






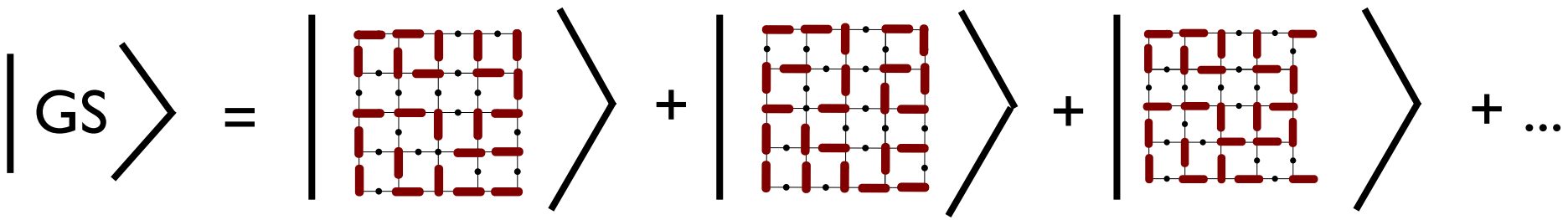
quantum 4 state clock model



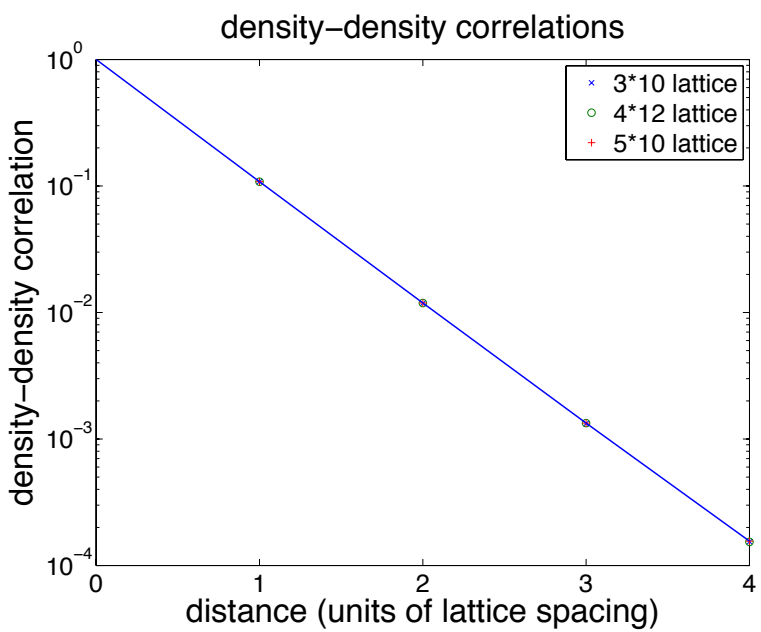


- Dipole liquid ground state:

  equal amplitude superposition of all classically allowed dipole coverings

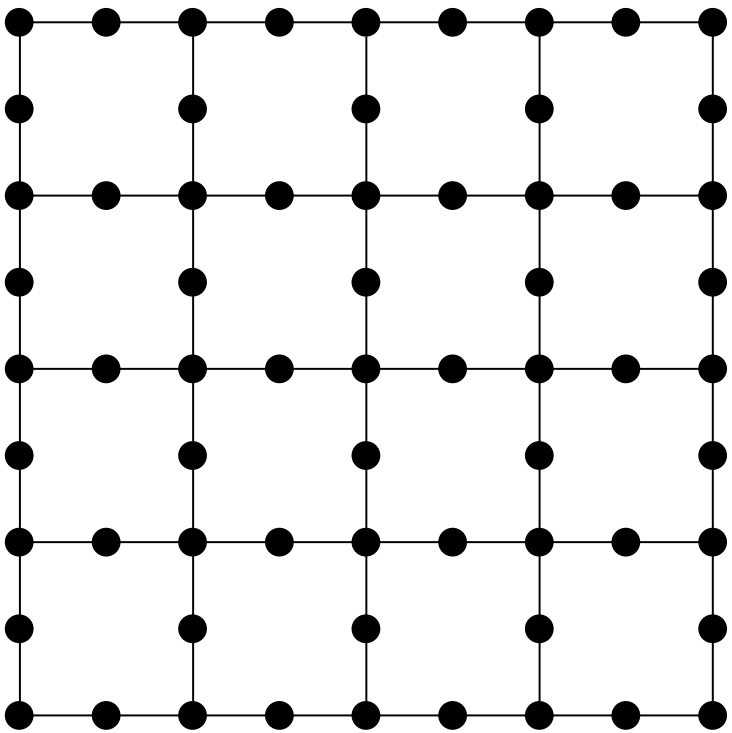


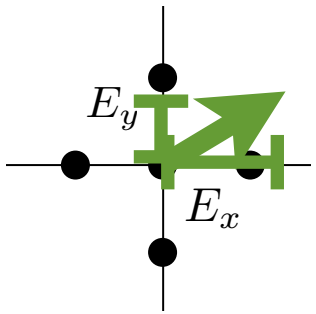
- exponentially decaying correlations
- gapped excitations
- no broken symmetry



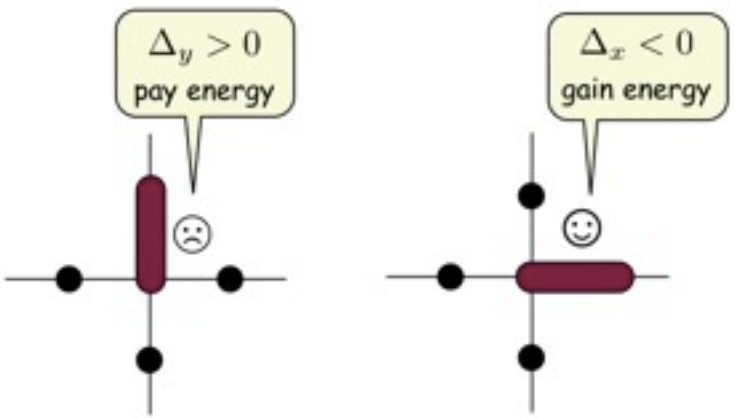
Near-diagonally tilted decorated square lattice

$$\vec{E} = \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$



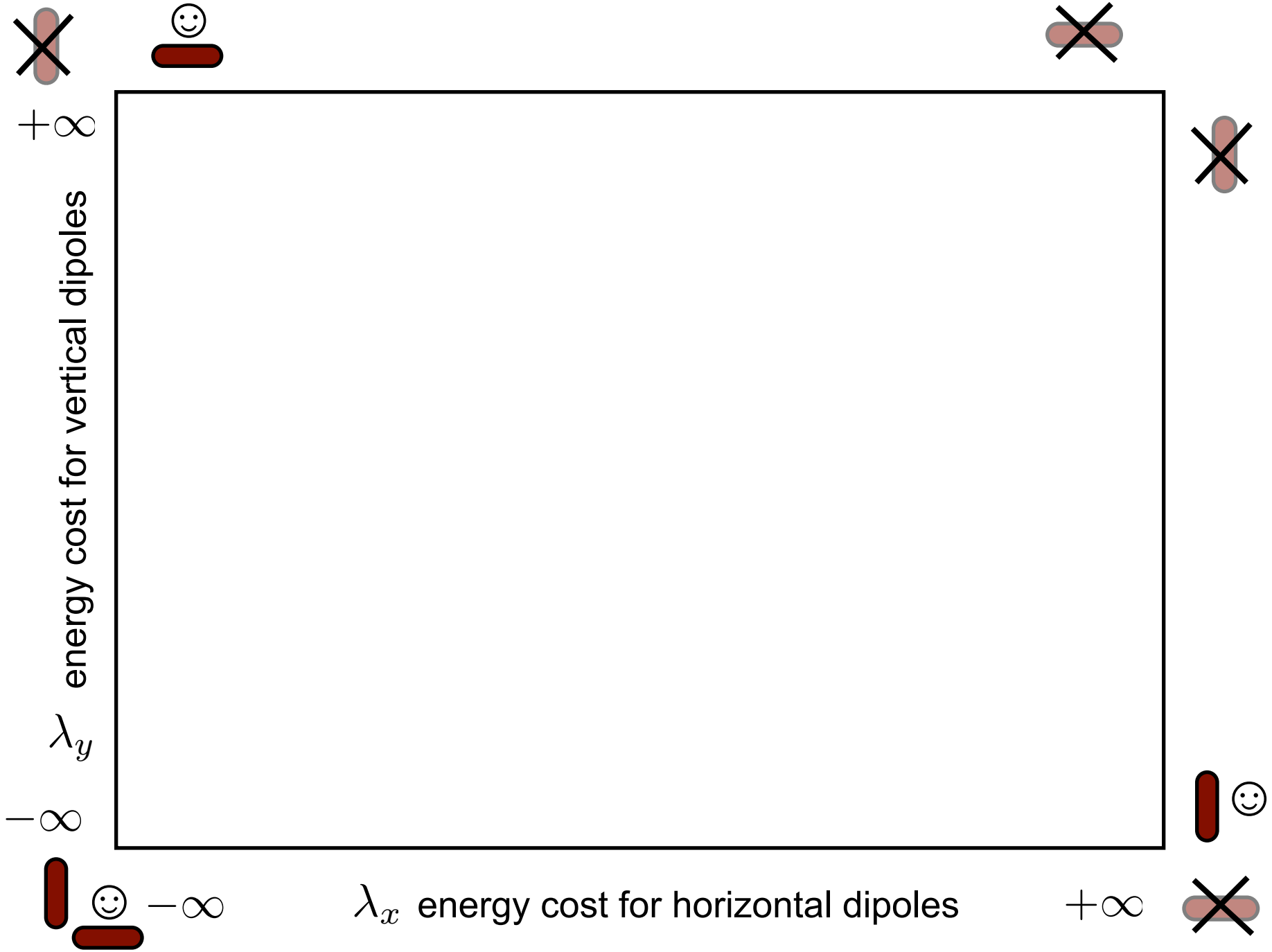


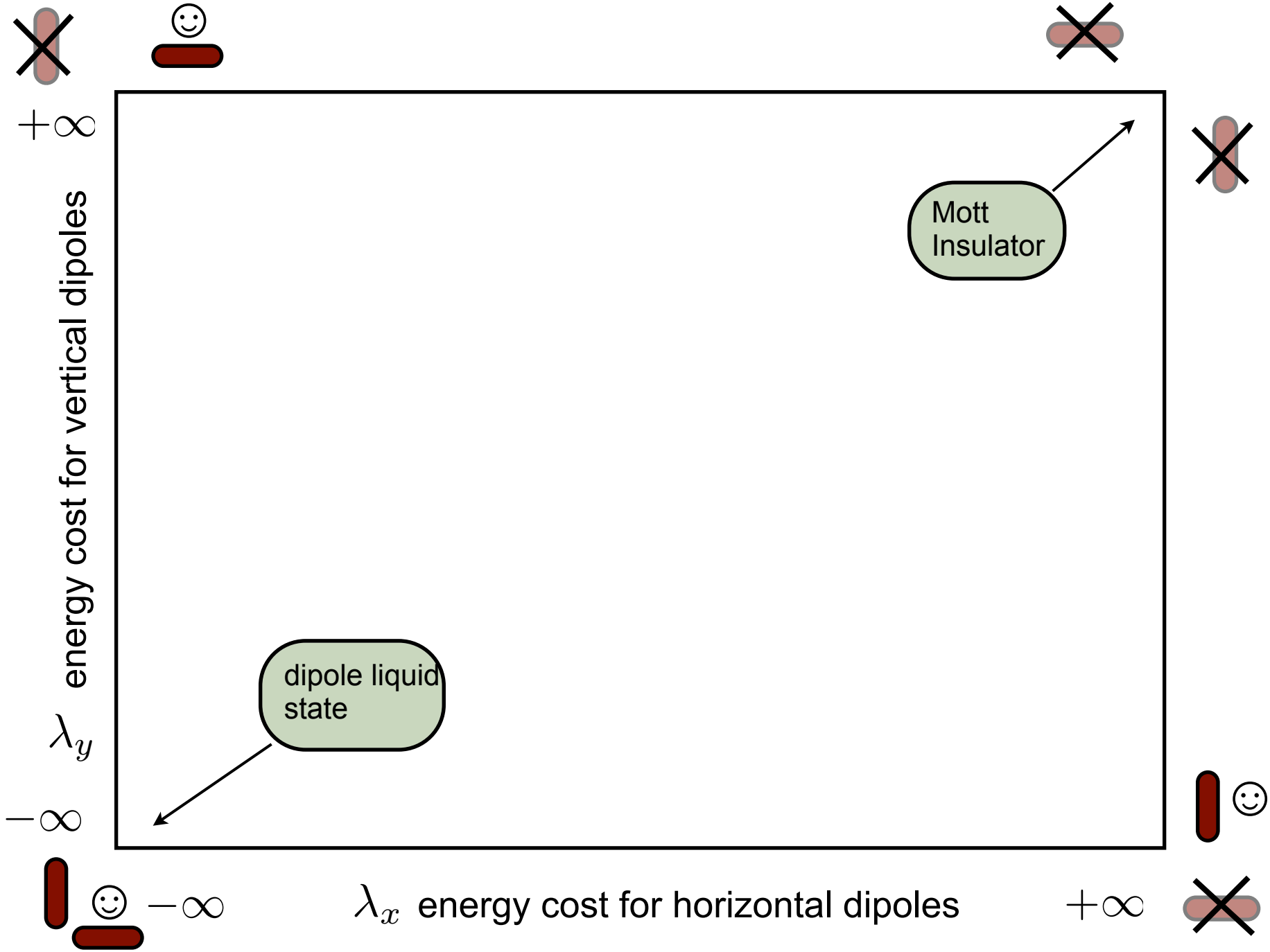
$$\Delta_x = U - E_x$$
$$\Delta_y = U - E_y$$

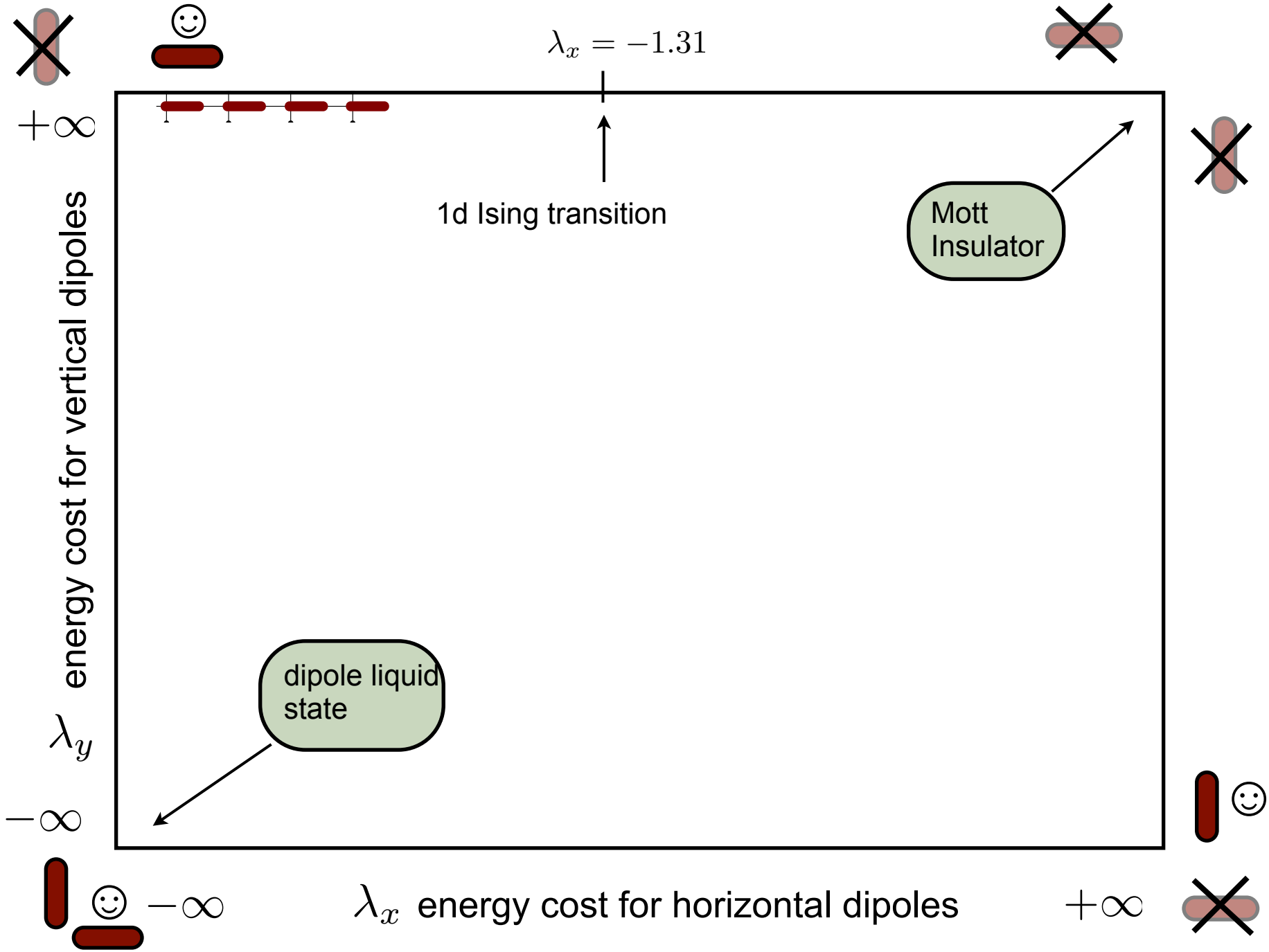


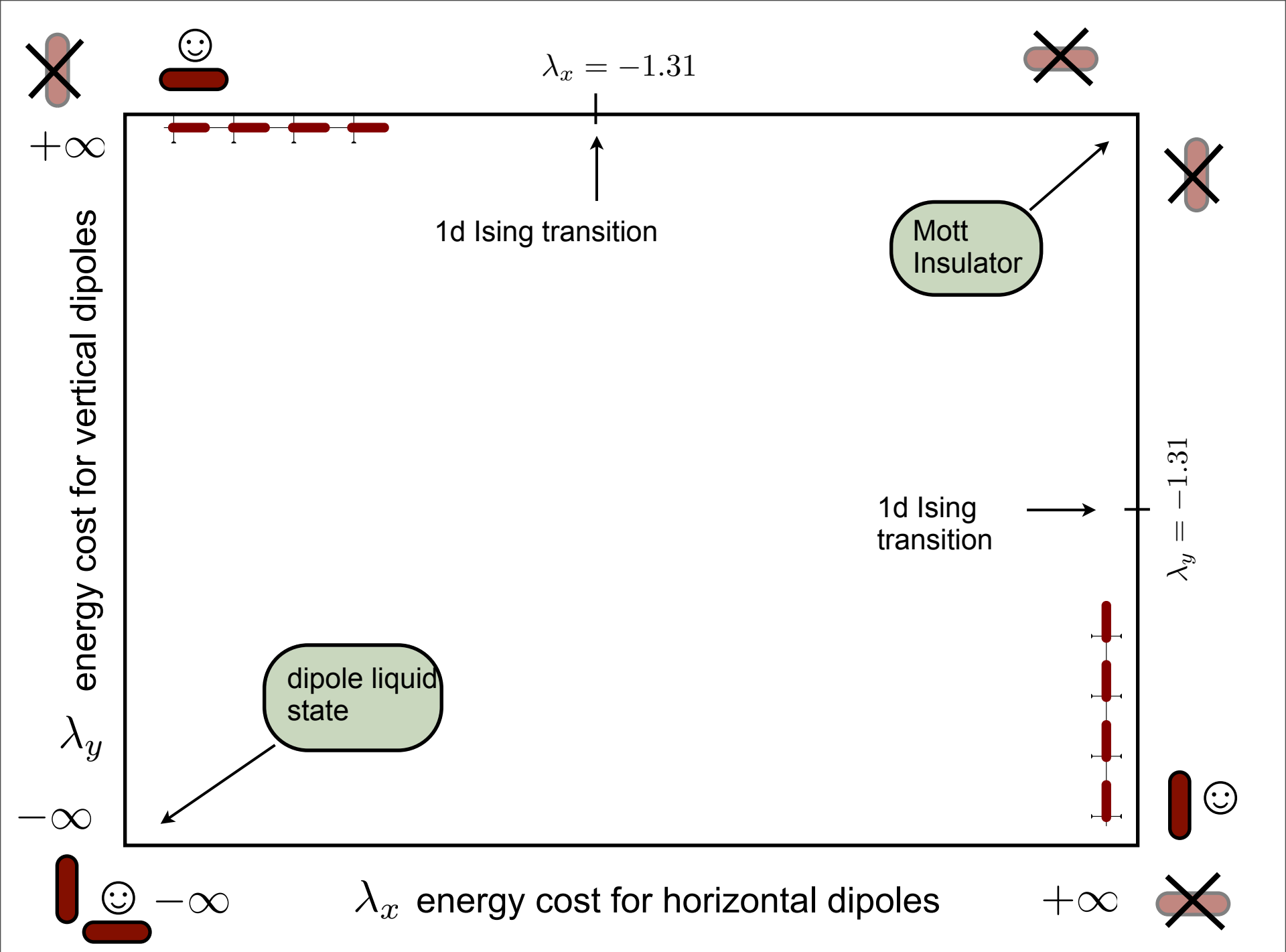
2 tuning parameters

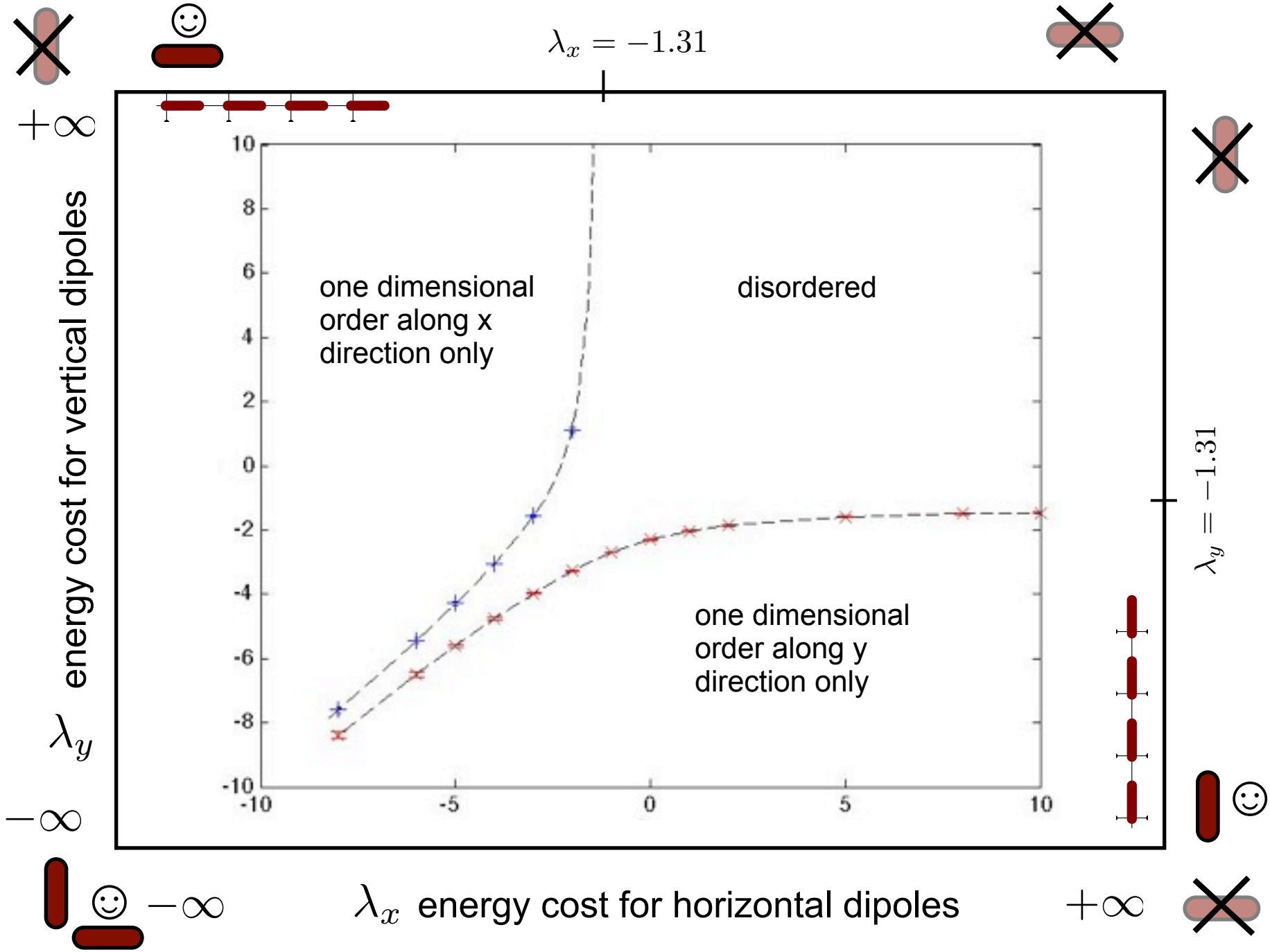
$$\lambda_x = \Delta_x / t\sqrt{2}$$
$$\lambda_y = \Delta_y / t\sqrt{2}$$

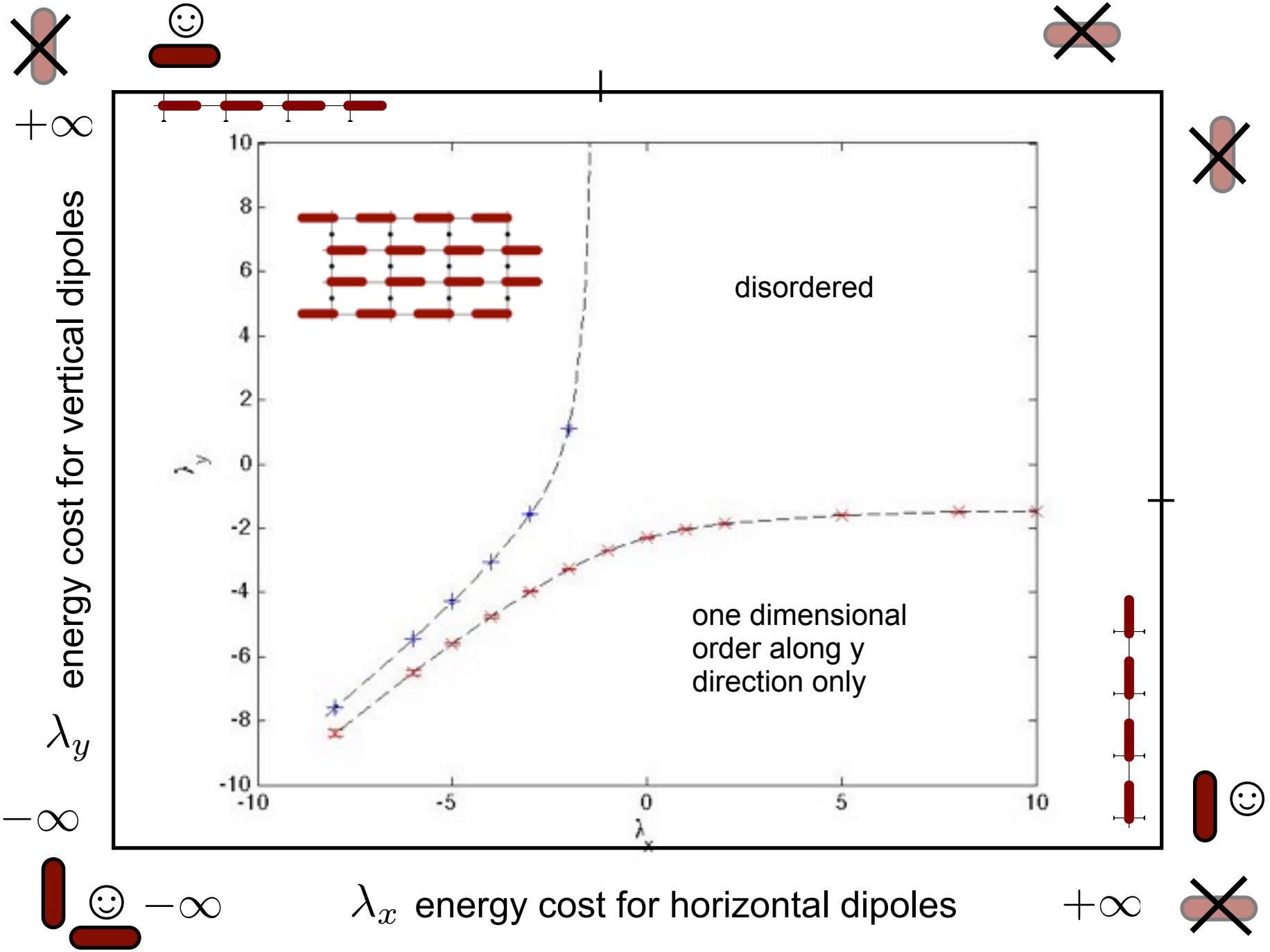

$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$

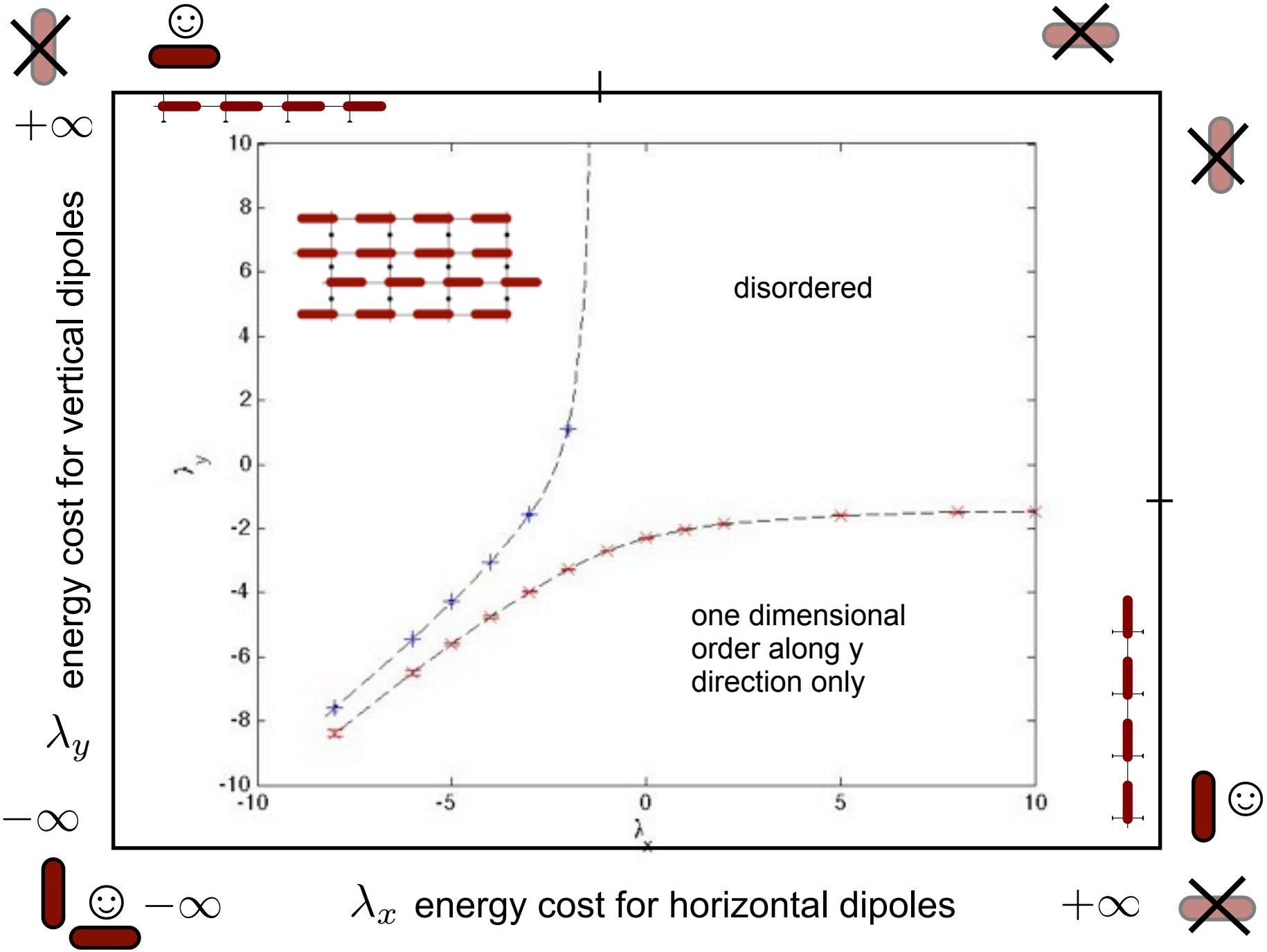

$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
Mott
Insulator
dipole liquid
state
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$

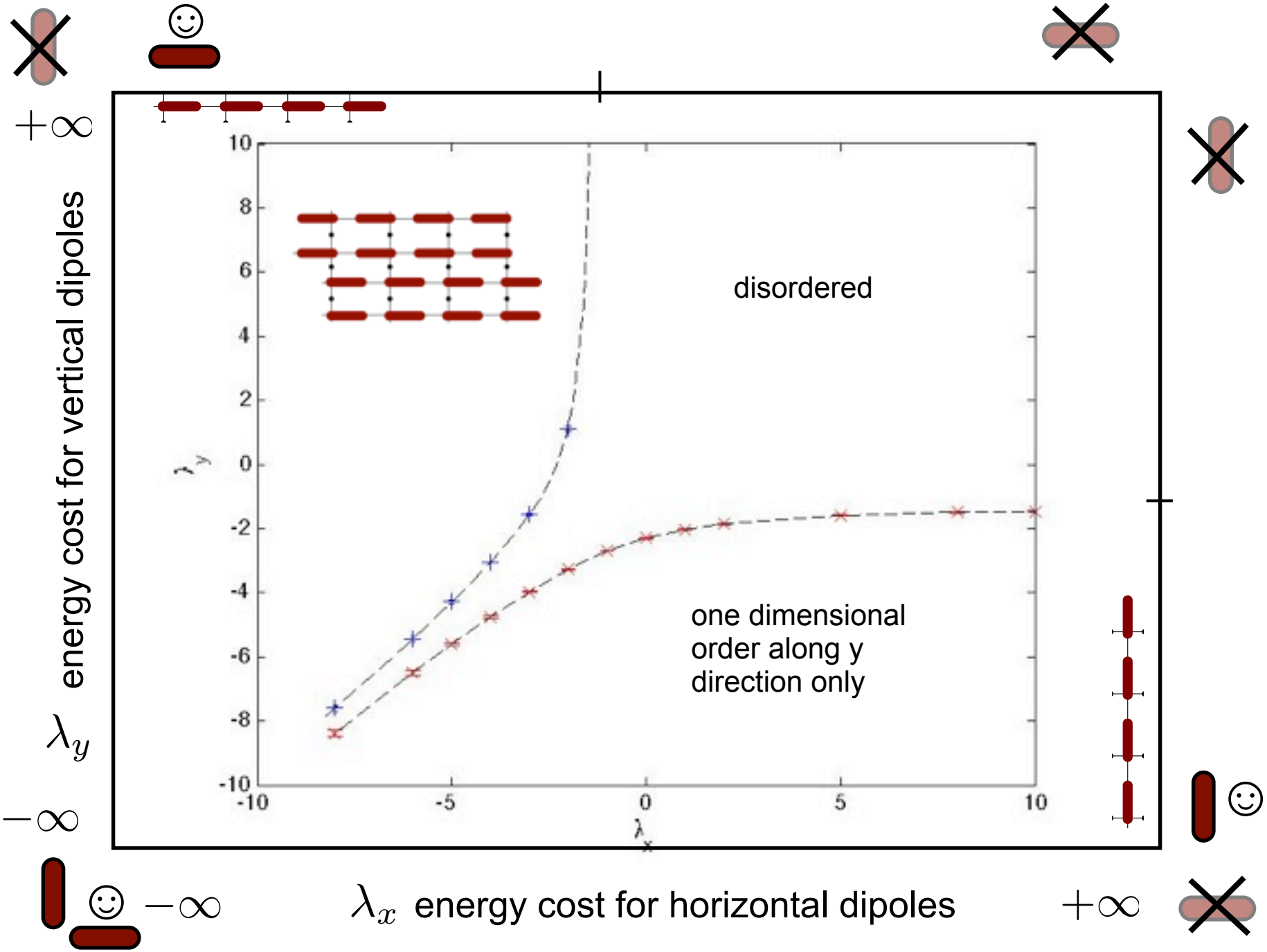

$\lambda_x = -1.31$
1d Ising transition
Mott Insulator
dipole liquid state
$+\infty$
$-\infty$
λ_y energy cost for vertical dipoles
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$

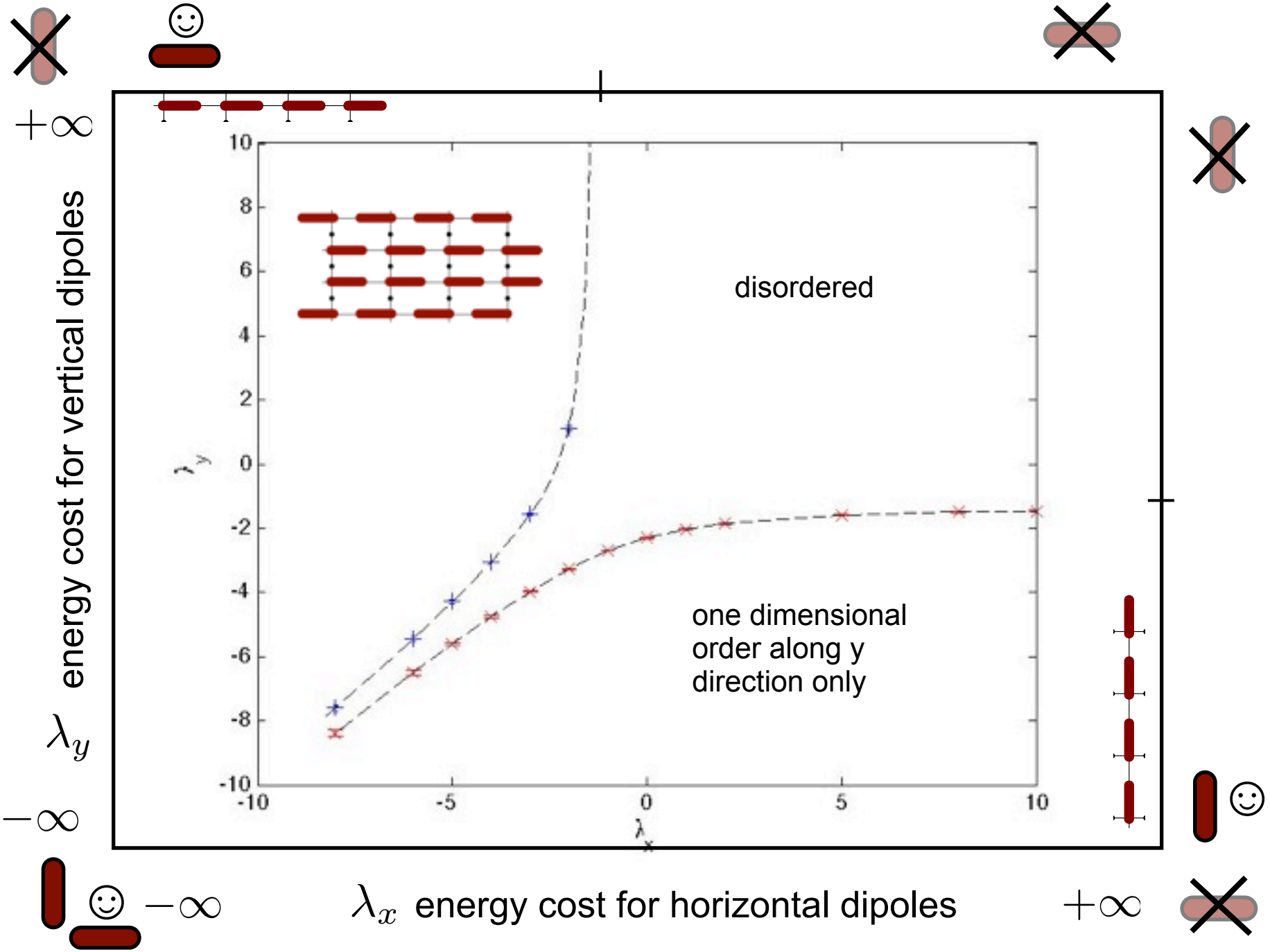

$\lambda_x = -1.31$
1d Ising transition
Mott Insulator
1d Ising transition
$\lambda_y = -1.31$
dipole liquid state
$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$

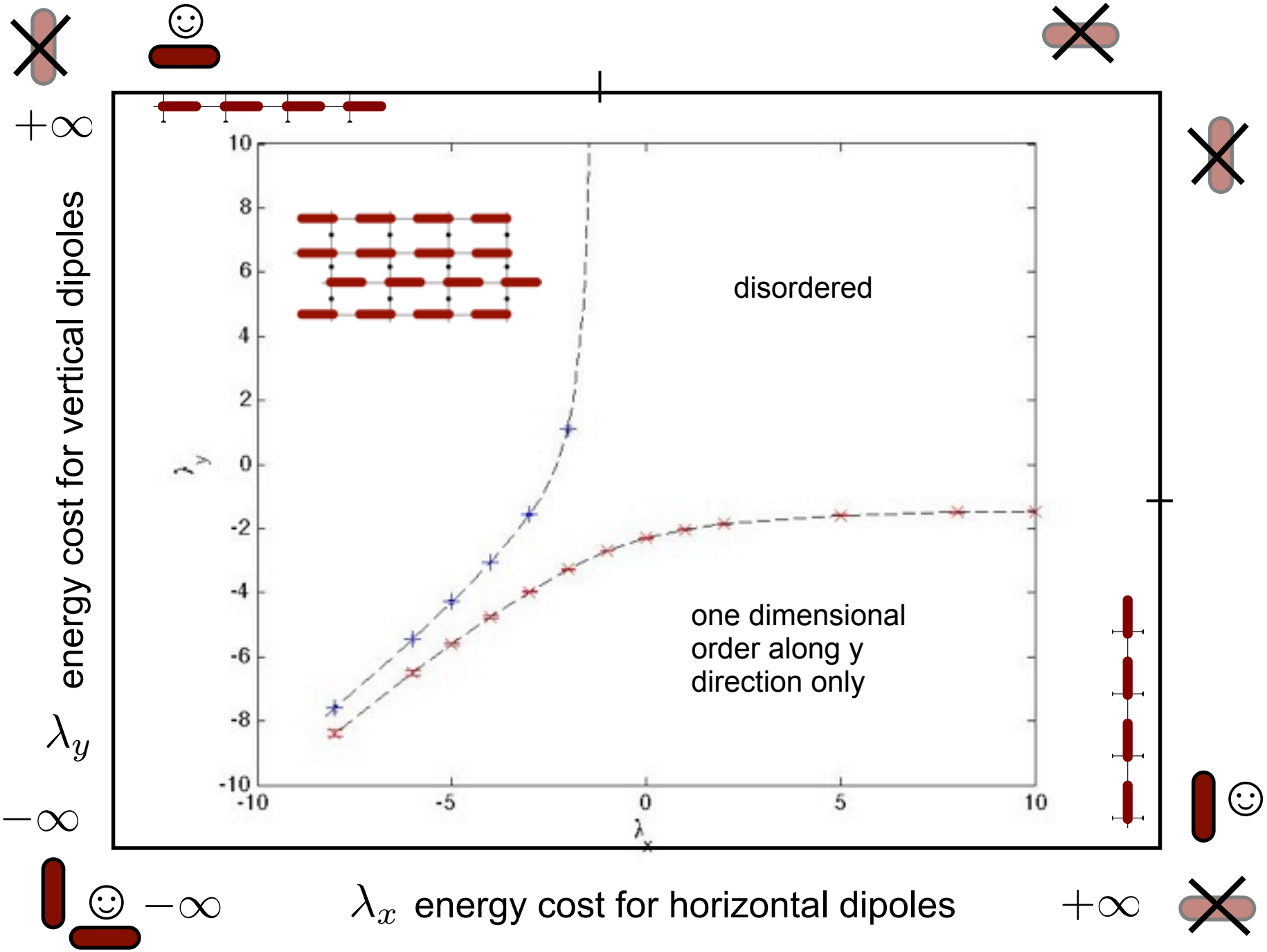

$\lambda_x = -1.31$
$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
one dimensional
order along x
direction only
disordered
one dimensional
order along y
direction only
$\lambda_y = -1.31$
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10

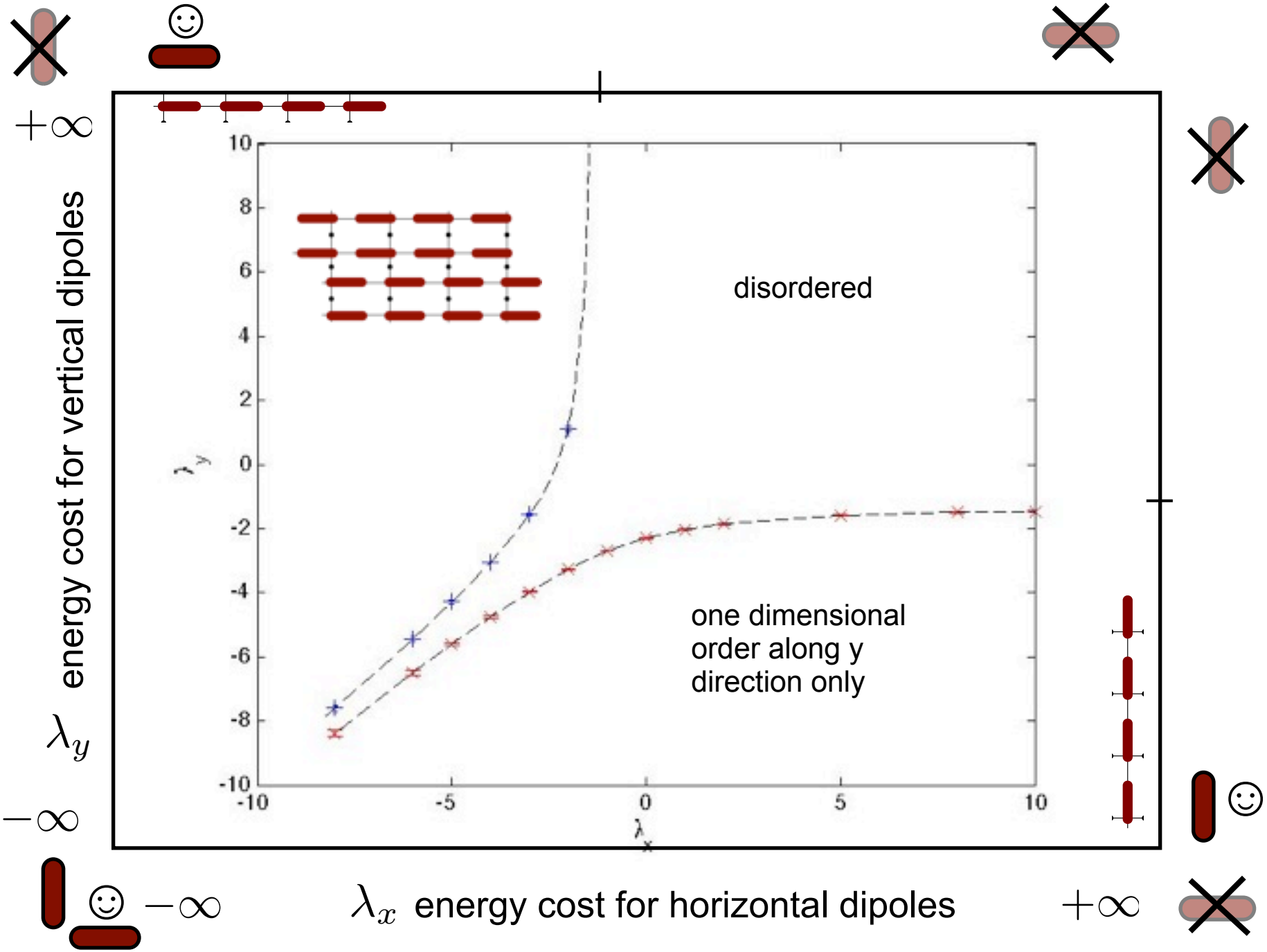

$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
disordered
one dimensional
order along y
direction only
λ_y
λ_x
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$


$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
disordered
one dimensional
order along y
direction only
λ_y
λ_x
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$


$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
disordered
one dimensional
order along y
direction only
λ_y
λ_x
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$


$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
disordered
one dimensional
order along y
direction only
λ_y
λ_x
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$

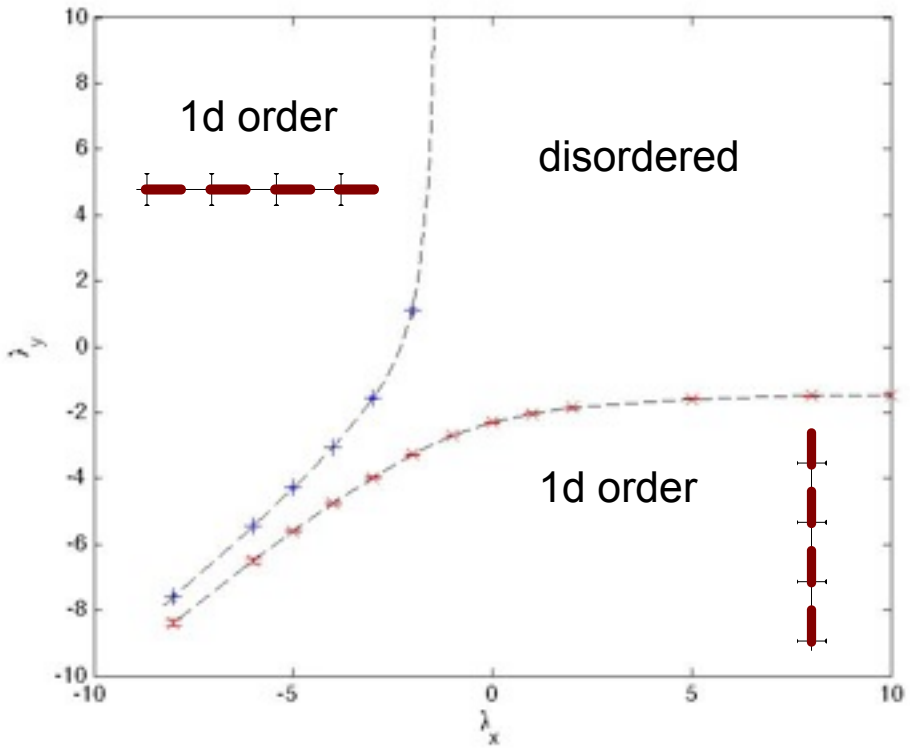

$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
disordered
one dimensional
order along y
direction only
λ_y
λ_x
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$

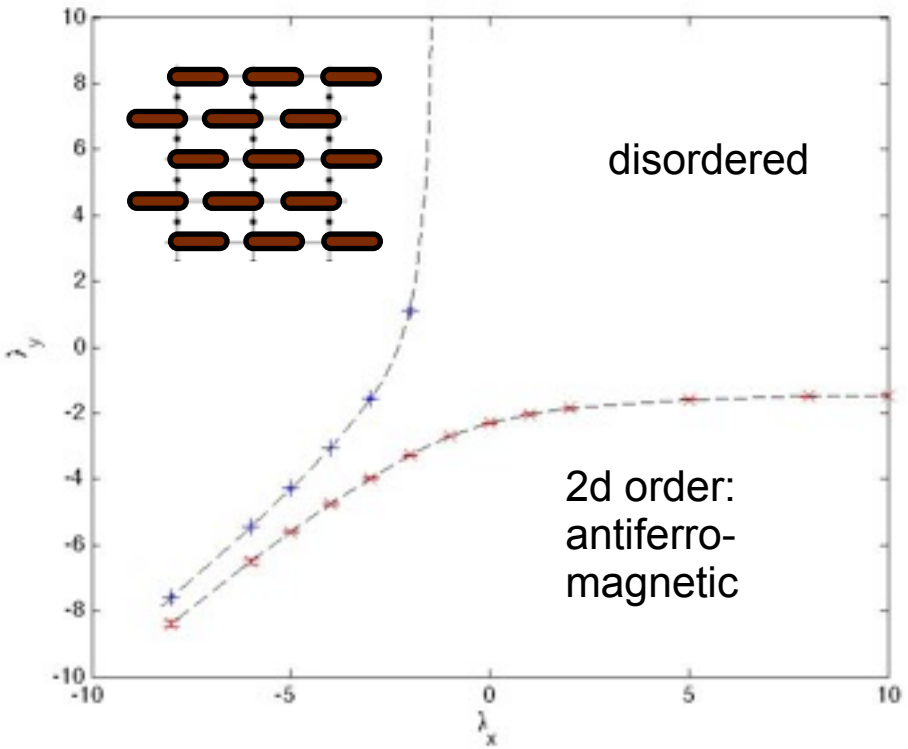

$+\infty$
energy cost for vertical dipoles
λ_y
$-\infty$
disordered
one dimensional
order along y
direction only
λ_y
λ_x
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10
$-\infty$
λ_x energy cost for horizontal dipoles
$+\infty$

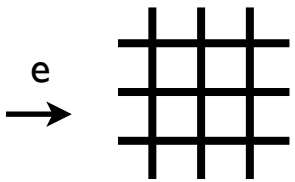
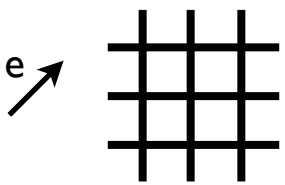
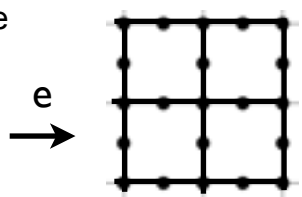
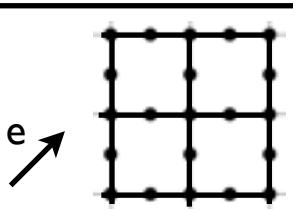
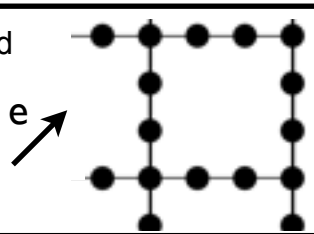
Decorated Square -- Phase Diagram

realistic systems $L \sim 10 - 100$

thermodynamic limit $L \gg 10^7$





Lattice and tilt configuration	U_3 important	U_3 negligible
square lattice tilted along principal lattice direction 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
square lattice diagonal tilt 	Ising order + transverse superfluid	"Tetris-Runaway-Instability" ?
decorated square tilt along lattice direction 	decoupled 1D systems	"Tetris-Runaway-Instability" ?
decorated square diagonal tilt 	quantum liquid state	$n_0 = 1$: quantum dimer model $n_0 > 1$: density wave order
doubly decorated square diagonal tilt 	quantum dimer model	Susanne Pielawa