Bosons in tilted Mott insulators

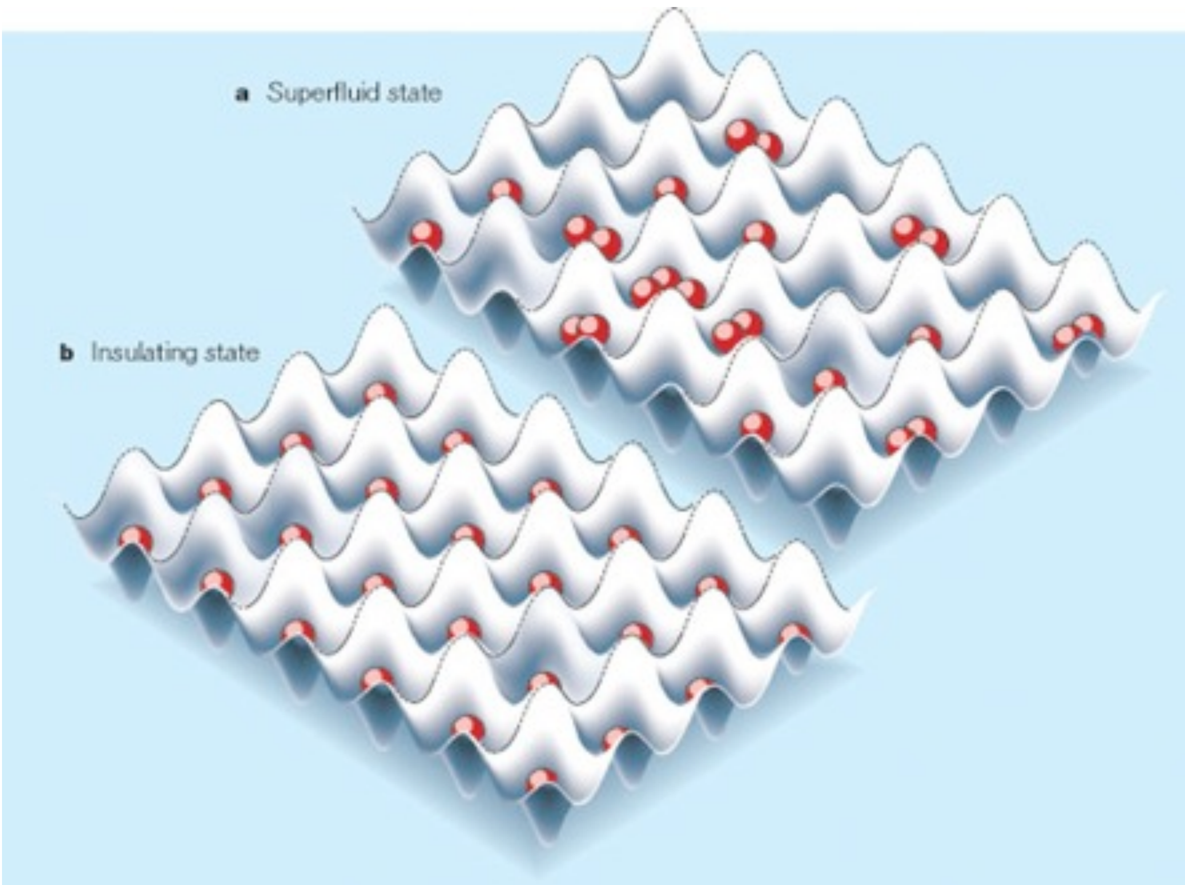
  

Susanne Pielawa | Takuya Kitagawa | Erez Berg

S. Sachdev, K. Sengupta, and S.M. Girvin, Phys. Rev. B 66, 075128 (2002)
S. Pielawa, T. Kitagawa, E. Berg, S. Sachdev, arXiv:1101.2897

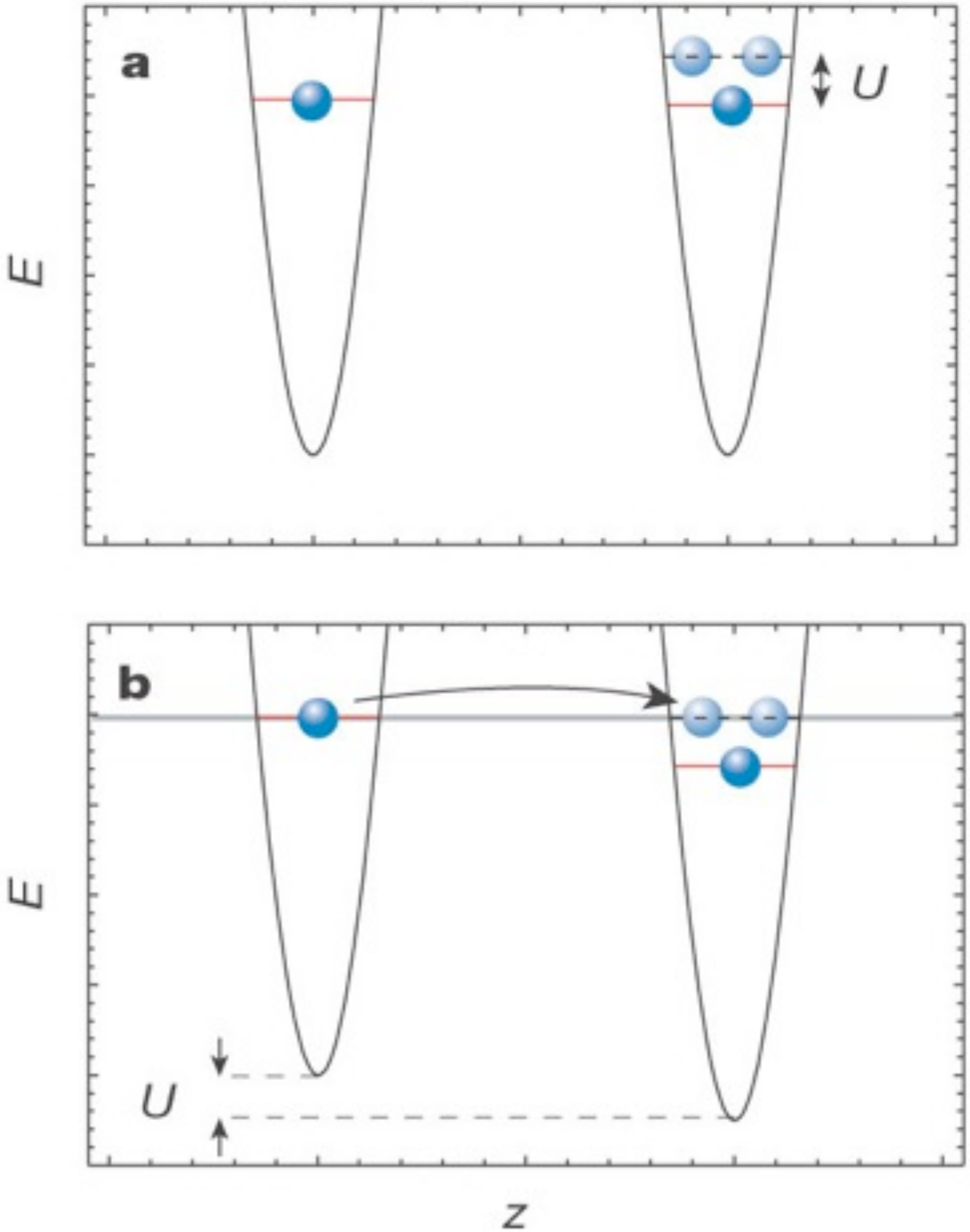
sachdev.physics.harvard.edu

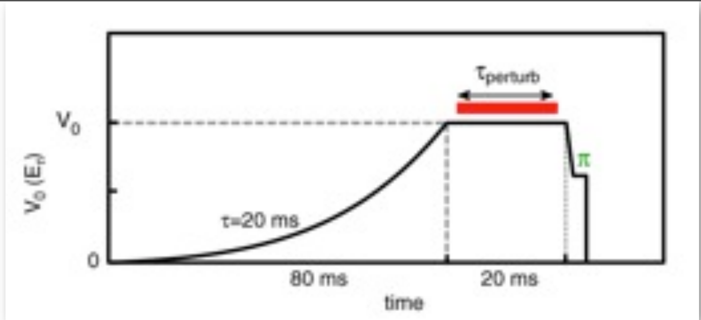
Superfluid-insulator transition of ^{87}Rb atoms in a magnetic trap and an optical lattice potential

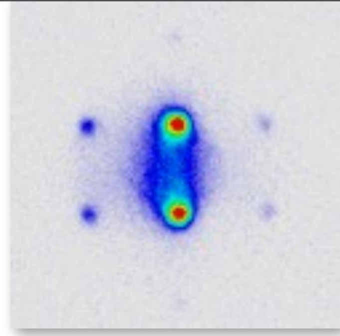


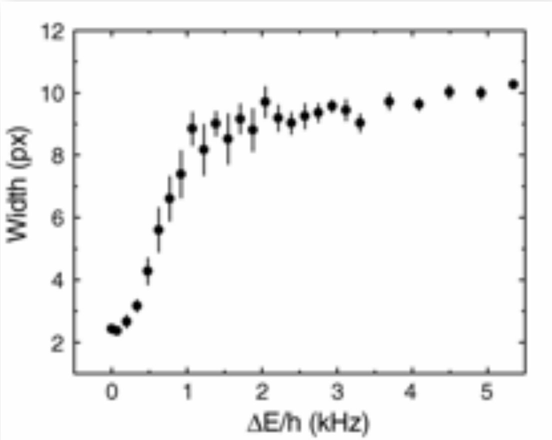
M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

Applying an “electric” field to the Mott insulator

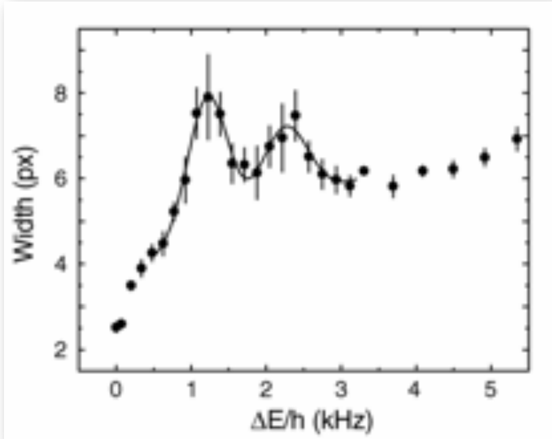




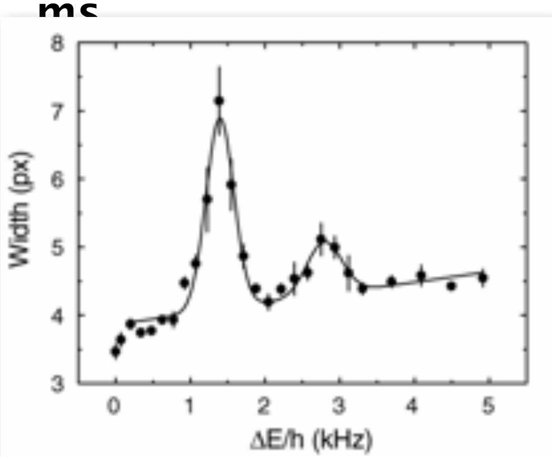




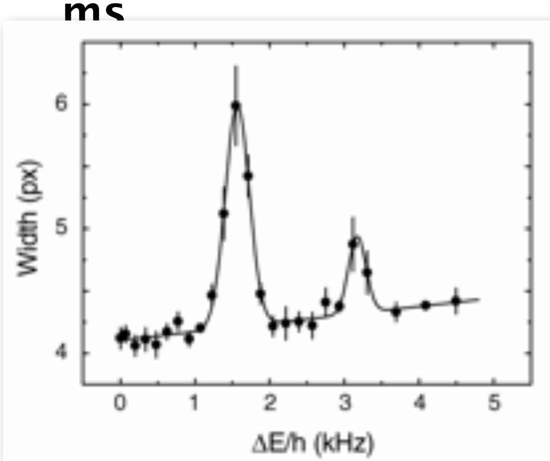
V_0=10 E_{recoil} $\tau_{perturb}$ = 2 ms



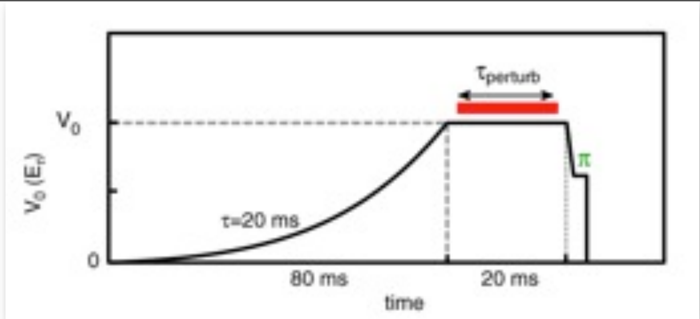
V_0= 13 E_{recoil} $\tau_{perturb}$ = 4 ms

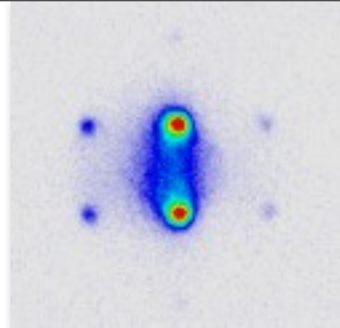


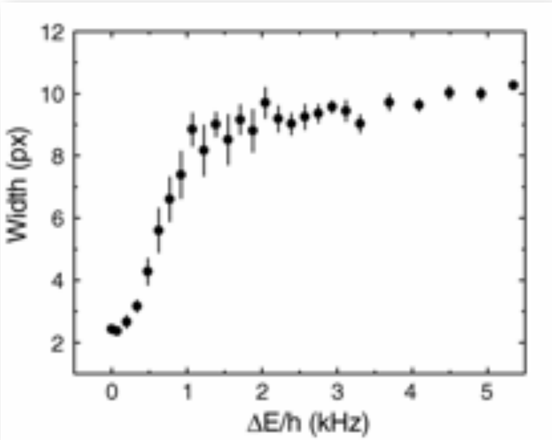
V_0= 16 E_{recoil} $\tau_{perturb}$ = 9



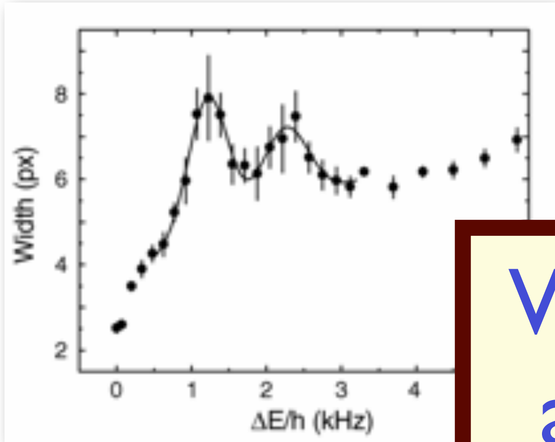
V_0= 20 E_{recoil} $\tau_{perturb}$ = 20 ms





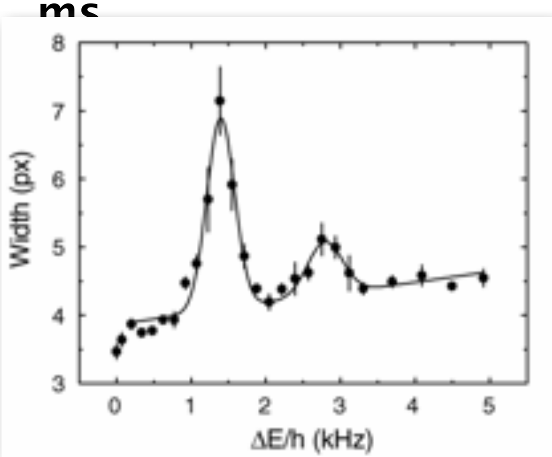


V_0=10 E_{recoil} $\tau_{perturb}$ = 2 ms

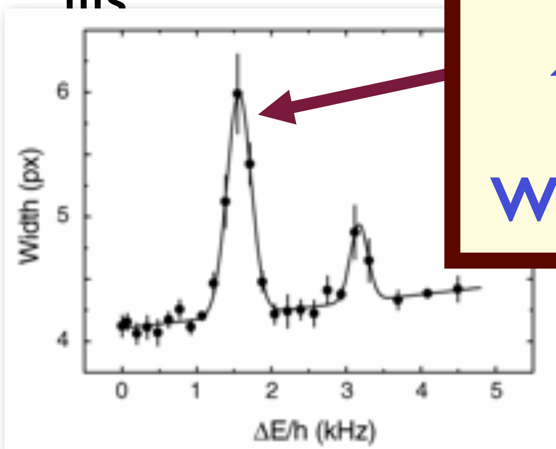


V_0= 13 E_{recoil} τ_{pert} ms

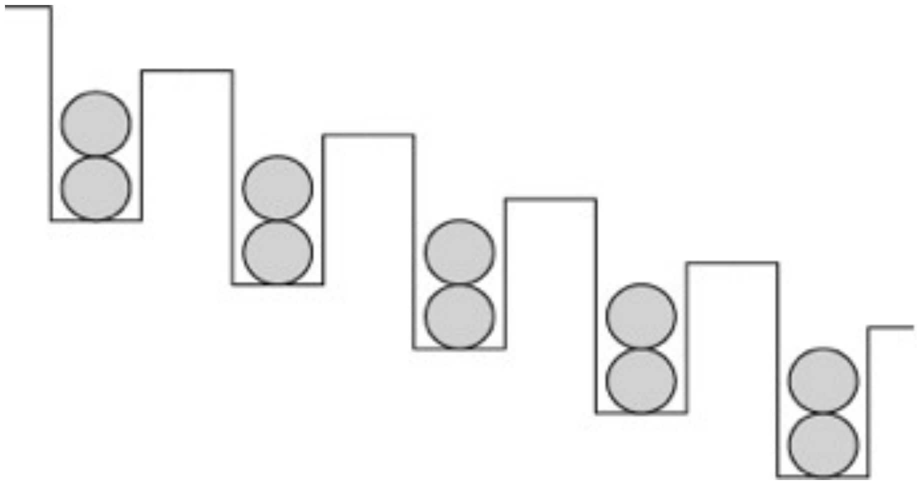
Why is there a peak (and not a threshold) when E = U ?



V_0= 16 E_{recoil} $\tau_{perturb}$ = 9



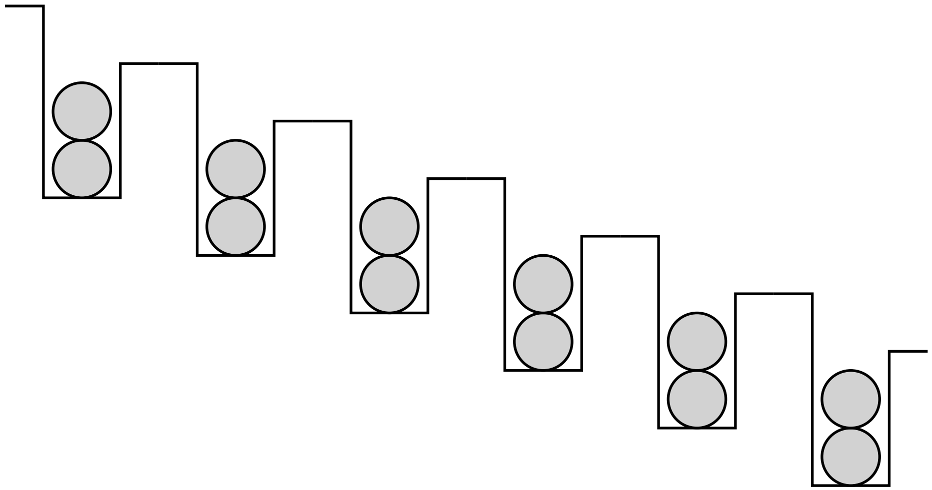
V_0= 20 E_{recoil} $\tau_{perturb}$ = 20 ms

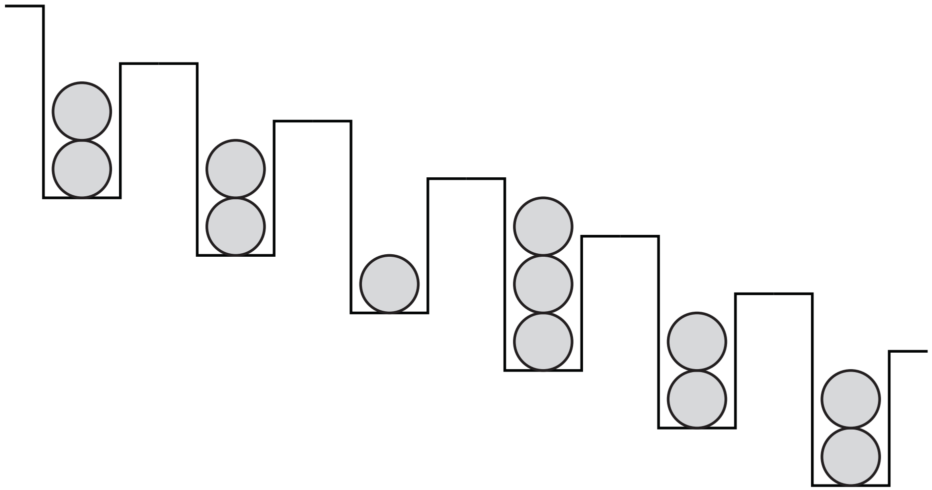


$$H = -t\sum_{\langle ij \rangle}\left(b_i^\dagger b_j + b_j^\dagger b_i\right) + \frac{U}{2}\sum_i n_i\left(n_i - 1\right) - \sum_i \boldsymbol{E}\cdot\boldsymbol{r}_i n_i$$

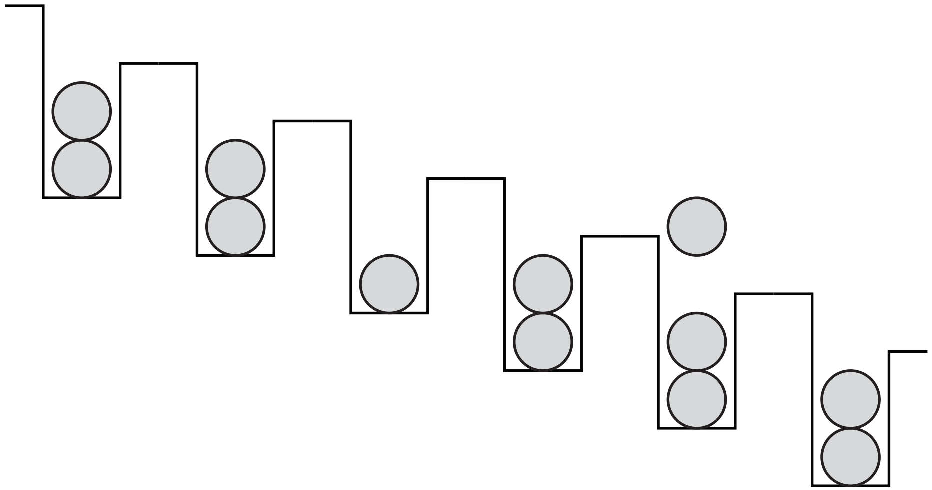
$$n_i = b_i^\dagger b_i$$

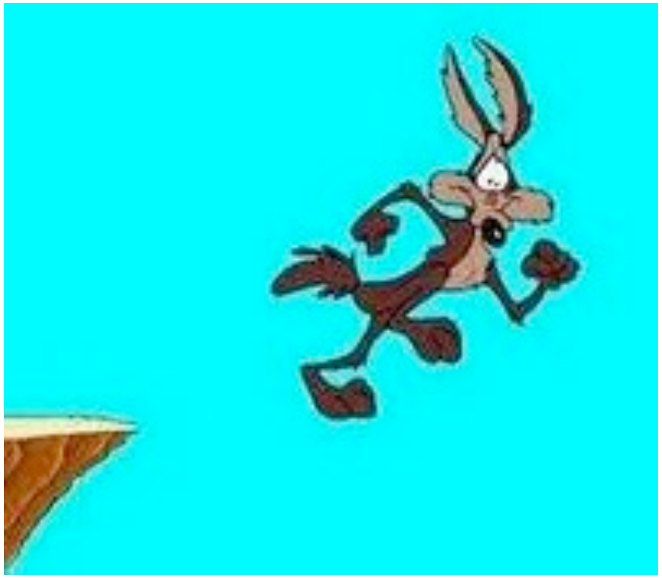
$$\left|U - E\right|, t \ll E, U$$



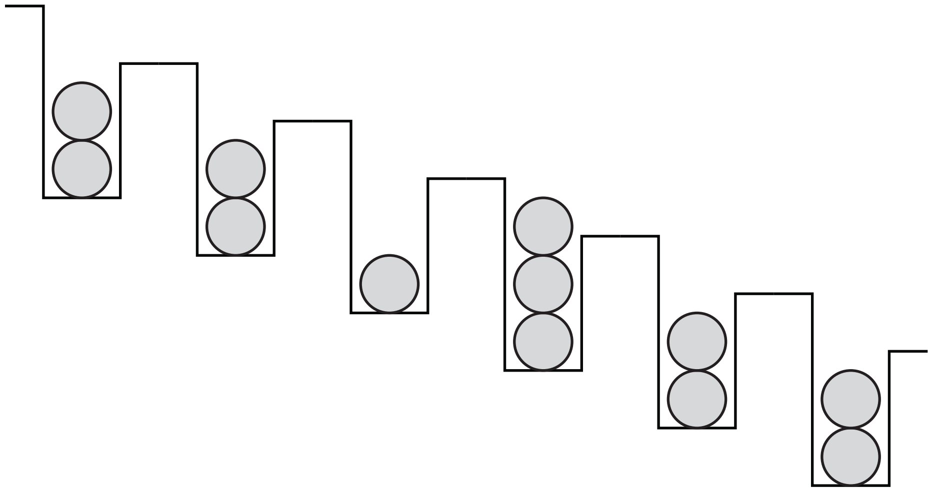


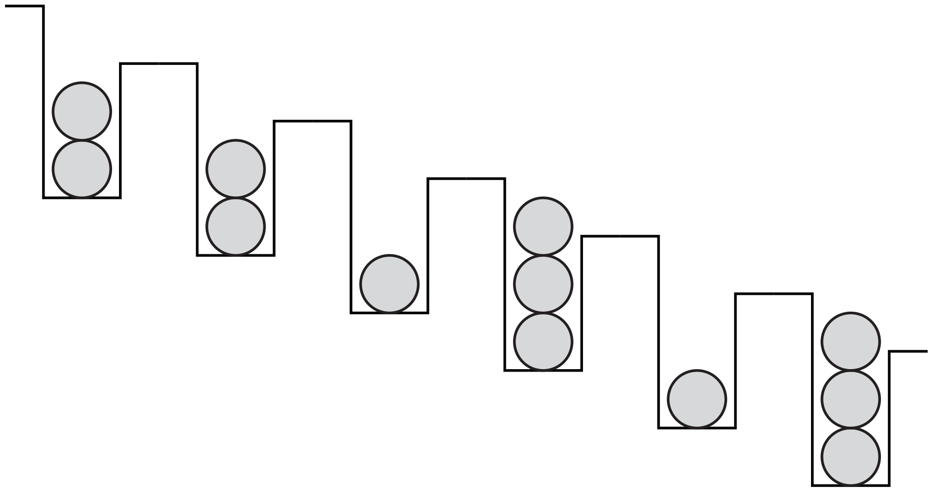
Resonant transition when $E=U$



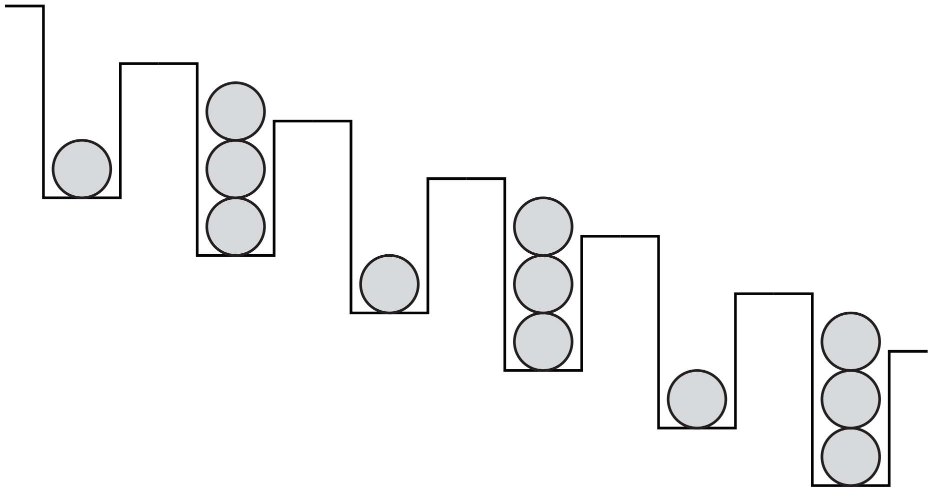


Virtual state

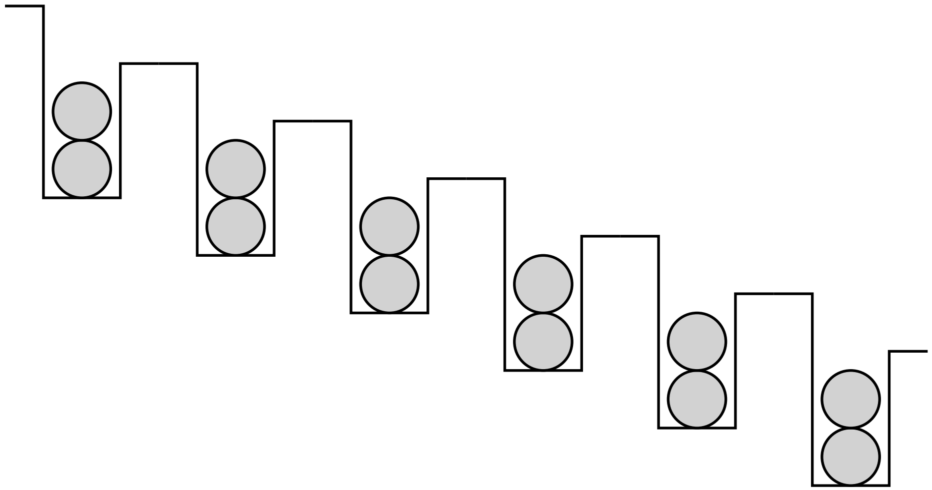


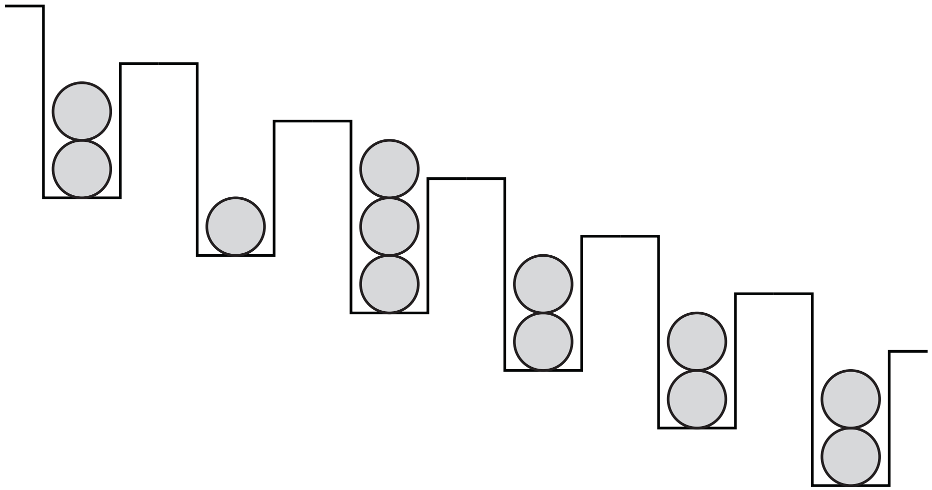


Resonant transition when $E=U$

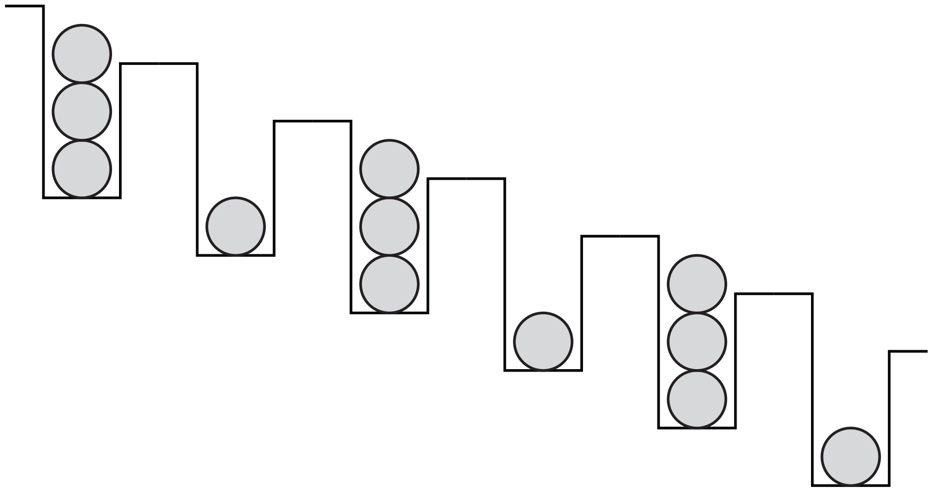


Resonant transition when *E*=*U*

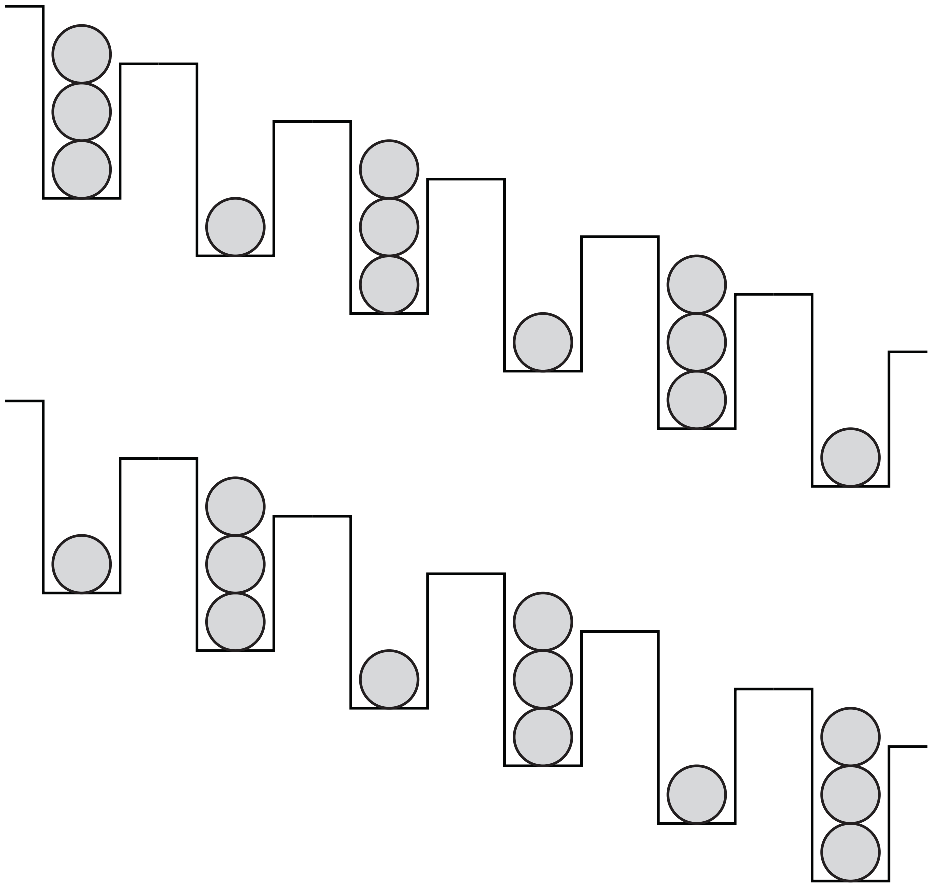




Resonant transition when *E*=*U*



Resonant transition when $E=U$



Two states with Ising density wave order

Hamiltonian for resonant dipole states (in one dimension)

$d_\ell^\dagger \Rightarrow$ Creates dipole on link ℓ

$$H_d = -\sqrt{6}t \sum_\ell \left(d_\ell^\dagger + d_\ell \right) + (U - E) \sum_\ell d_\ell^\dagger d_\ell$$

Constraints: $d_\ell^\dagger d_\ell \leq 1 \quad ; \quad d_{\ell+1}^\dagger d_{\ell+1} d_\ell^\dagger d_\ell = 0$

Determine phase diagram of H_d as a function of $(U\text{-}E)/t$

Hamiltonian for resonant dipole states (in one dimension)

$d_\ell^\dagger \Rightarrow$ Creates dipole on link ℓ

$$H_d = -\sqrt{6}t \sum_\ell \left(d_\ell^\dagger + d_\ell \right) + (U - E) \sum_\ell d_\ell^\dagger d_\ell$$

Constraints: $\quad d_\ell^\dagger d_\ell \leq 1 \quad ; \quad d_{\ell+1}^\dagger d_{\ell+1} d_\ell^\dagger d_\ell = 0$

Determine phase diagram of H_d as a function of $(U-E)/t$

Note: there is no explicit dipole hopping term.

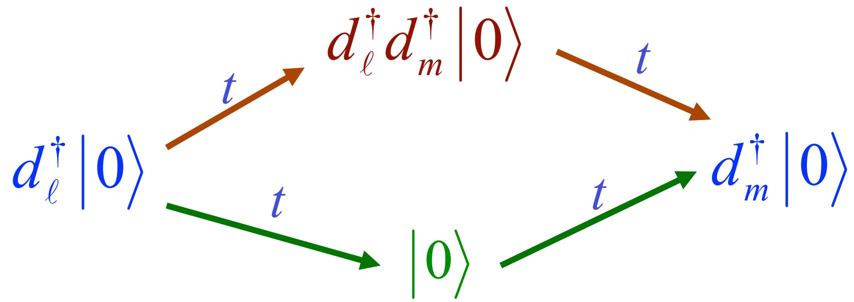
However, dipole hopping is generated by the interplay of terms in H_d and the constraints.

Weak electric fields: $(U\text{-}E) \gg t$

Ground state is dipole vacuum (Mott insulator) $|0\rangle$

First excited levels: single dipole states $d_\ell^\dagger|0\rangle$

Effective hopping between dipole states



If both processes are permitted, they exactly cancel each other.
The top processes is blocked when ℓ, m are nearest neighbors

$\Rightarrow$ A nearest-neighbor dipole hopping term $\sim \dfrac{t^2}{U-E}$ is generated

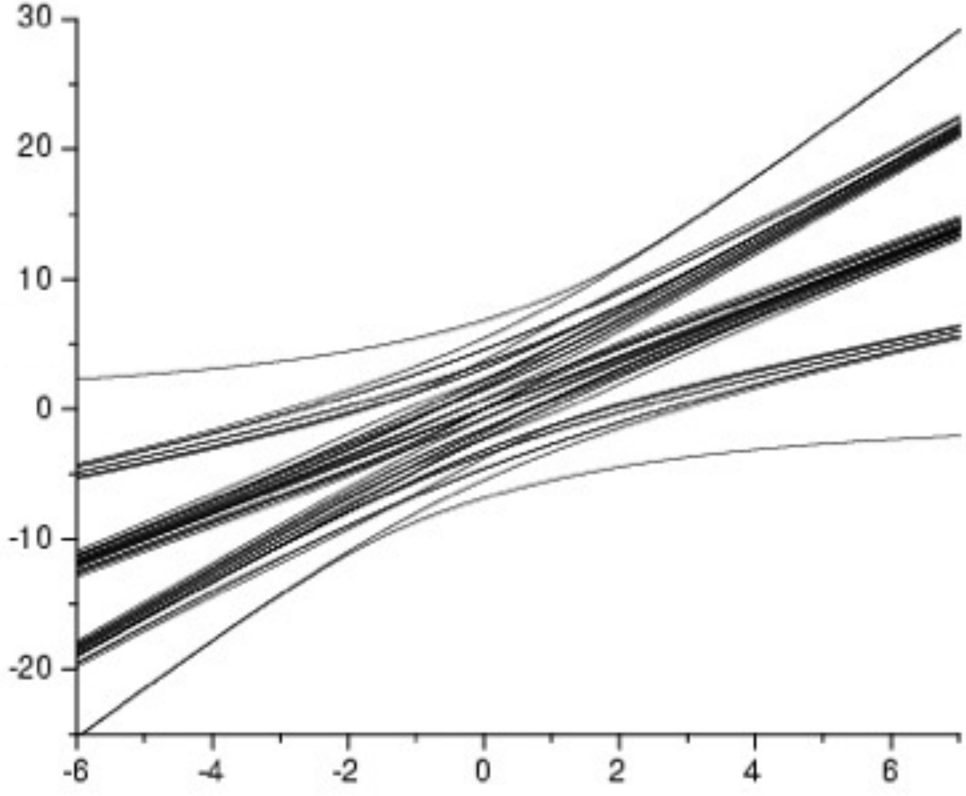
Strong electric fields: $(E\text{-}U) \gg t$

Ground state has maximal dipole number.

Two-fold degeneracy associated with Ising density wave order:

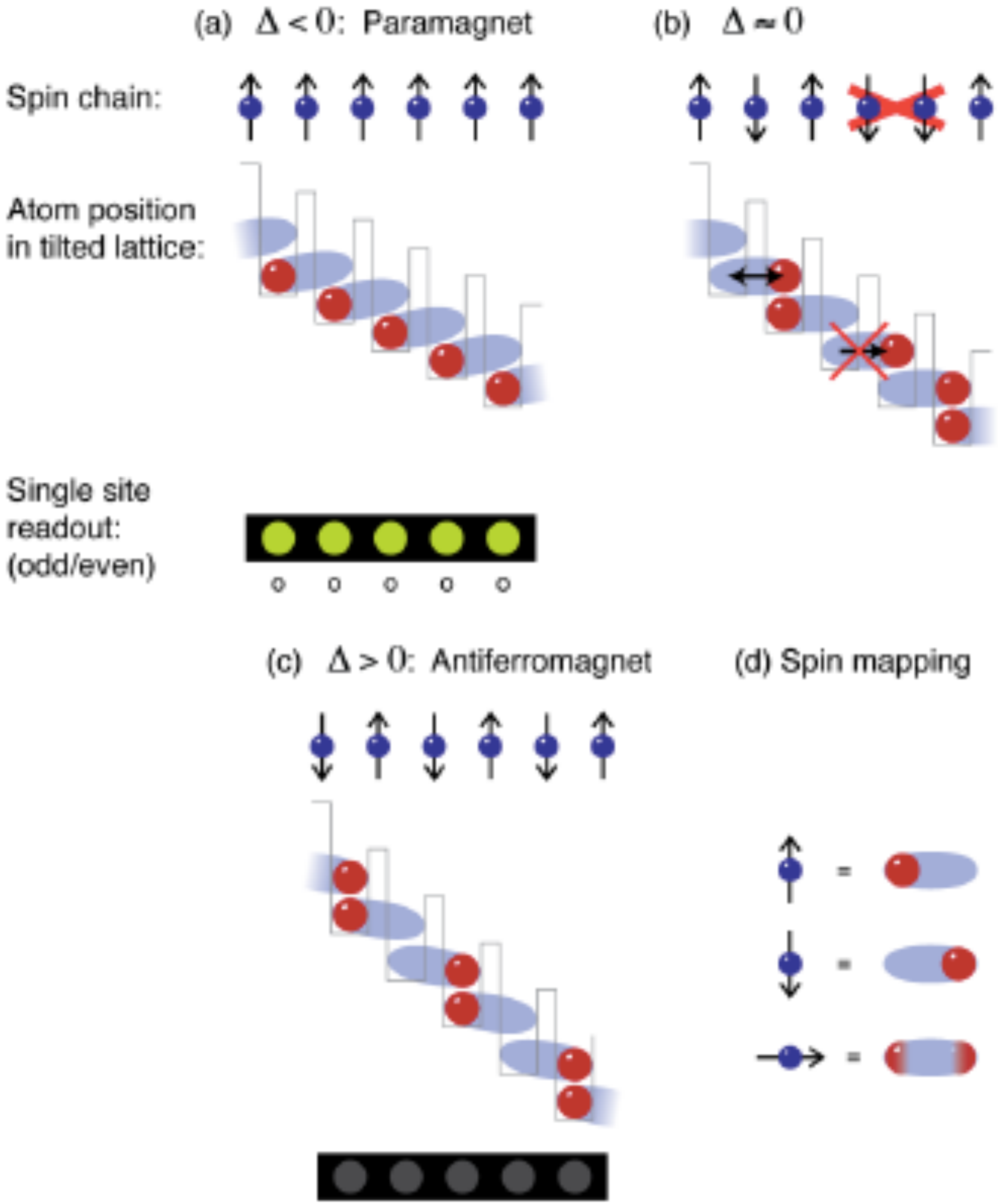
$$\cdots d_1^\dagger d_3^\dagger d_5^\dagger d_7^\dagger d_9^\dagger d_{11}^\dagger \cdots |0\rangle \qquad or \qquad \cdots d_2^\dagger d_4^\dagger d_6^\dagger d_8^\dagger d_{10}^\dagger d_{12}^\dagger \cdots |0\rangle$$

Eigenvalues

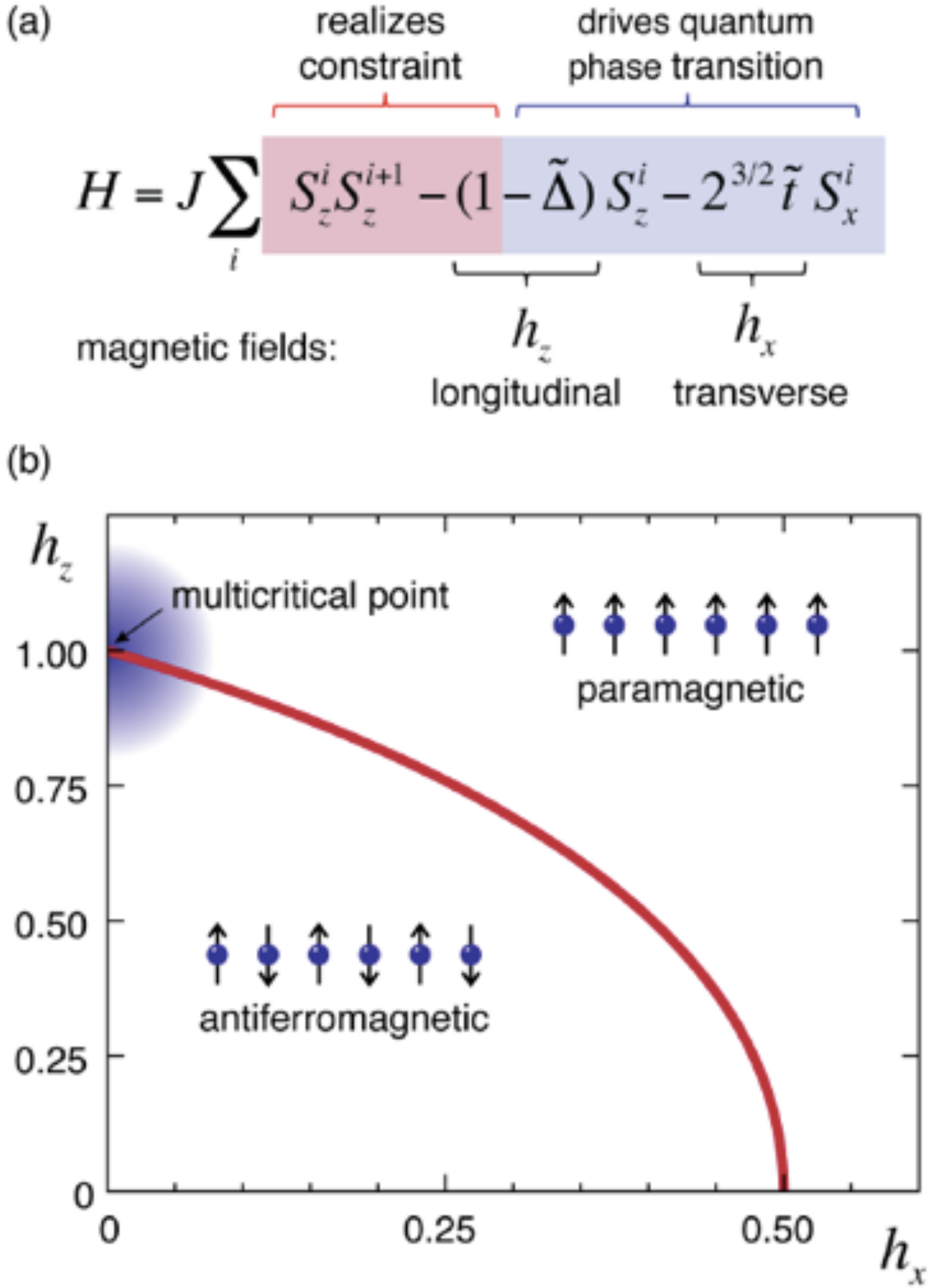


$(U\text{-}E)/t$

Mapping to Ising Antiferromagnet in a longitudinal and transverse field

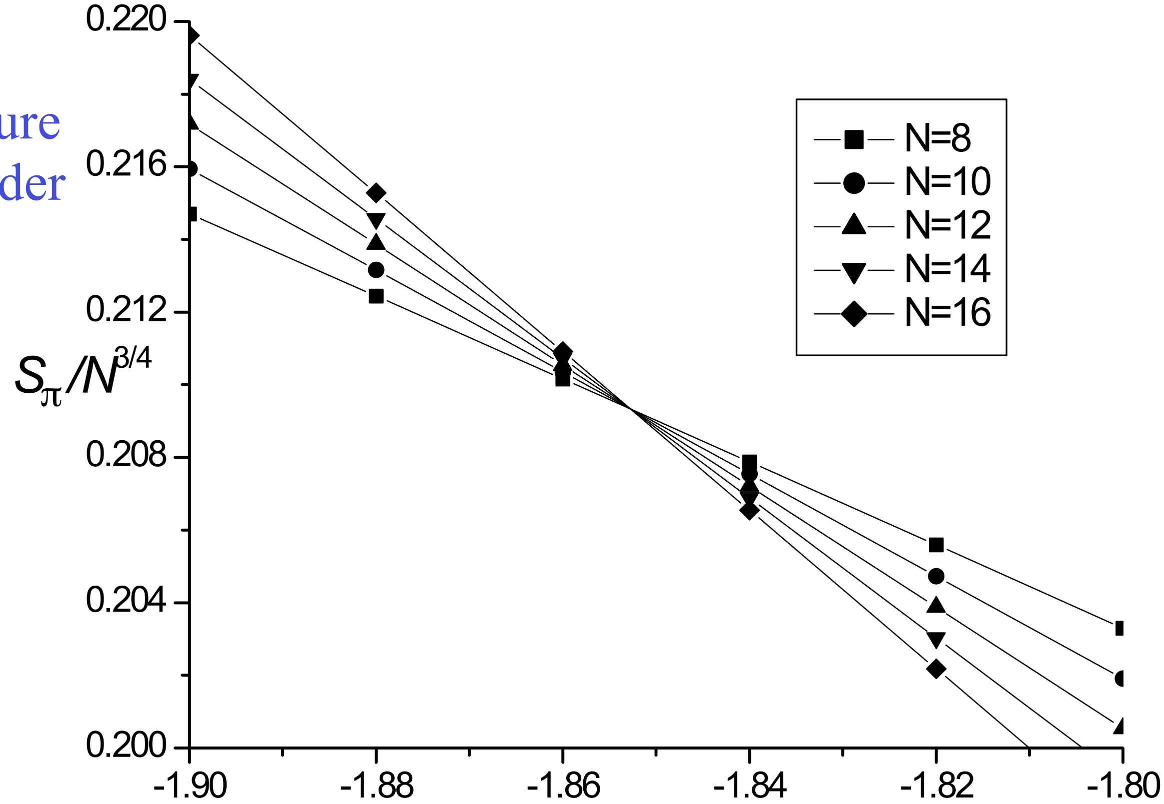


Mapping
to Ising
Antiferromagnet
in
a longitudinal
and transverse
field



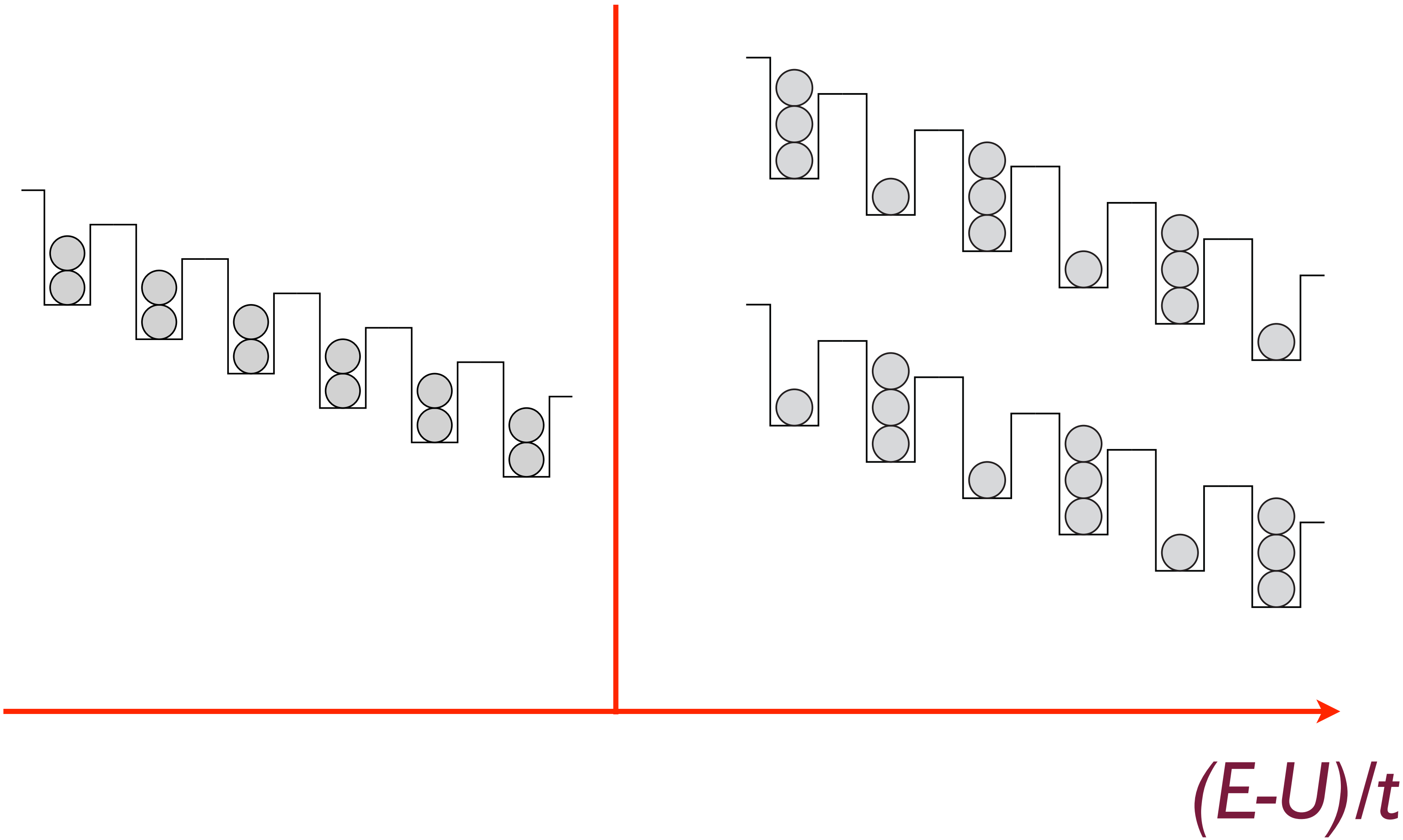
Ising quantum critical point at *E-U=1.08 t*

Equal-time structure factor for Ising order parameter

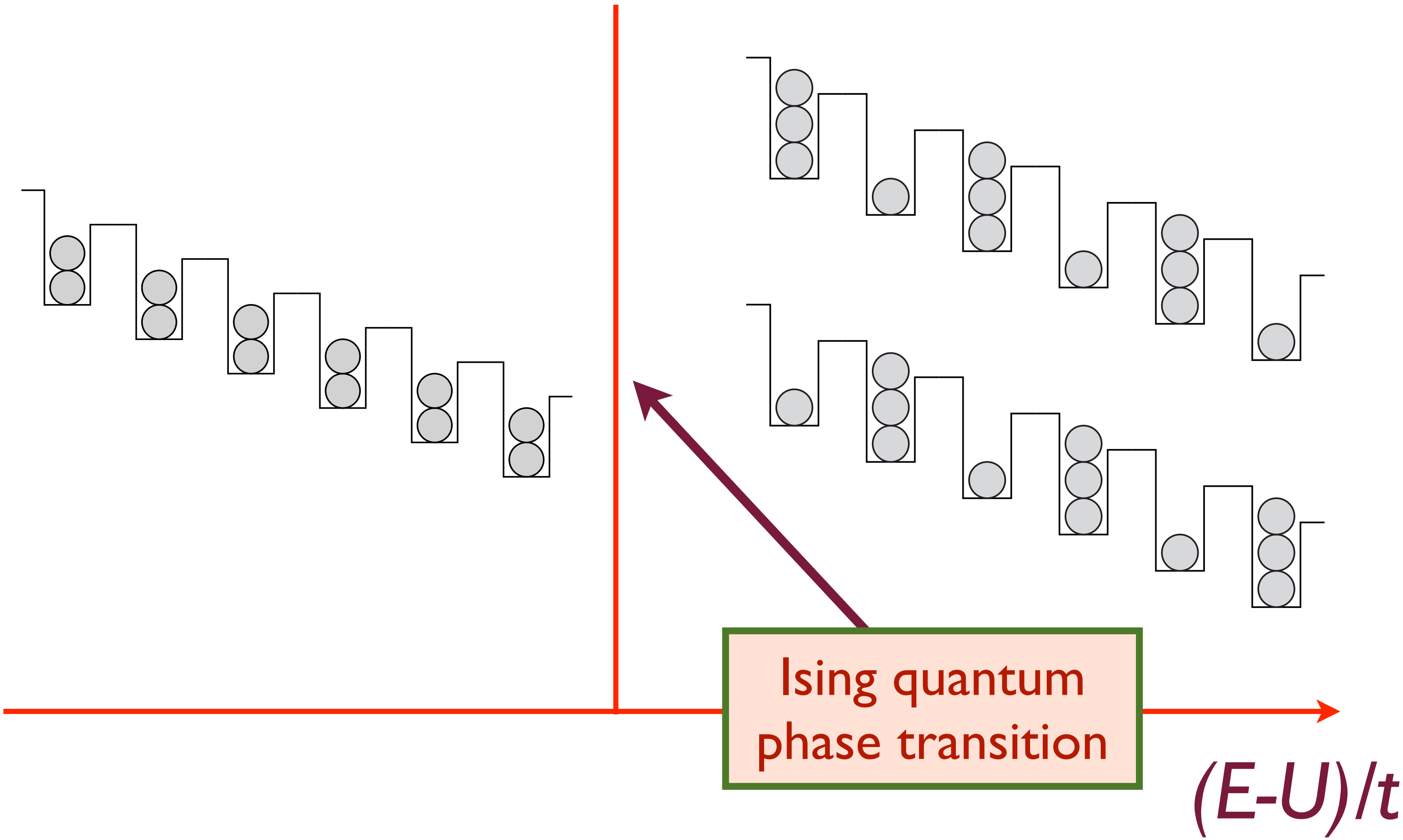


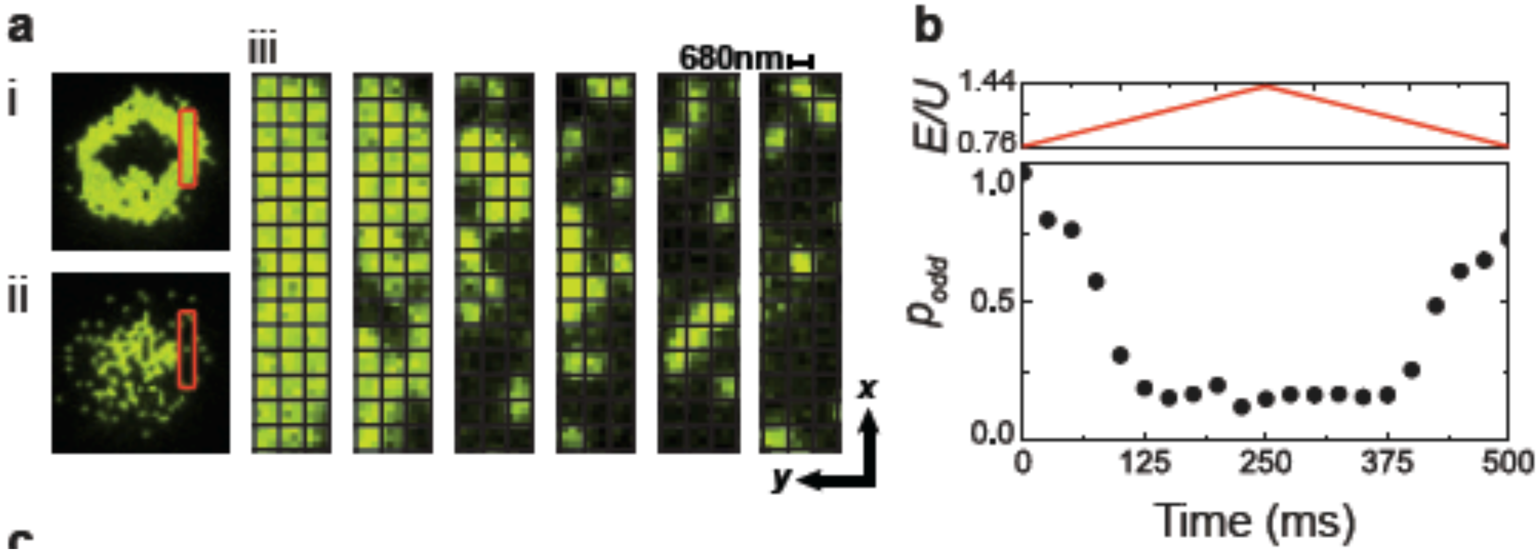
(U-E)/t

Phase diagram of boson model

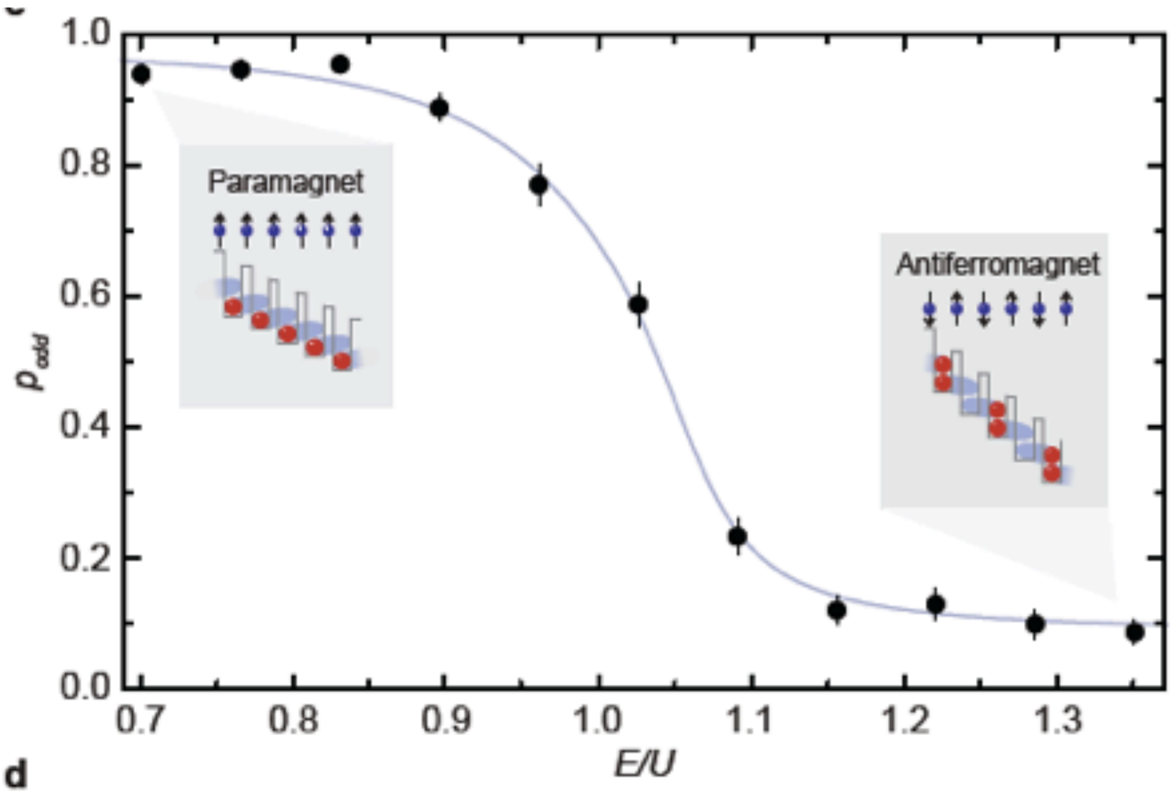


Phase diagram
of boson model

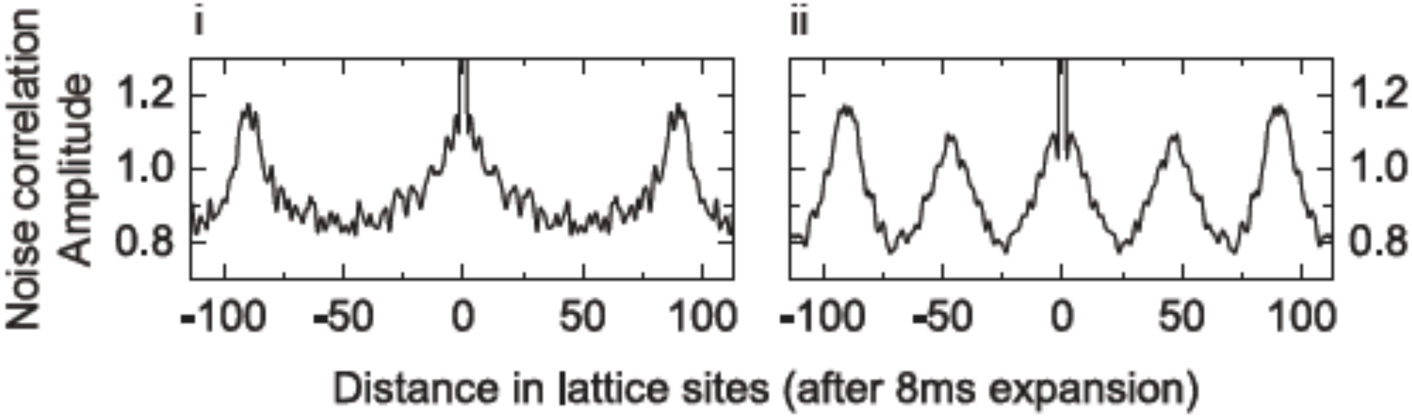




Jonathan Simon, Waseem S. Bakr, Ruichao Ma, M. Eric Tai, Philipp M. Preiss, and Markus Greiner, submitted



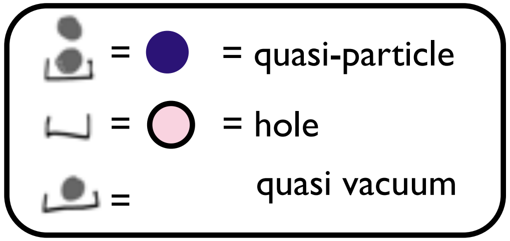
Jonathan Simon, Waseem S. Bakr, Ruichao Ma, M. Eric Tai, Philipp M. Preiss, and Markus Greiner, submitted



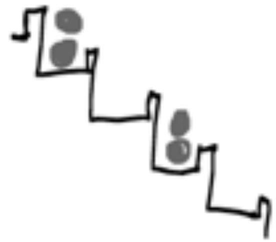
Jonathan Simon, Waseem S. Bakr, Ruichao Ma,
M. Eric Tai, Philipp M. Preiss,
and Markus Greiner, submitted

Square lattice tilted along lattice direction

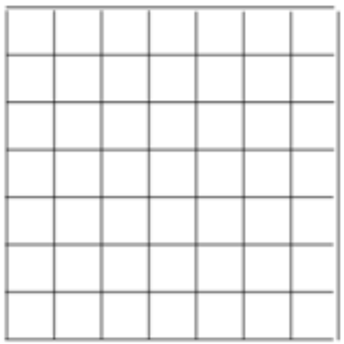
small tilt $\frac{\Delta}{t} \gg 1$



strong tilt $\frac{\Delta}{t} \ll -1$

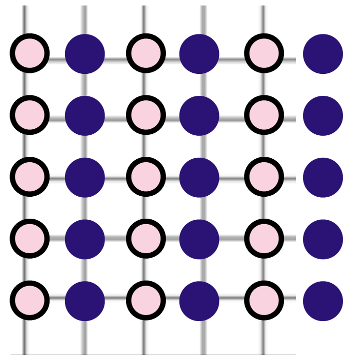


e



MI phase

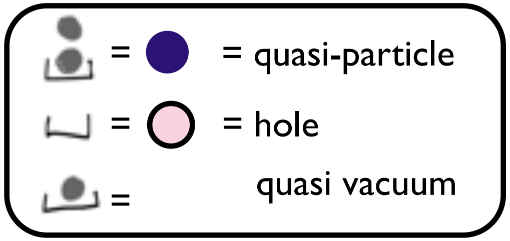
e



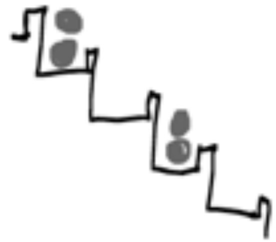
Ising

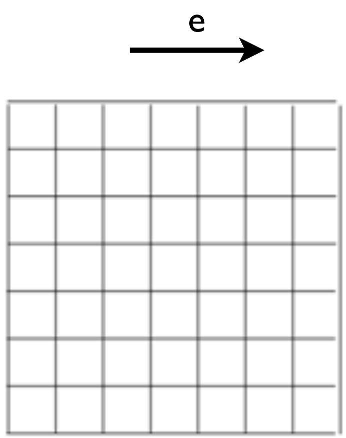
Square lattice tilted along lattice direction

small tilt $\frac{\Delta}{t} \gg 1$

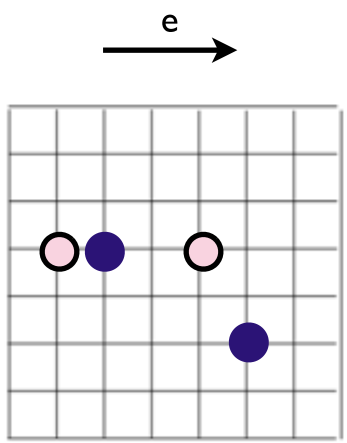


strong tilt $\frac{\Delta}{t} \ll -1$

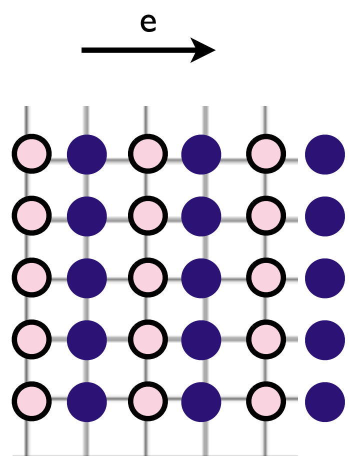




MI phase



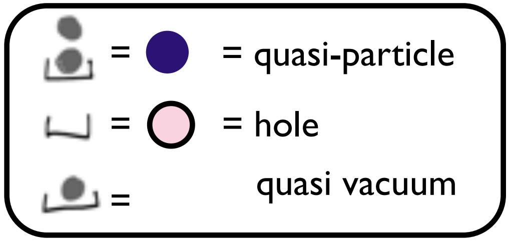
transverse superfluid



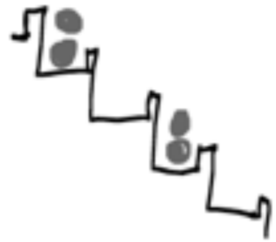
Ising

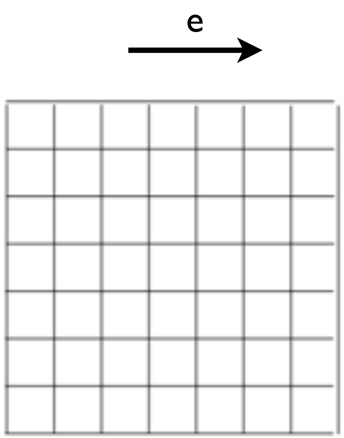
Square lattice tilted along lattice direction

small tilt $\frac{\Delta}{t} \gg 1$

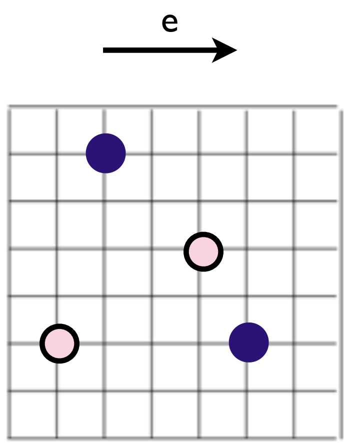


strong tilt $\frac{\Delta}{t} \ll -1$

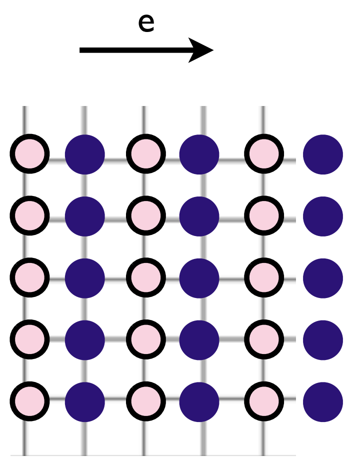




MI phase



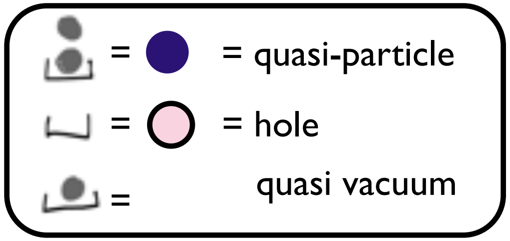
transverse superfluid



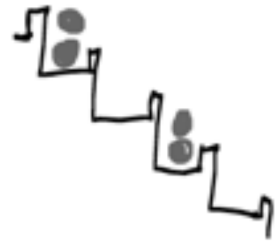
Ising

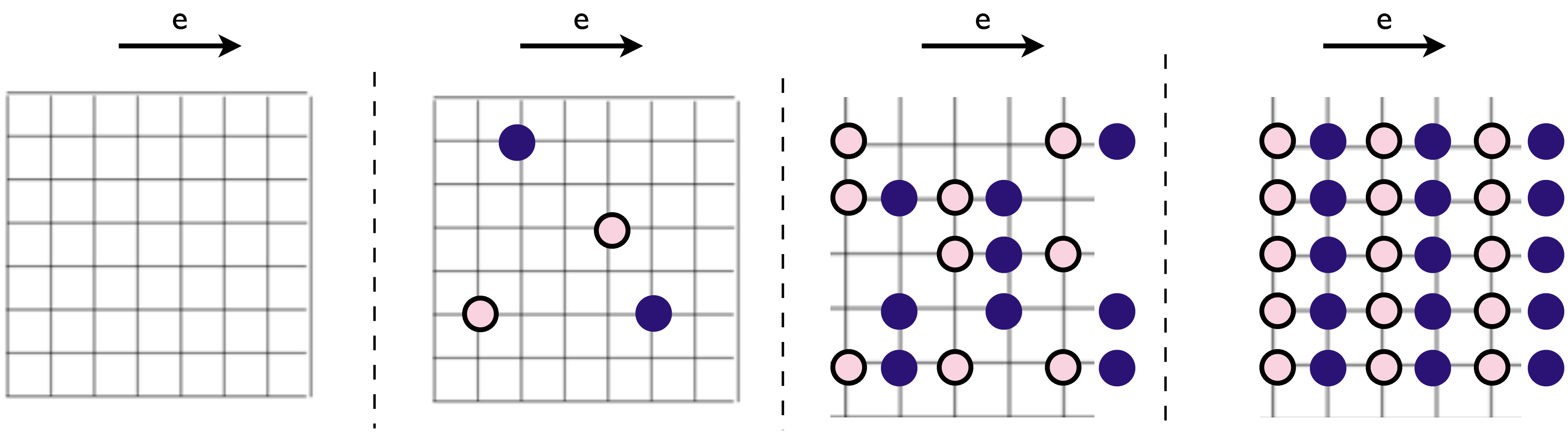
Square lattice tilted along lattice direction

small tilt $\frac{\Delta}{t} \gg 1$



strong tilt $\frac{\Delta}{t} \ll -1$





MI phase

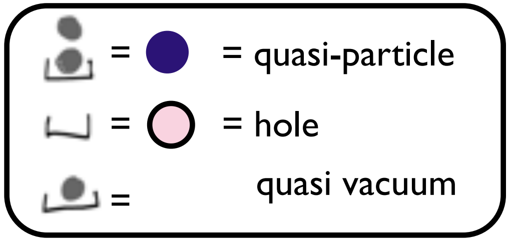
transverse superfluid

transverse superfluid & Ising

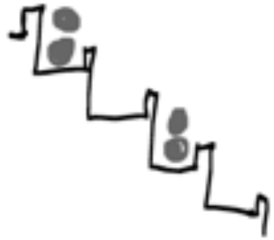
Ising

Diagonal tilt: density wave order persists

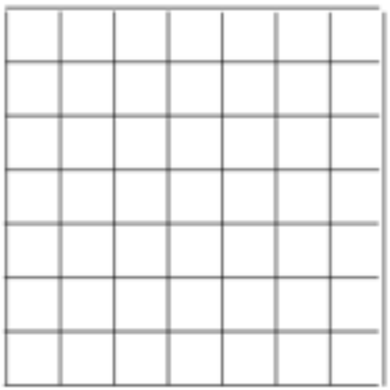
small tilt $\frac{\Delta}{t} \gg 1$

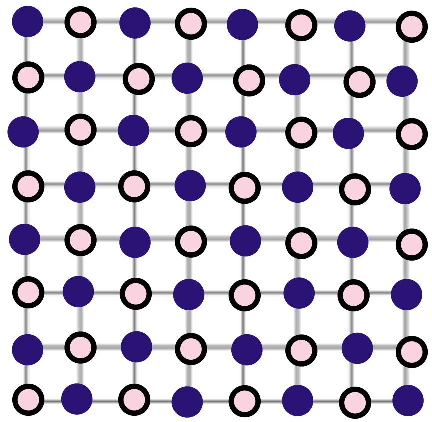


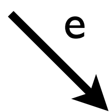
strong tilt $\frac{\Delta}{t} \ll -1$



two fold degenerate





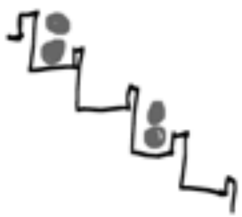


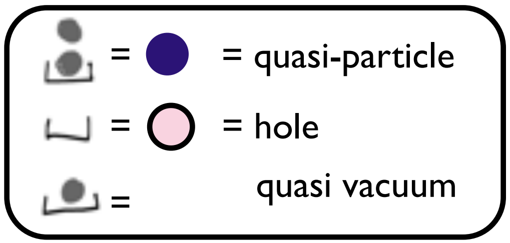
Tilted triangular lattice

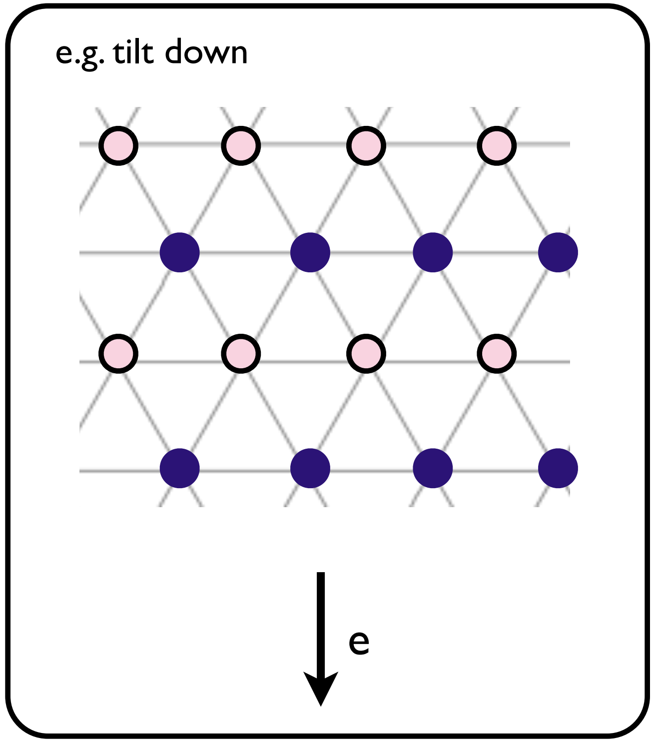
Ising and superfluid transition like in case of square lattice

tilt any direction: ordered state for strong tilt

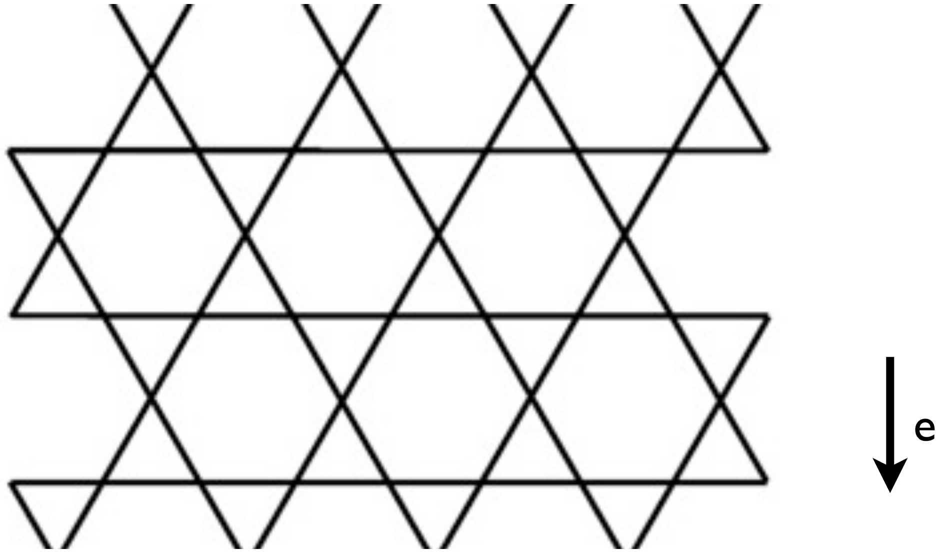
strong tilt $\frac{\Delta}{t} \ll -1$







Kagome lattice

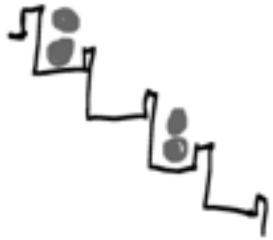


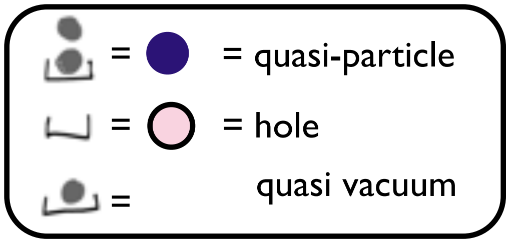
Kagome lattice

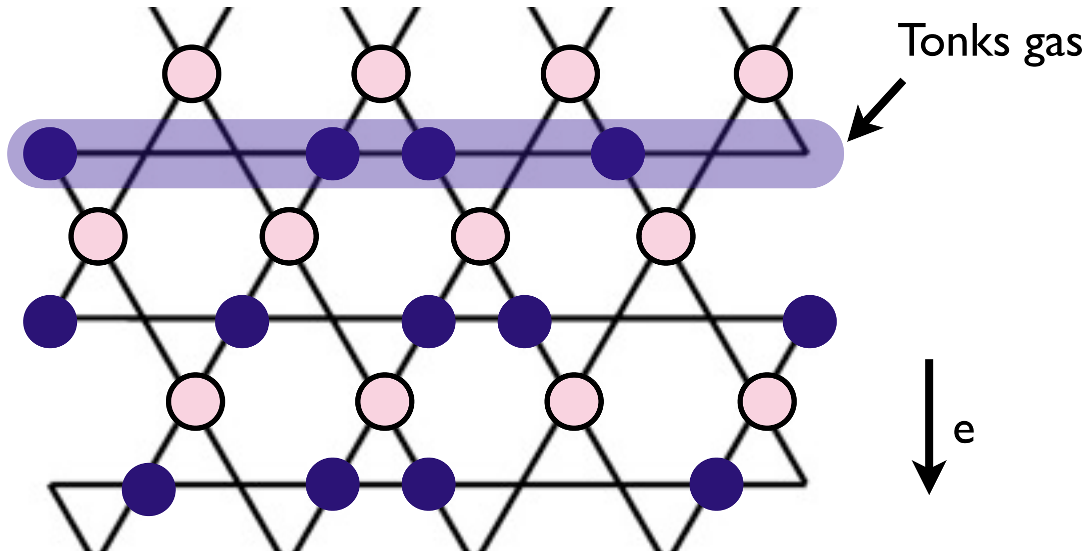
new: unique ground state in both limits

superfluid in strong tilting limit due to frustration

strong tilt $\frac{\Delta}{t} \ll -1$







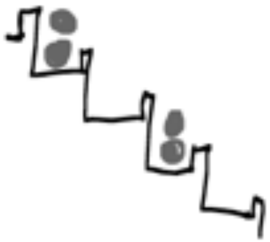
next:

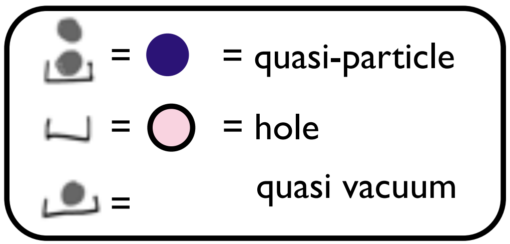
Kagome lattice

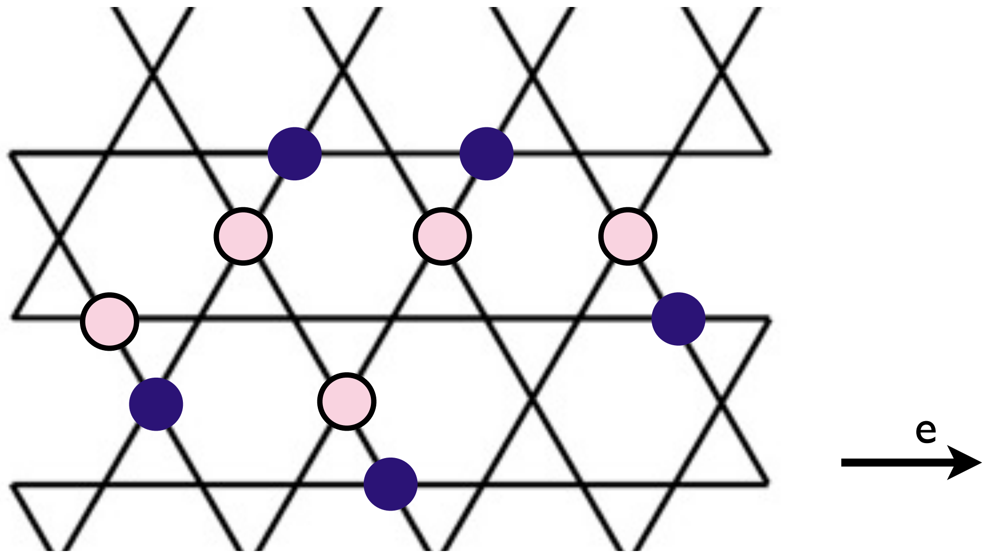
new: unique ground state in both limits

superfluid in strong tilting limit due to frustration

strong tilt $\frac{\Delta}{t} \ll -1$





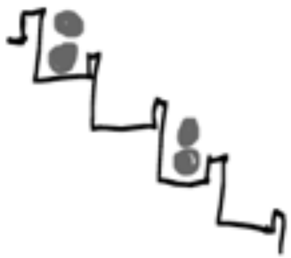


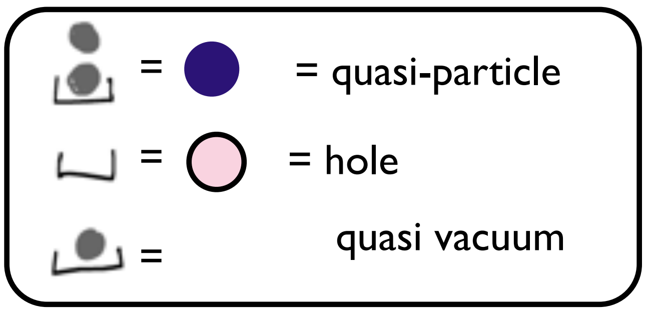
next: tilting towards the right gives rise to interesting spin-liquid-like state. This situation can also be realized by a diluted square lattice in diagonal tilt

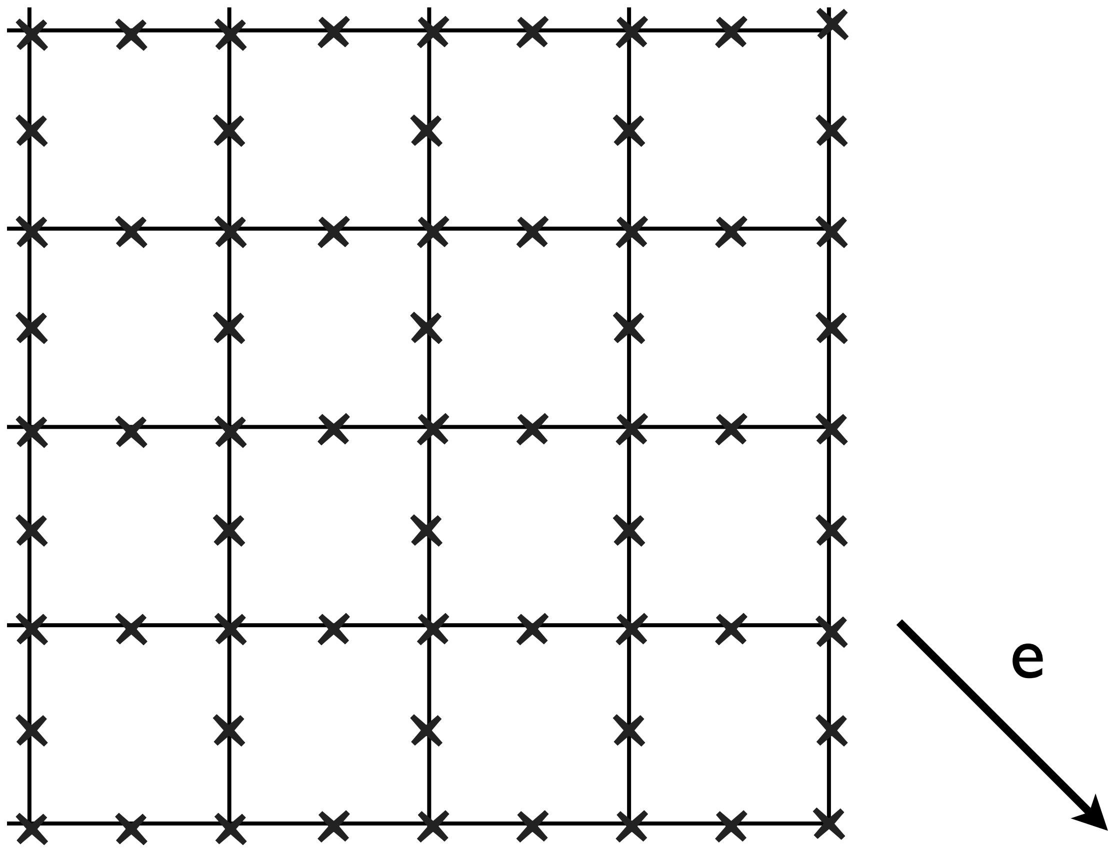
Decorated square lattice: spin-liquid-like state

diagonal tilt: not all sites can participate in forming particle-hole pairs, and there is no transverse superfluidity

strong tilt $\frac{\Delta}{t} \ll -1$



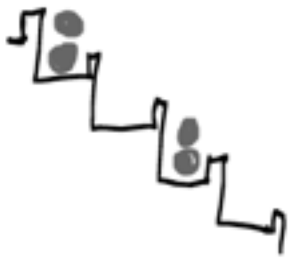


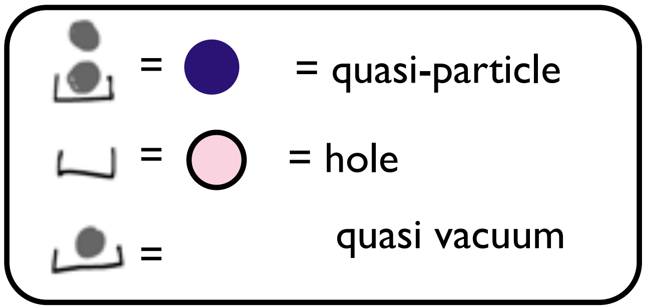


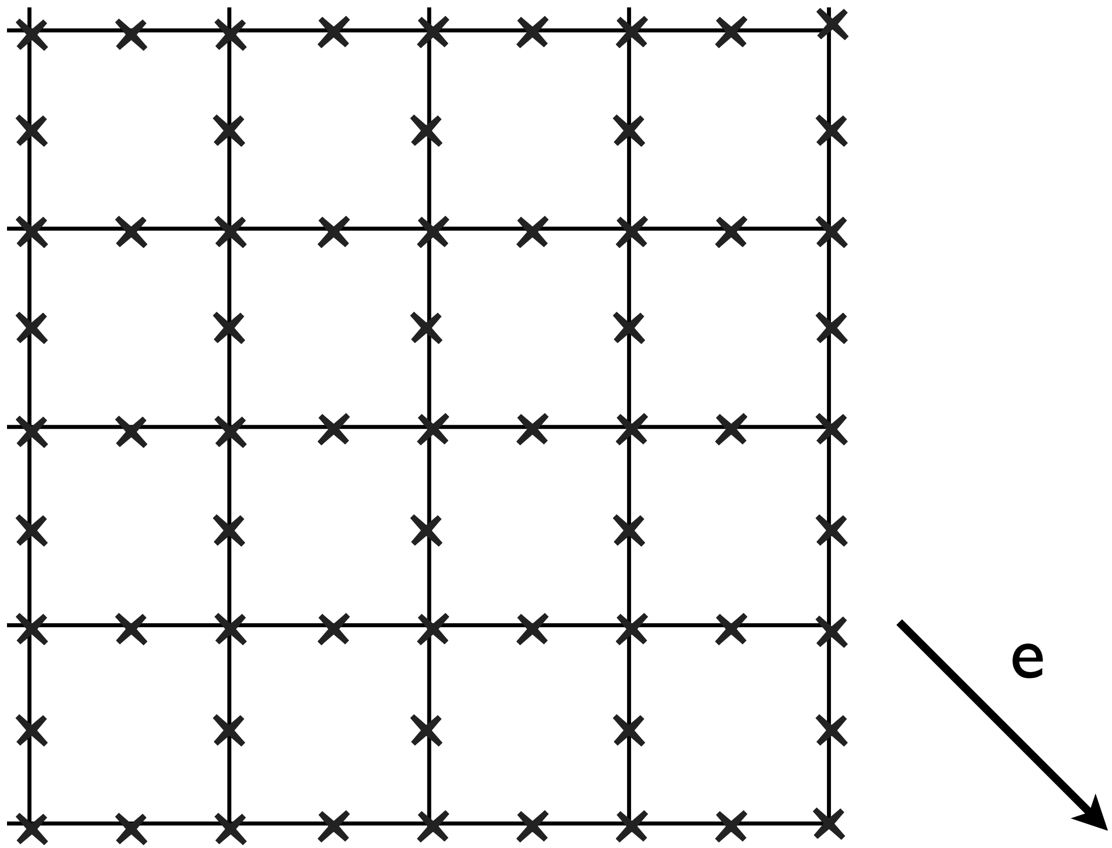
Decorated square lattice: spin-liquid-like state

diagonal tilt: not all sites can participate in forming particle-hole pairs, and there is no transverse superfluidity

strong tilt $\frac{\Delta}{t} \ll -1$



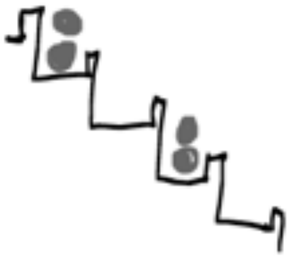


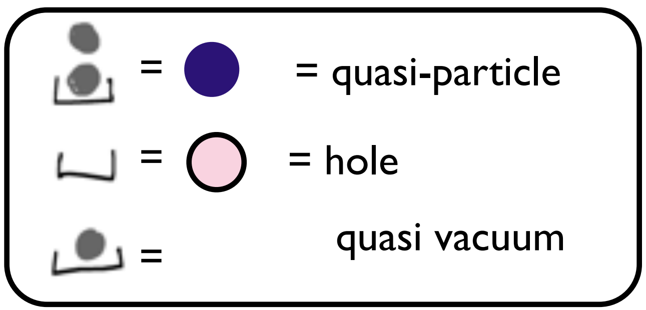


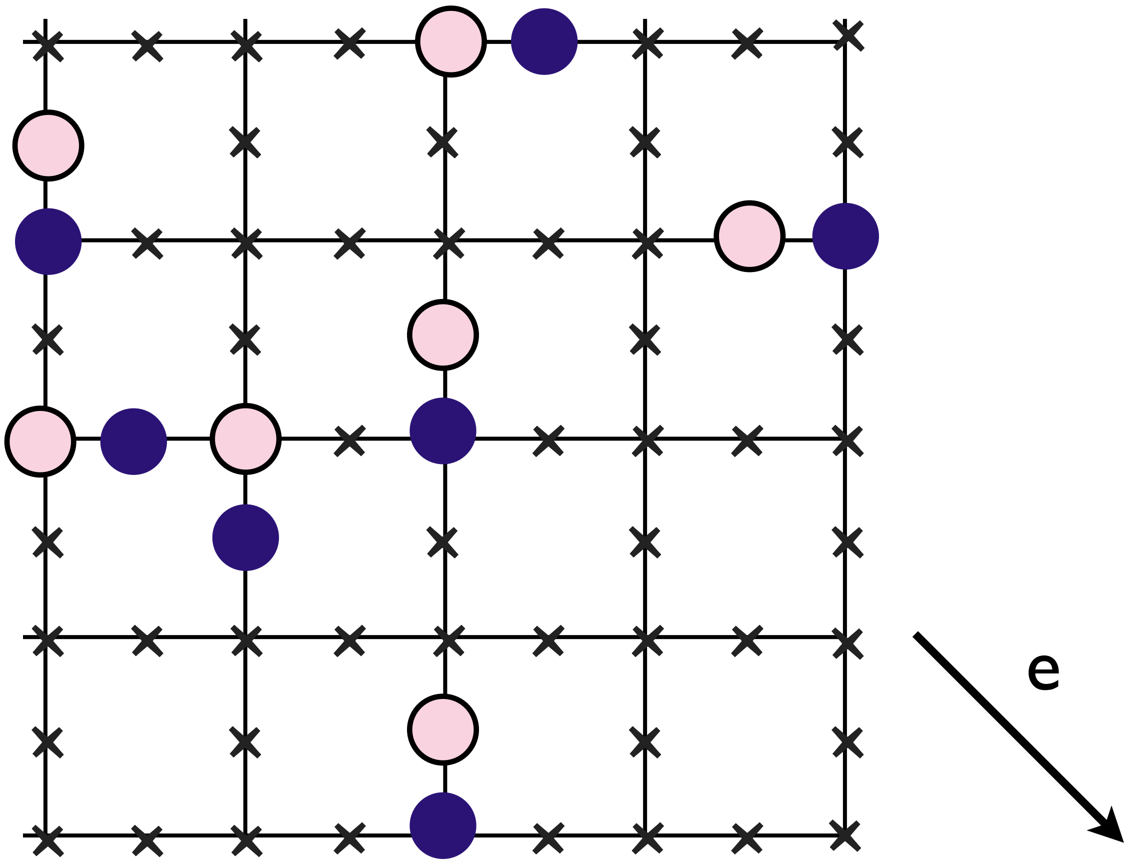
Decorated square lattice: spin-liquid-like state

diagonal tilt: not all sites can participate in forming particle-hole pairs, and there is no transverse superfluidity

strong tilt $\frac{\Delta}{t} \ll -1$



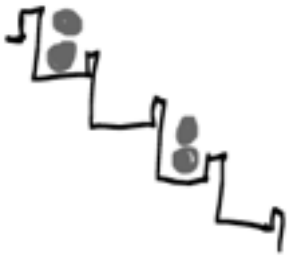


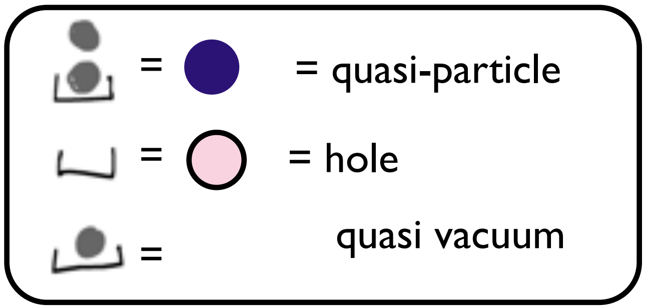


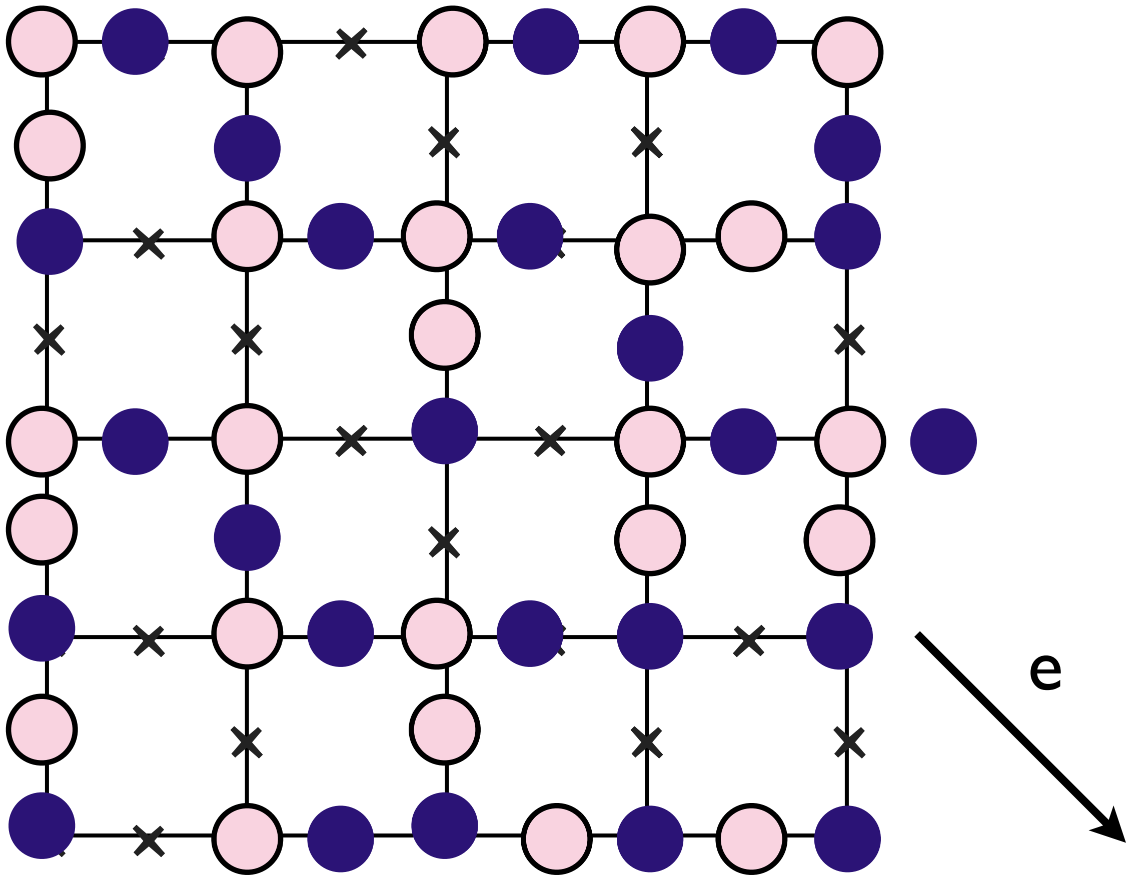
Decorated square lattice: spin-liquid-like state

diagonal tilt: not all sites can participate in forming particle-hole pairs, and there is no transverse superfluidity

strong tilt $\frac{\Delta}{t} \ll -1$

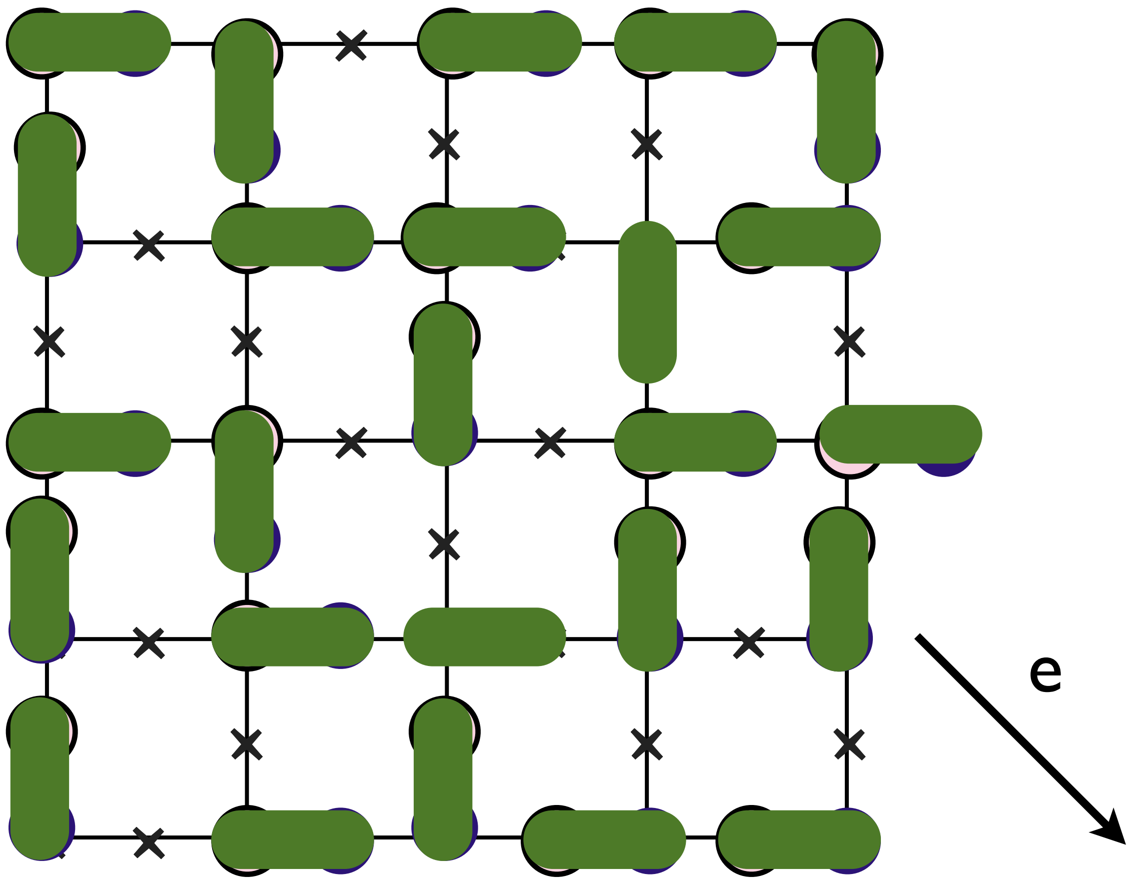






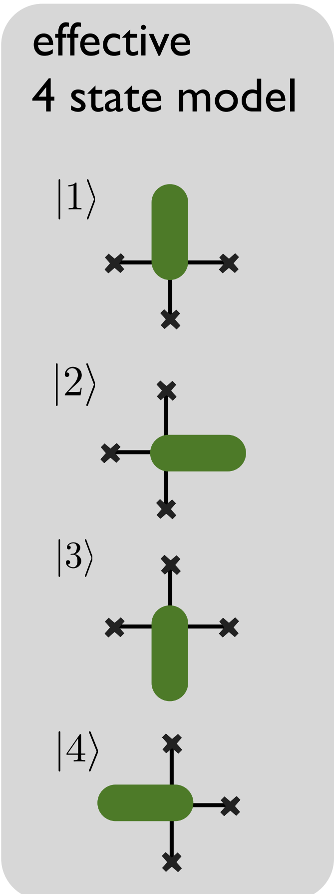
Decorated square lattice: spin-liquid-like state

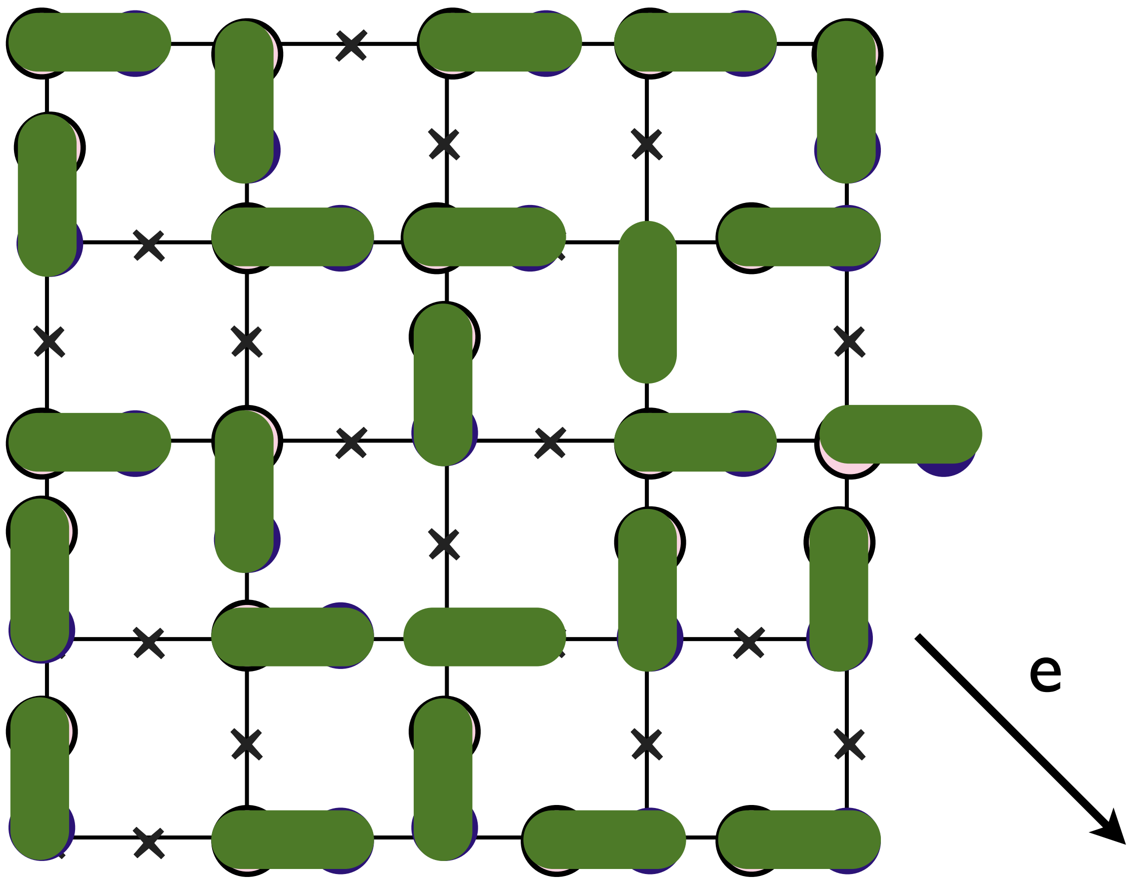
Effective model in strong tilting limit



Decorated square lattice: spin-liquid-like state

Effective model in strong tilting limit

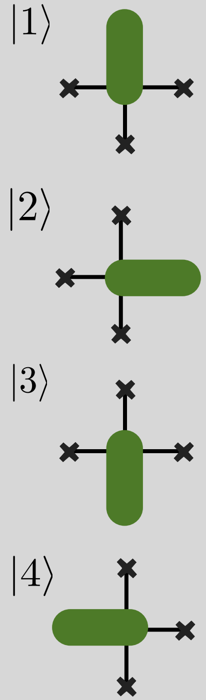


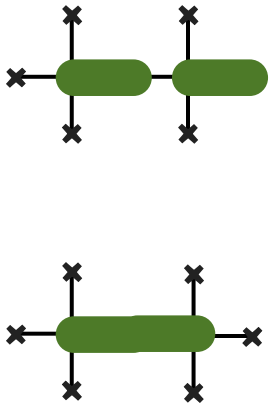


Decorated square lattice: spin-liquid-like state

Effective model in strong tilting limit

effective
4 state model



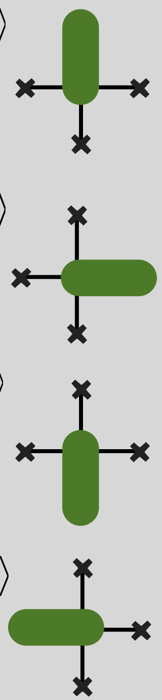


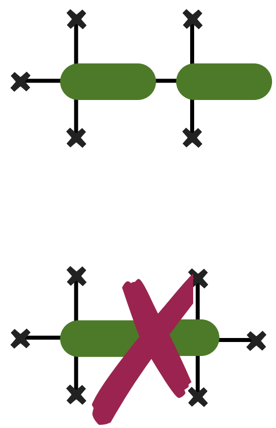
Decorated square lattice: spin-liquid-like state

Effective model in strong tilting limit

effective
4 state model

$|1\rangle$ $|2\rangle$ $|3\rangle$ $|4\rangle$

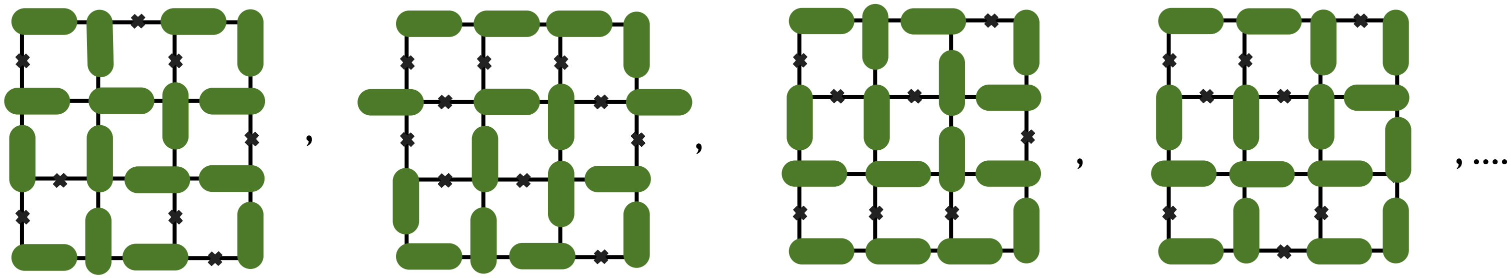




constraint!

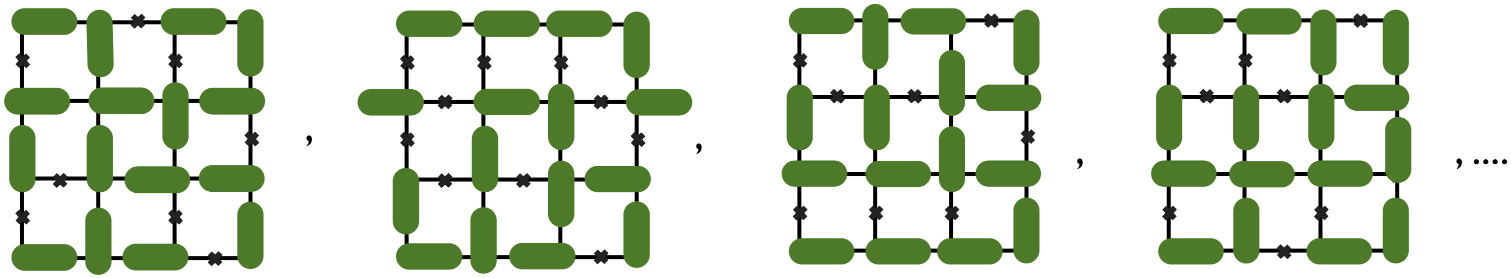
Decorated square lattice: spin-liquid-like state

- t=0 : many degenerate ground states that maximize number of particle-hole pairs



Decorated square lattice: spin-liquid-like state

- t=0 : many degenerate ground states that maximize number of particle-hole pairs

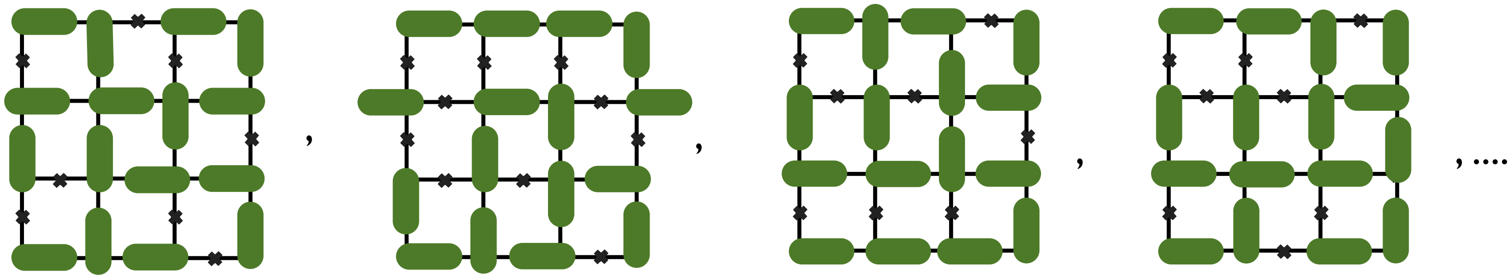


- finite hopping t :

$$H = \hat{P}_c \tilde{H} \hat{P}_c \qquad \tilde{H} = \sum_{lm} H_{lm}; \qquad H_{lm} = -t_{\rm eff} \sum_{i,j=0}^{4} |i\rangle \langle j|$$

Decorated square lattice: spin-liquid-like state

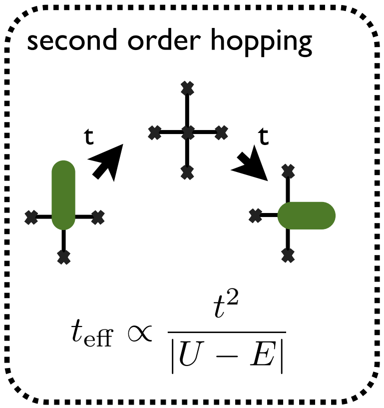
- t=0 : many degenerate ground states that maximize number of particle-hole pairs



- finite hopping t :

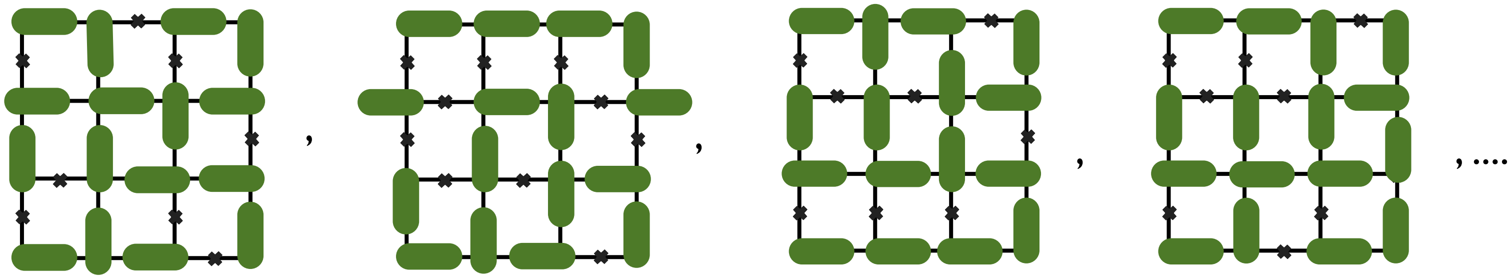
$$H = \hat{P}_c \tilde{H} \hat{P}_c$$

$$\tilde{H} = \sum_{lm} H_{lm}; \qquad H_{lm} = -t_{\text{eff}} \sum_{i,j=0}^{4} |i\rangle \langle j|$$



Decorated square lattice: spin-liquid-like state

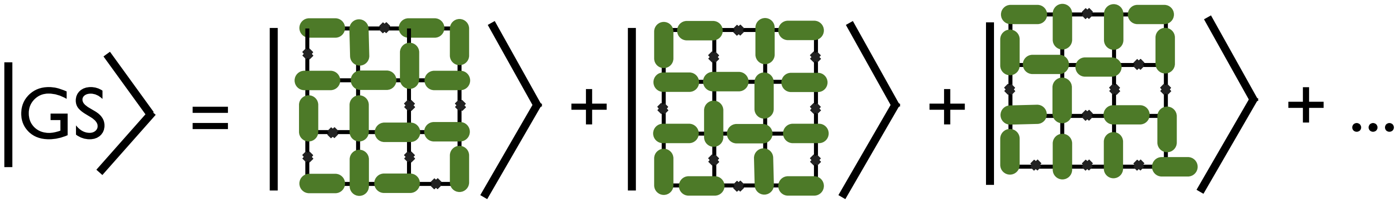
- t=0 : many degenerate ground states that maximize number of particle-hole pairs



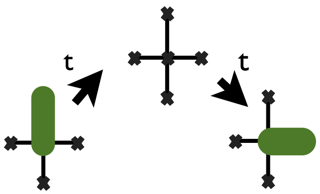
- finite hopping t :

$$H = \hat{P}_c \tilde{H} \hat{P}_c \qquad \tilde{H} = \sum_{lm} H_{lm}; \qquad H_{lm} = -t_{\text{eff}} \sum_{i,j=0}^{4} |i\rangle \langle j|$$

ground state : equal amplitude superposition of all allowed states



second order hopping

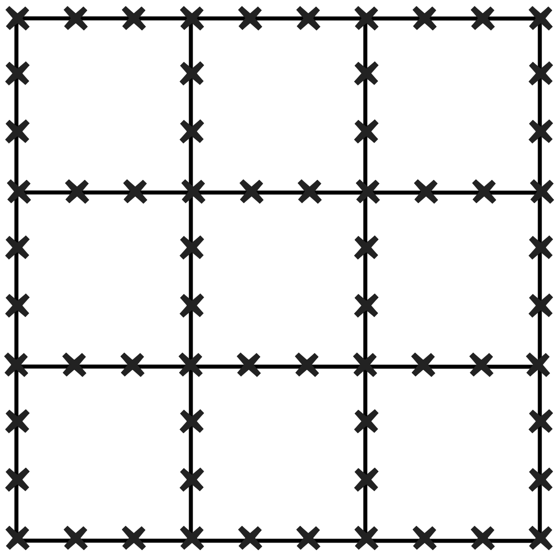


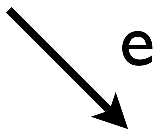
$$t_{\text{eff}} \propto \frac{t^2}{|U - E|}$$

- unique ground state: no broken symmetry, no topological property
- we can use classical statistical mechanics to calculate ground state correlations
- exponentially decaying correlations
- gapped excitations

Doubly-decorated square lattice

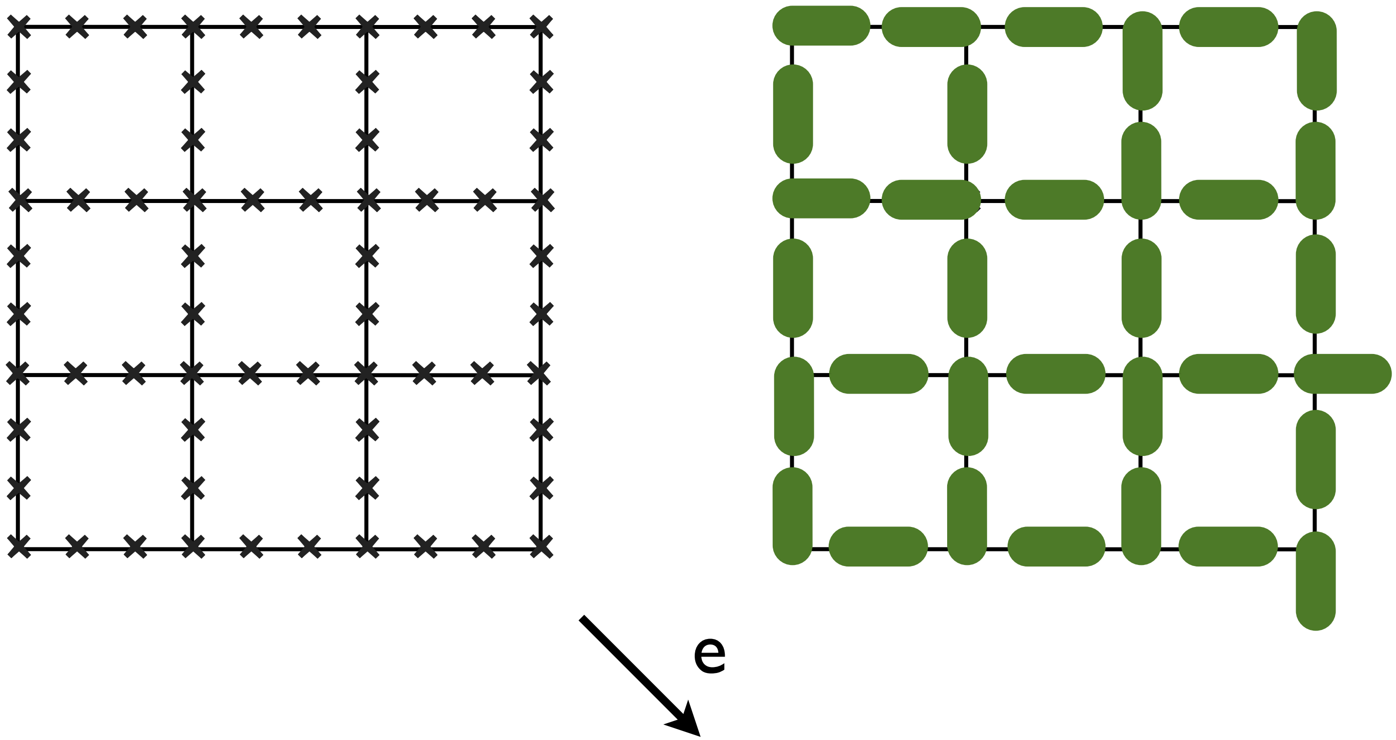
Realizing subspace for dimer model on square lattice





Doubly-decorated square lattice

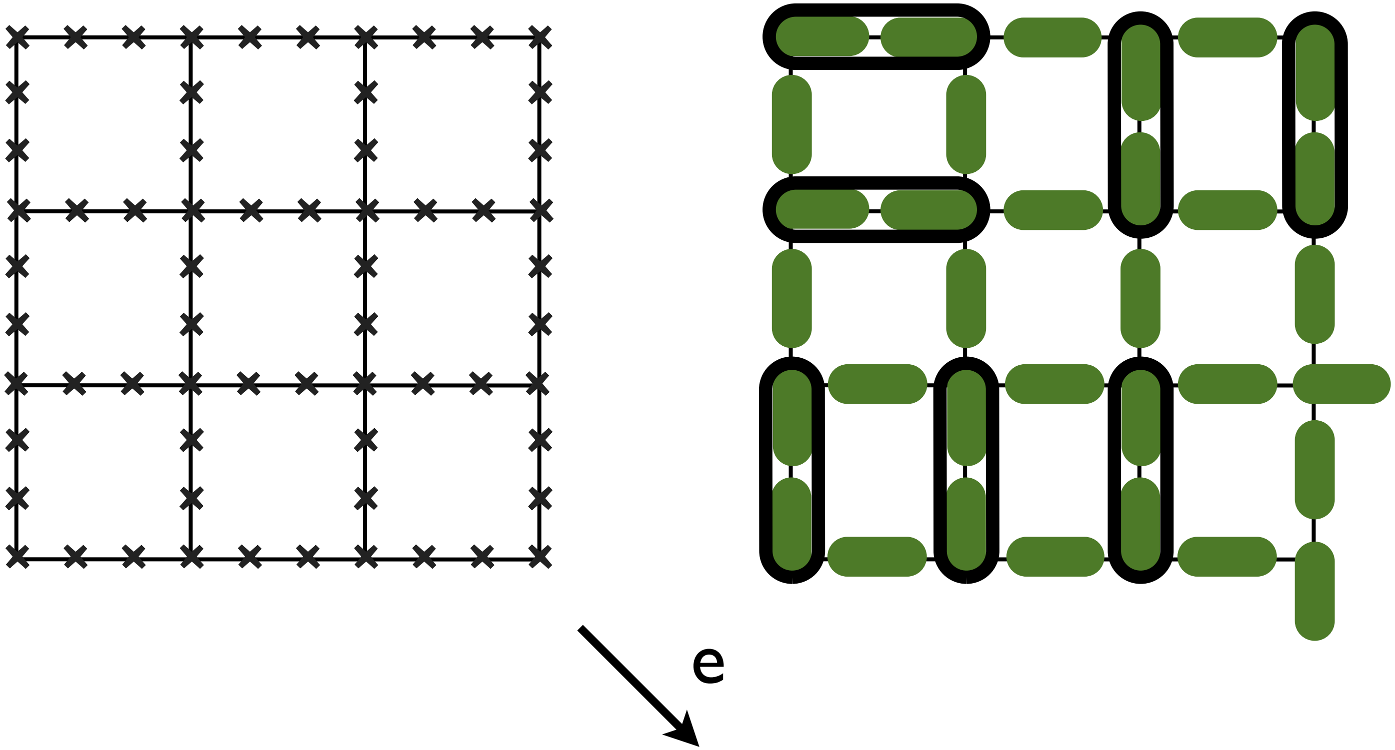
Realizing subspace for dimer model on square lattice



Dense dipole state

Doubly-decorated square lattice

Realizing subspace for dimer model on square lattice



Dense dipole state

Hilbert space and effective Hamiltonian of quantum dimer model

Conclusions

- rich possibility for correlated phases in the density sector of cold atoms
- accessible by tilting Mott insulators