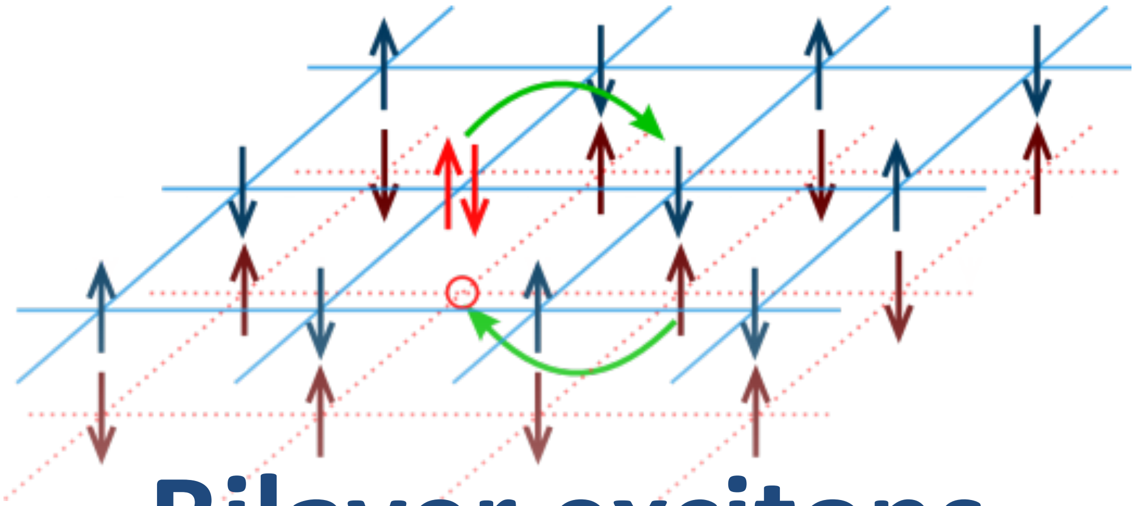

Bilayer excitons in strongly correlated materials

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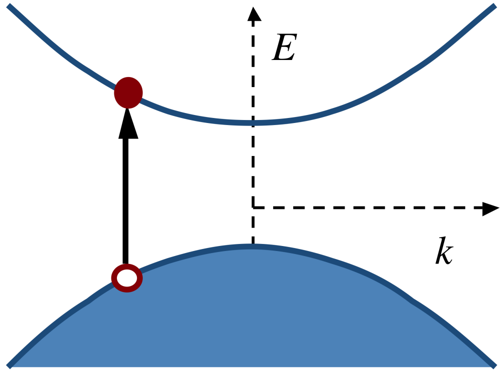
Introduction: Exciton condensation

Exciton:

Bound electron-hole pair



Bose **condensation**

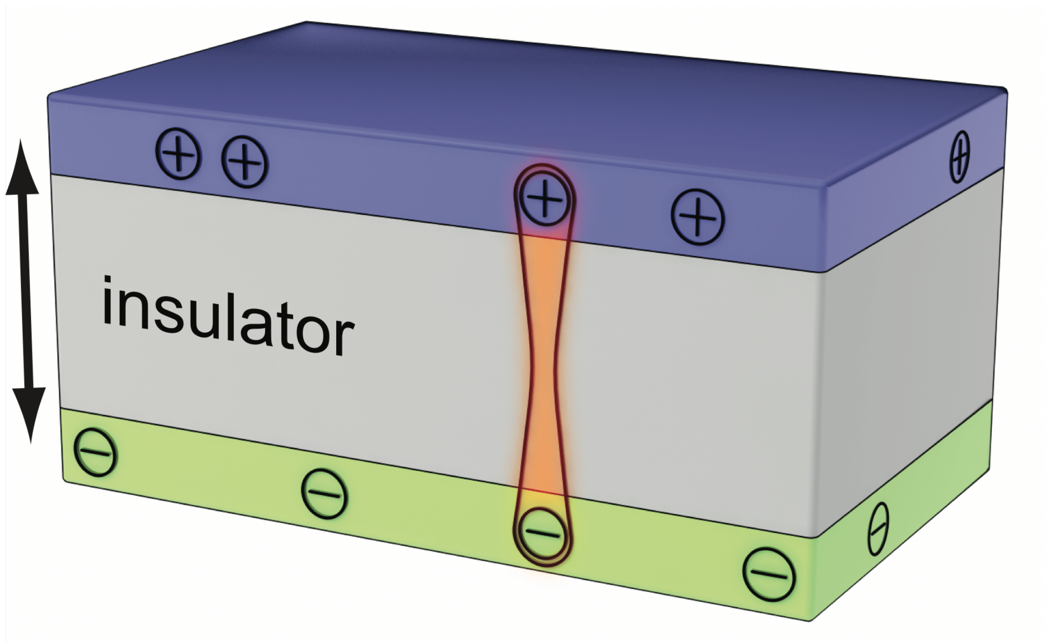
(BCS-style)

Good: Coulomb

Bad: Annihilation

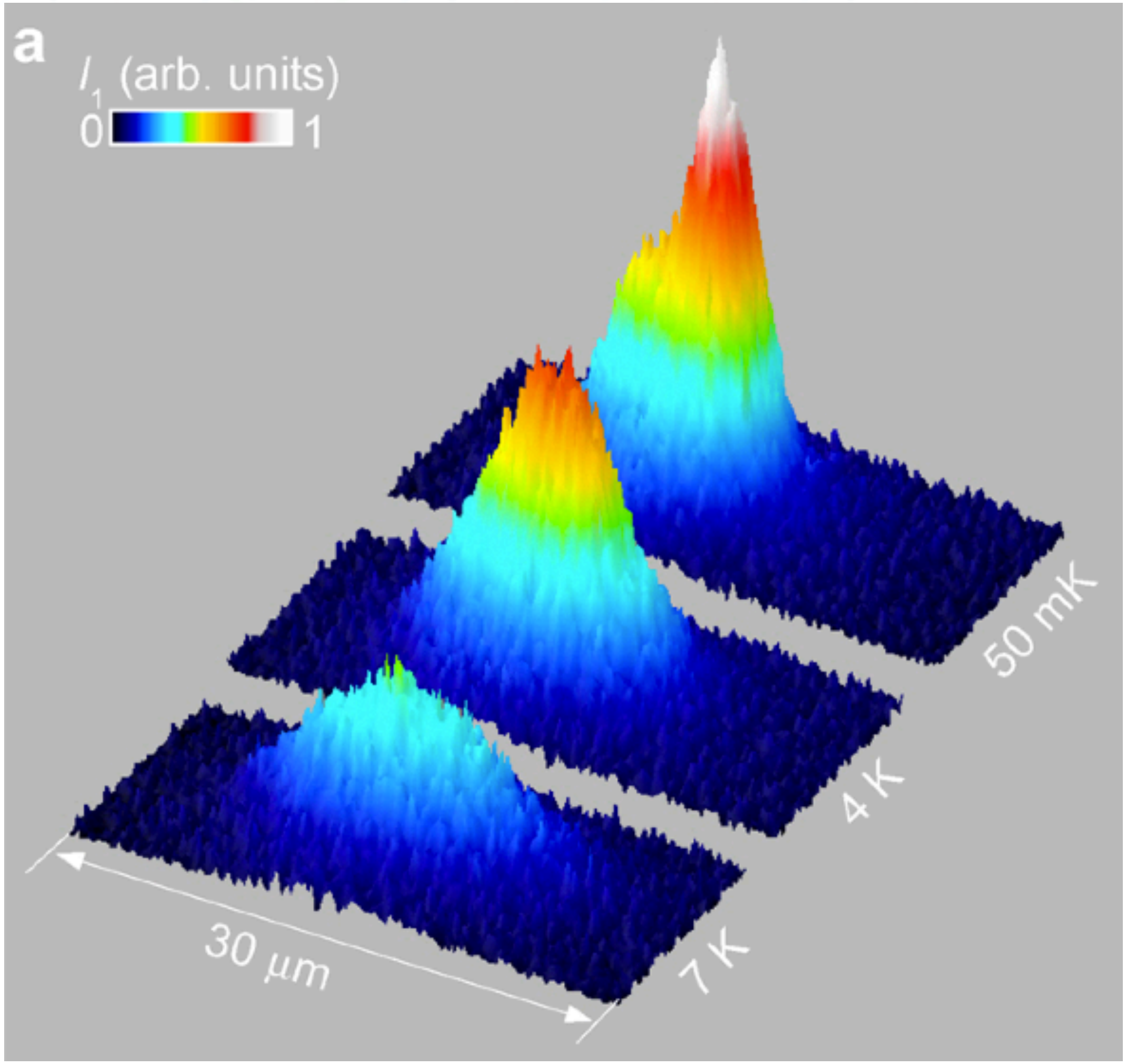
Solution:

Bilayer systems



Introduction: Exciton condensation

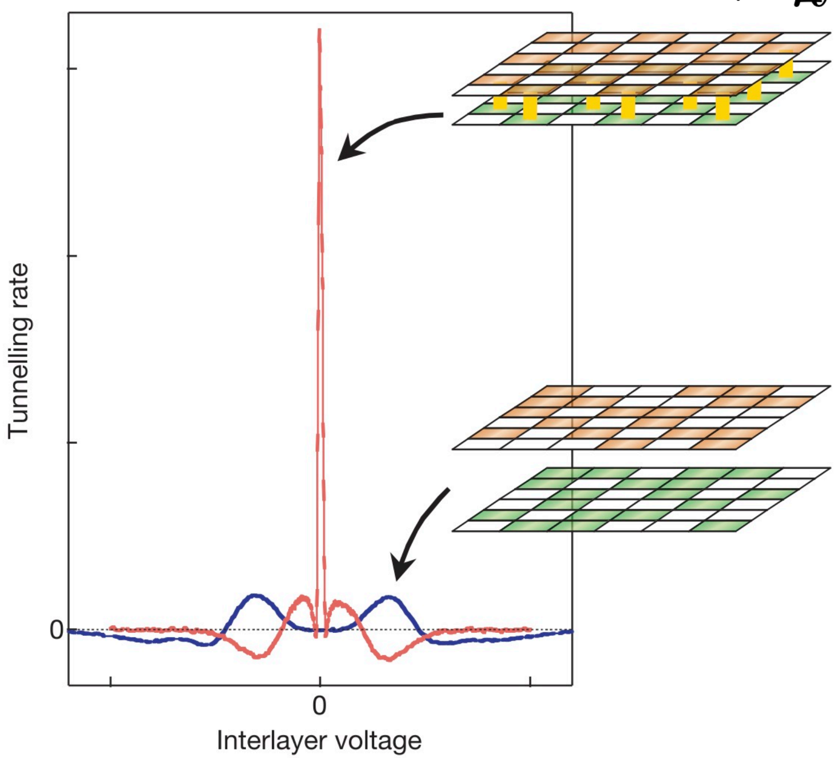
Pumped
bilayer
quantum
wells



Ref: High et al, Nano Lett 2012

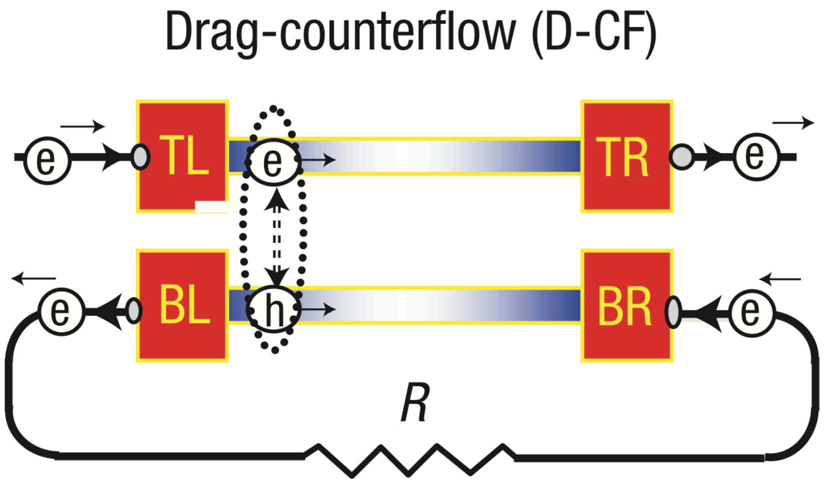
Introduction: Exciton condensation

Directly measure **order parameter** $\Delta = \langle c_{1k}^{\dagger} c_{2}^{\dagger} \rangle_k$



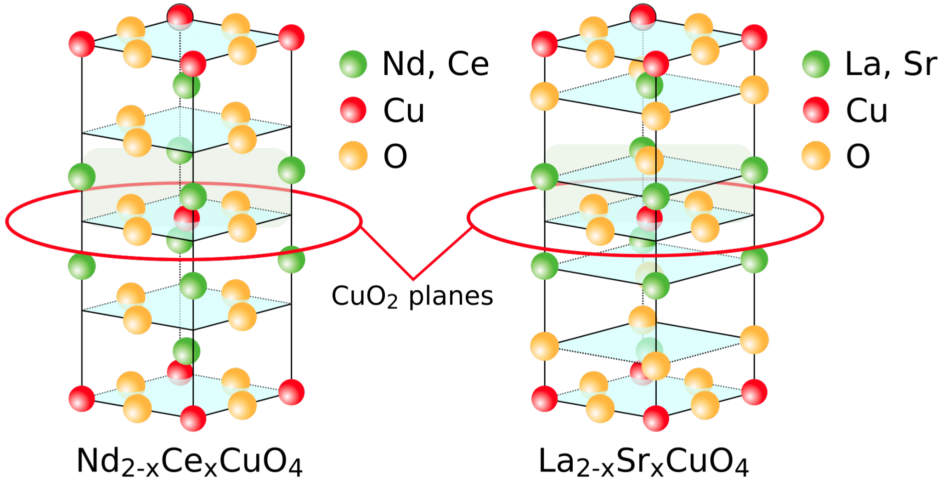
Ref: Eisenstein & MacDonald, Nature 2004

Counterflow **superfluidity**



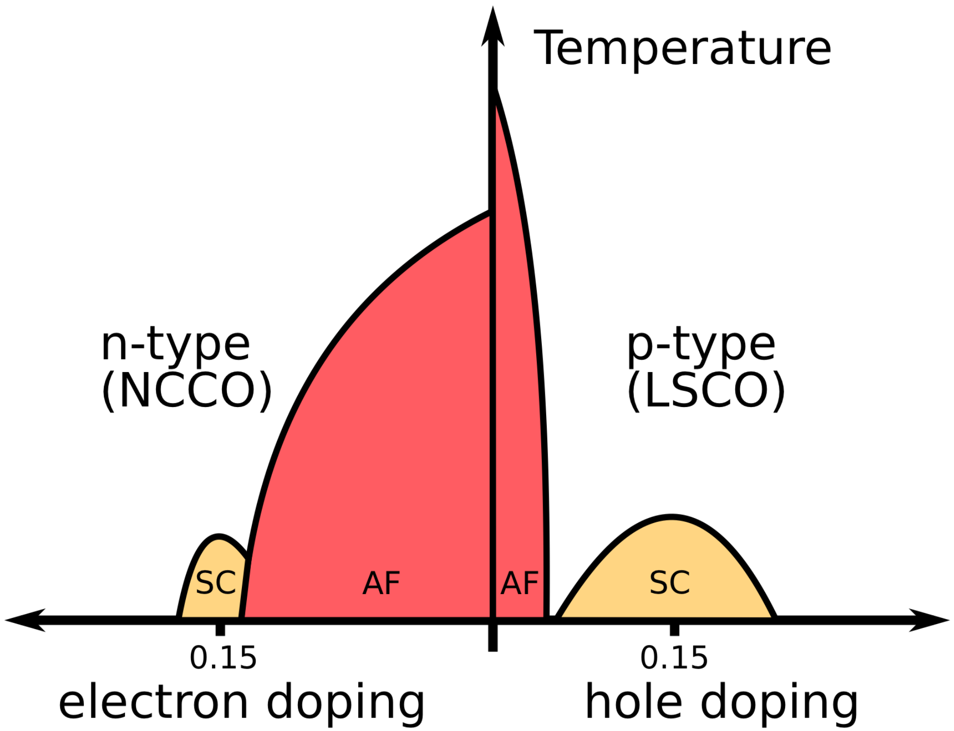
Ref: Su & MacDonald, Nat Phys 2008

Introduction: Strongly correlated materials



Example: **cuprates**

Quasi 2d CuO_2 planes



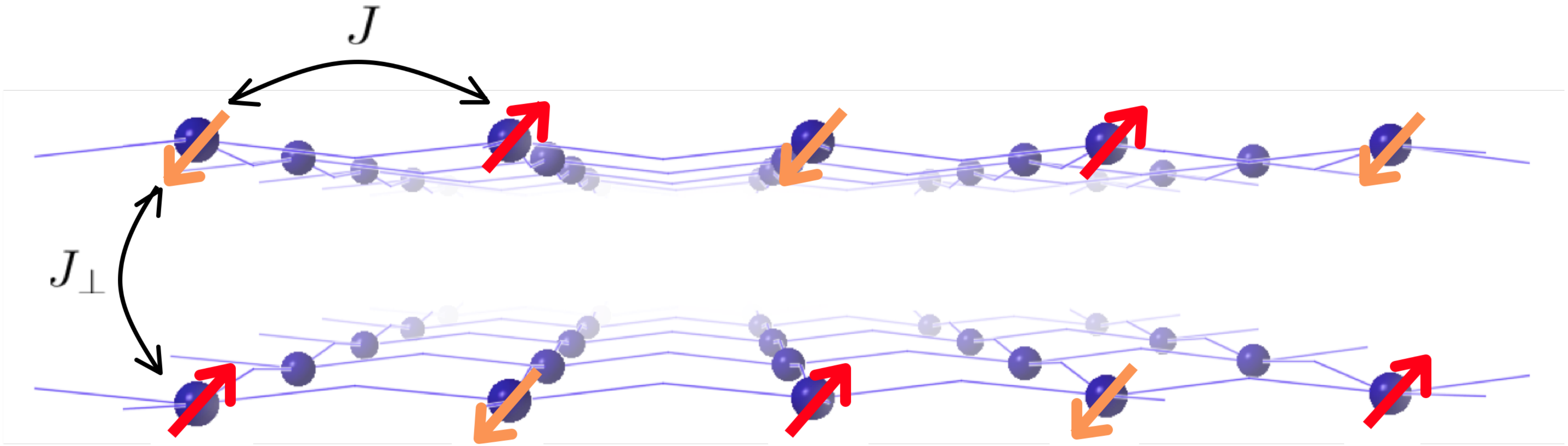
Mott insulator:

local moments

failure of band theory

Introduction: Strongly correlated materials

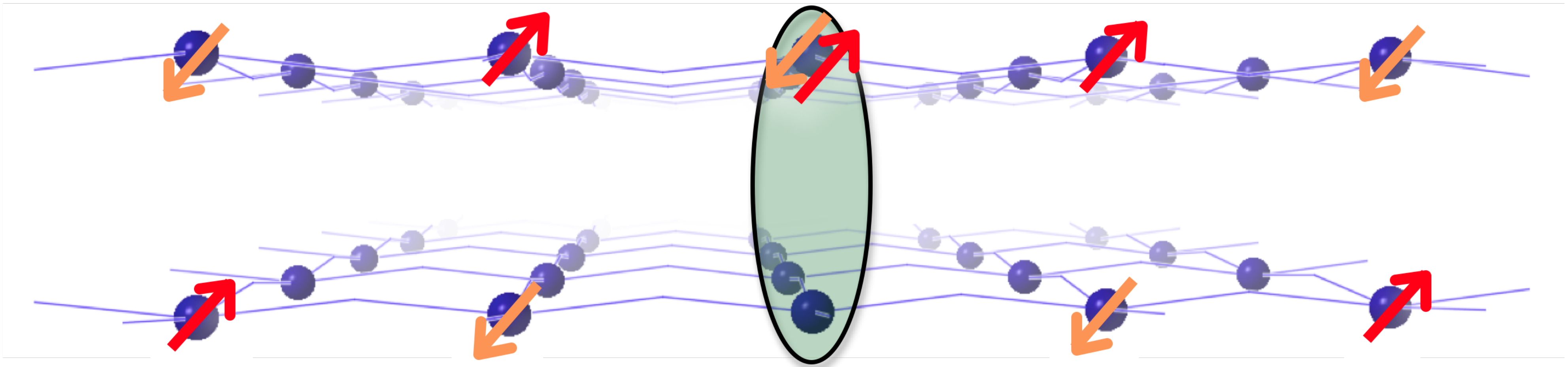
Antiferromagnetic order at half-filling



Heisenberg interactions $J\vec{S}_i \cdot \vec{S}_j$

Excitons in strongly correlated materials

Excitons are: ***doublon-holon pairs***



Exciton

Condensation? Other phenomena?

Work with Jan Zaanen  & Hans Hilgenkamp 

Lay-out of the rest of this talk

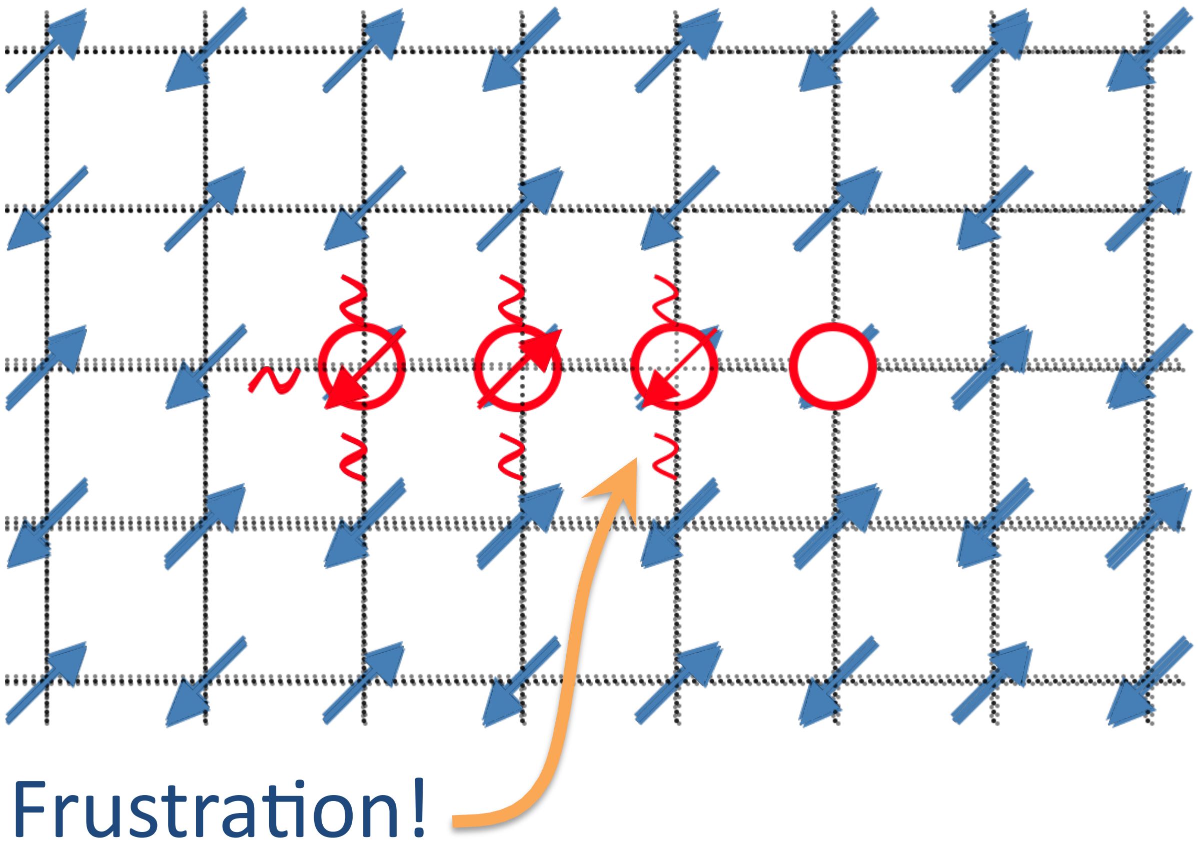
Two main questions:

1. What are the **dynamics** of a **single** exciton?

2. What is the **phase diagram** with a finite **density** of excitons?

Dopant in Mott insulator: Frustration

Moving hole in a Mott insulator:



Ising confinement

Linear potential: Ladder spectrum!

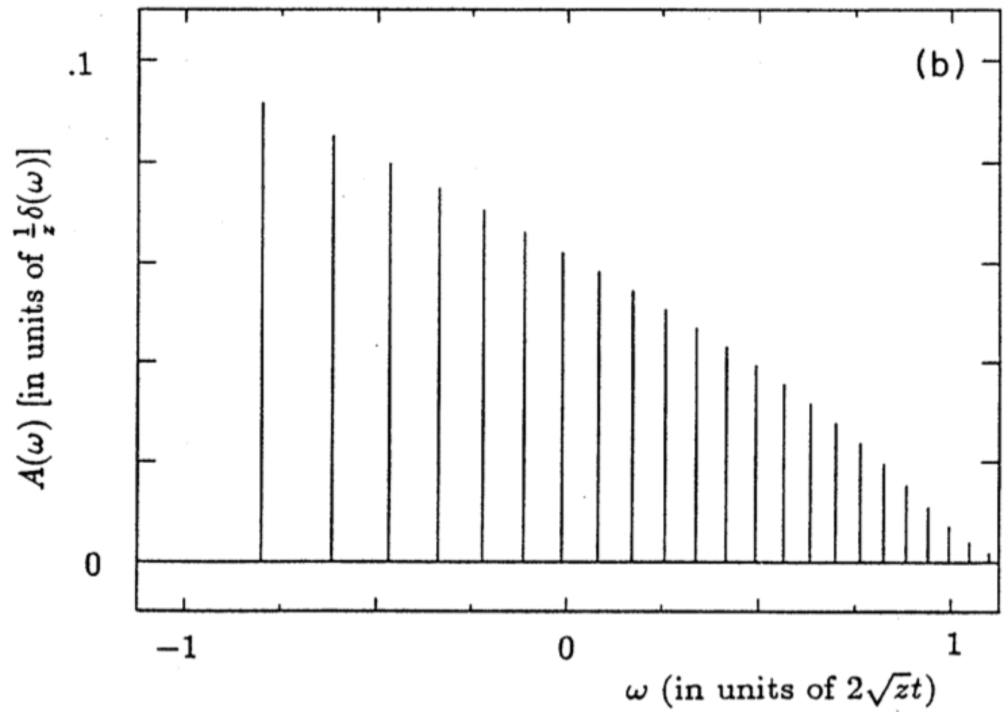


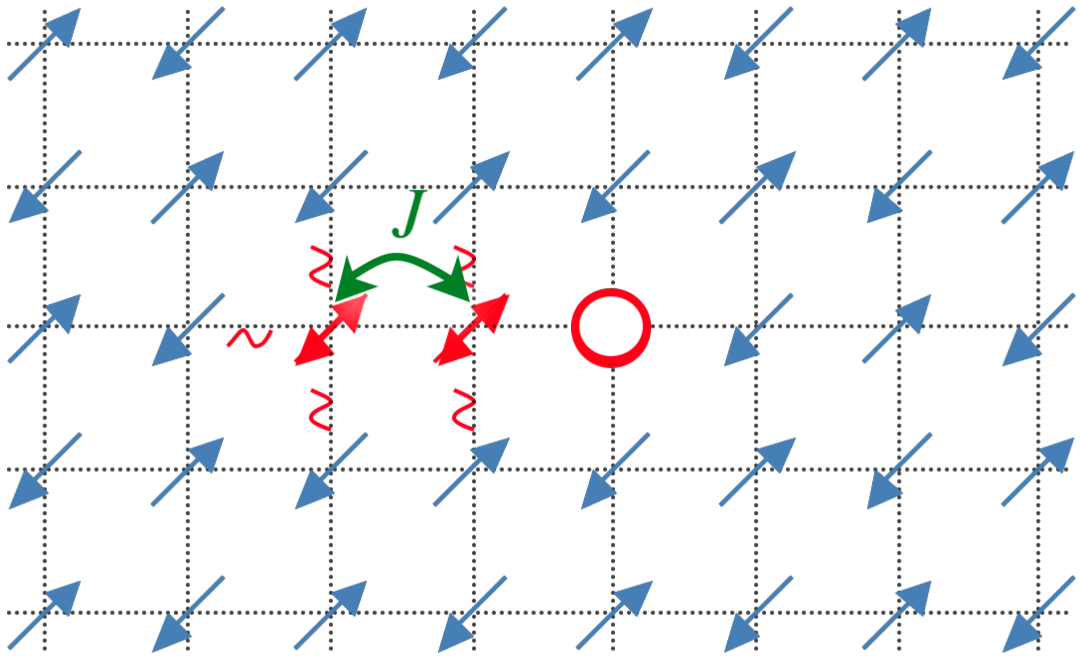
FIG. 3. Hole spectral function in the $J_\perp = 0$ limit. (a) The limit $J_z = 0$. (b) $J_z/t = 0.1$. The vertical lines represent delta functions with weight specified by their height.

Ref: Kane, Lee & Read, PRB 1989

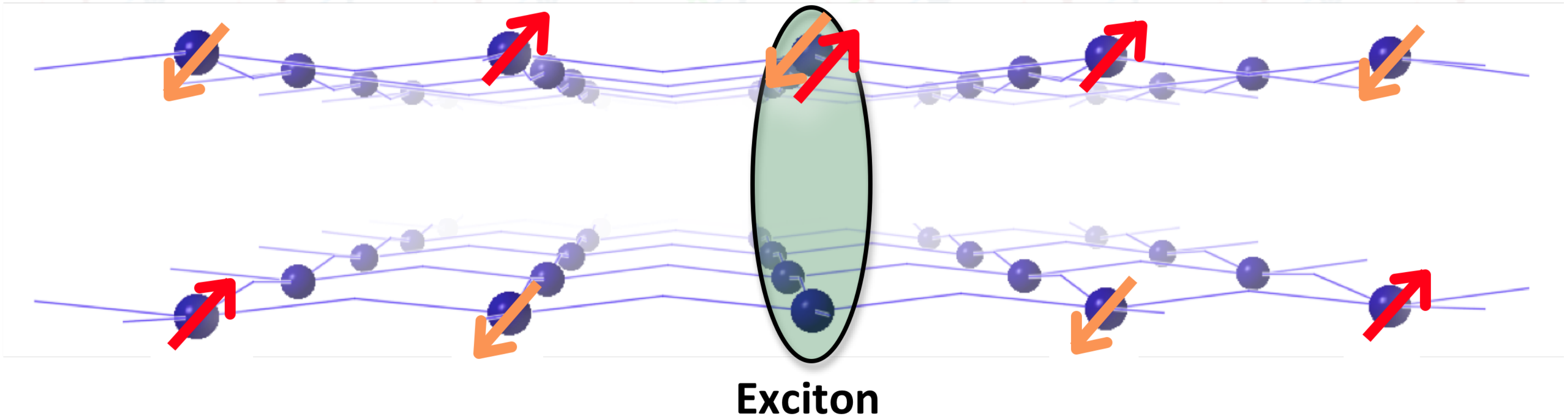
Quantum corrections: no confinement

Heisenberg antiferromagnet

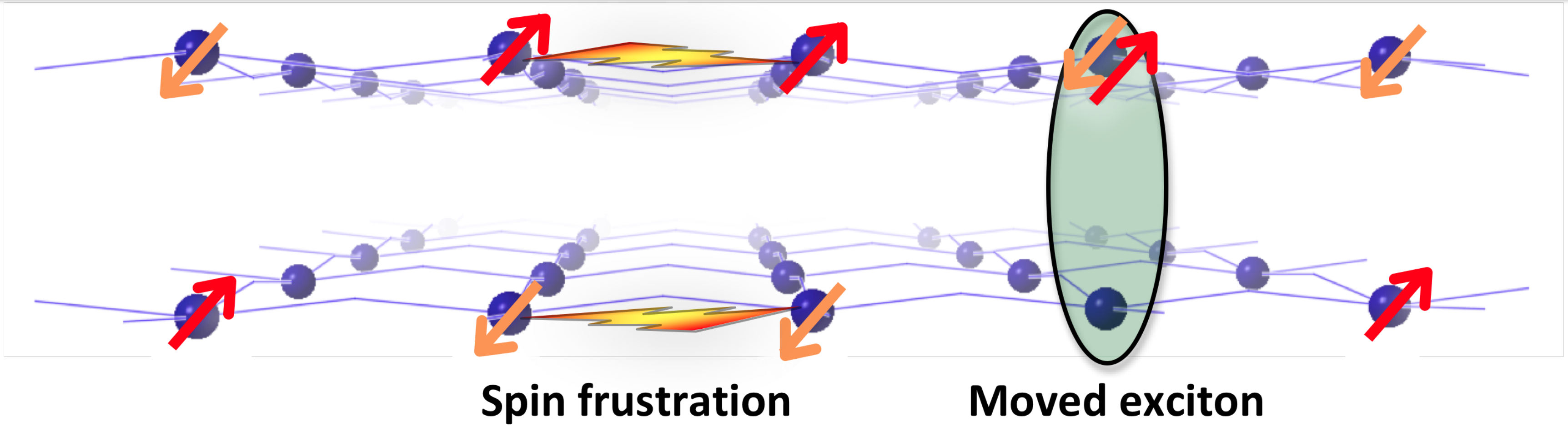
Frustration is repaired by $JS_i^+S_j^-$



Back to the bilayer: *exciton t-J model*

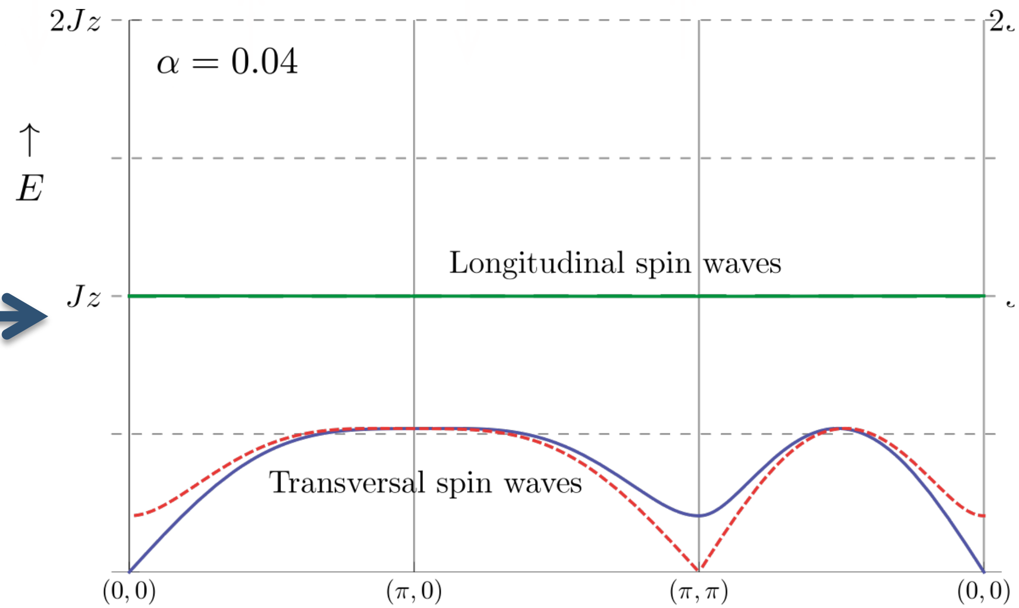


$$H = J \sum_{<ij>\, l} \mathbf{S}_{il} \cdot \mathbf{S}_{jl} + J_{\perp} \sum_{i} \mathbf{S}_{i1} \cdot \mathbf{S}_{i2} - t \sum_{<ij>} |E_j\rangle \left(|0\,0\rangle_i \langle 0\,0|_j + \sum_{m} |1\,m\rangle_i \langle 1\,m|_j \right) \langle E_i|$$



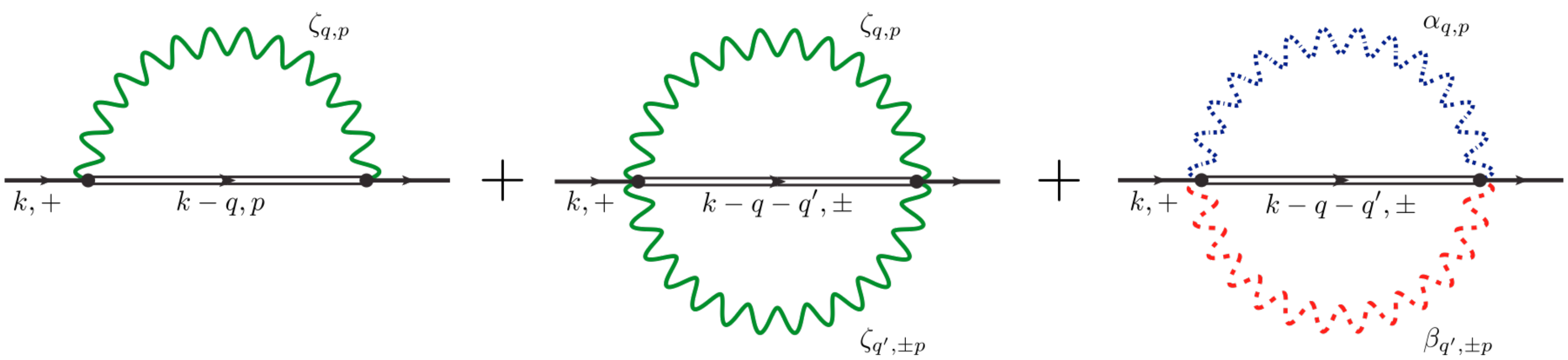
Spin wave theory

Moving exciton
excites and absorbs
spin waves



Exciton **self-energy**:

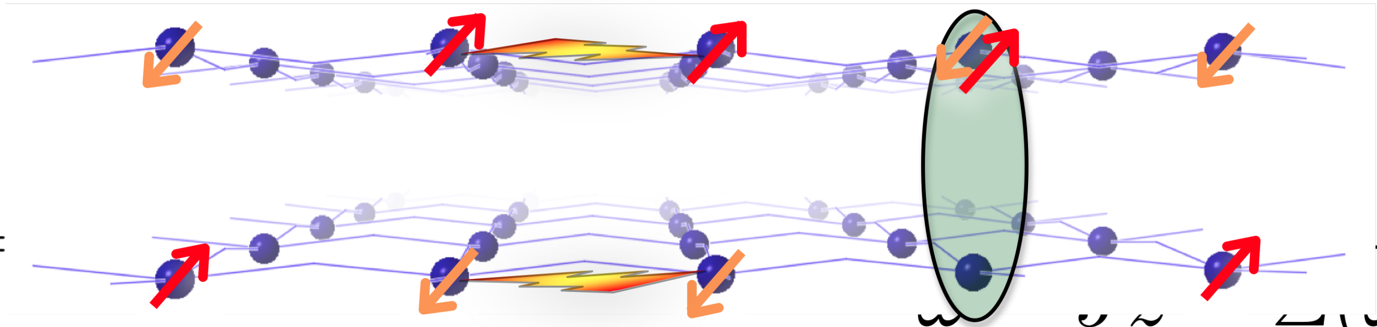
$\Sigma^+(k,\omega) =$



Dynamical frustration once again

Have to excite the **gapped spin wave** to move

$$\Sigma^+(k,\omega) =$$

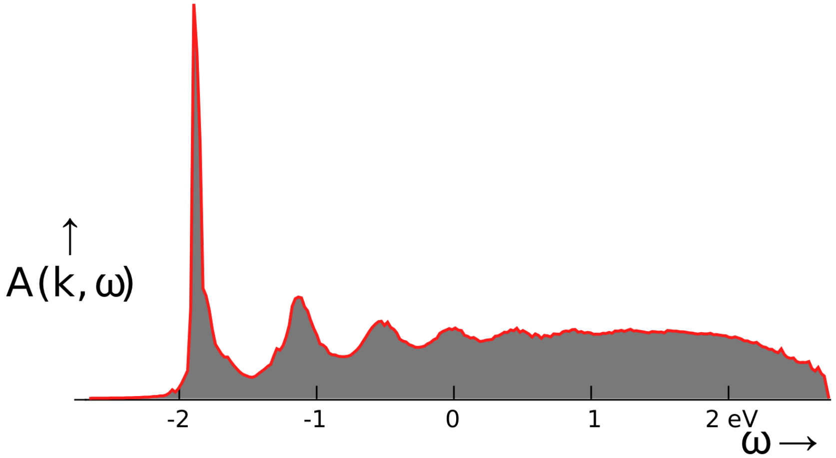


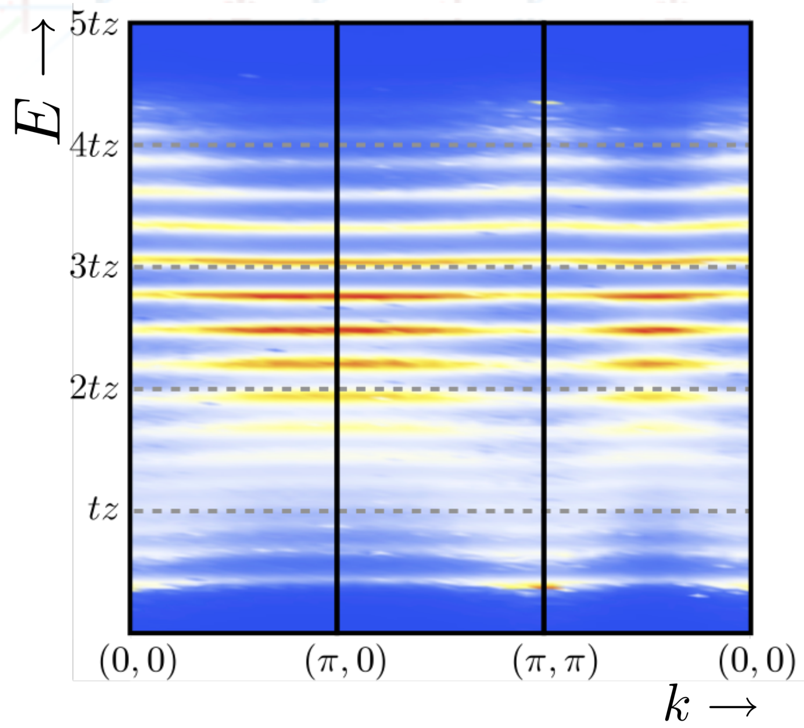
Same self-energy as **Ising confinement**!

Observable (at k=0) in **optical absorption**

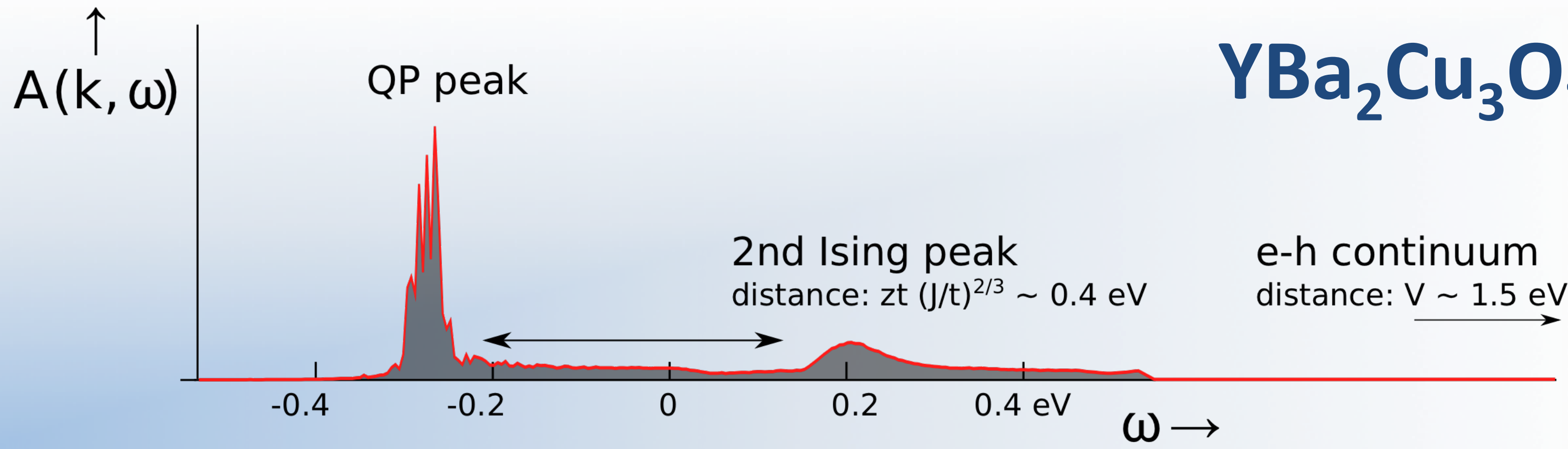
Results: Exciton spectral function

Ladder spectrum:



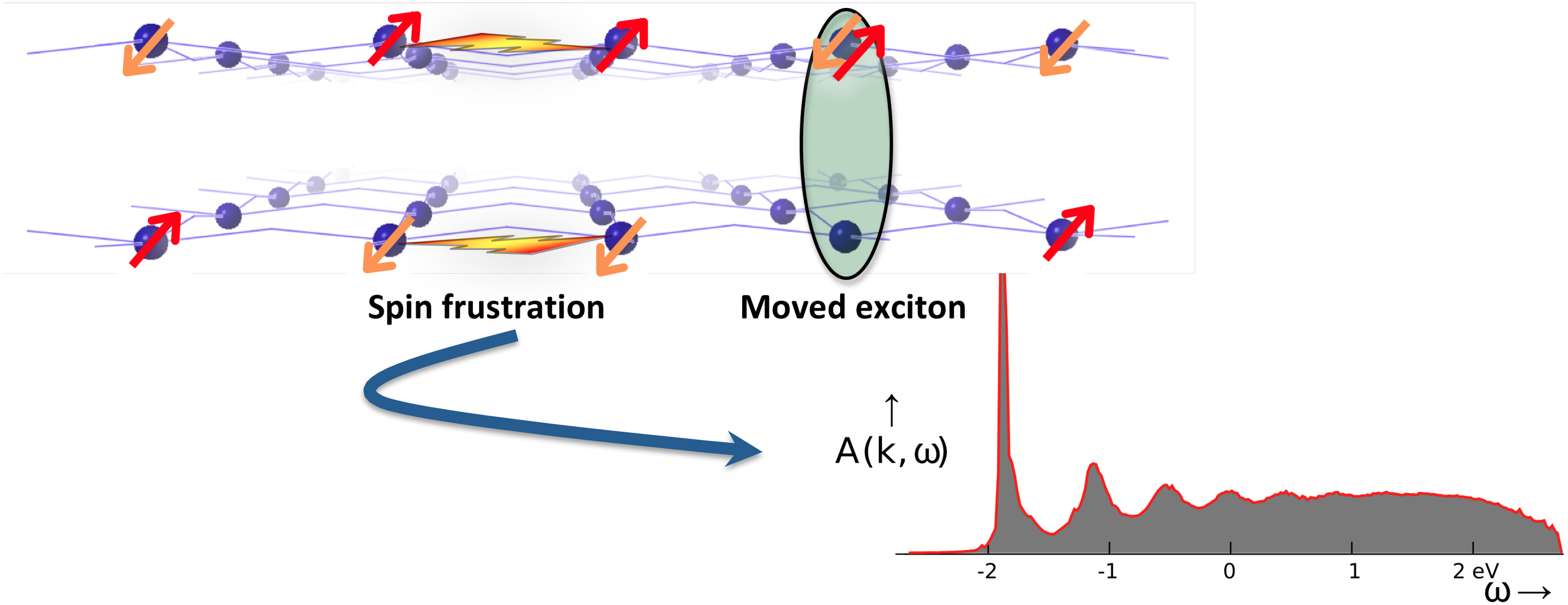


$YBa_2Cu_3O_7$



Summarizing single exciton results

Enhanced dynamical frustration



Ref: Rademaker, Wu, Zaanen & Hilgenkamp, EPL 2012;
Rademaker, Wu, Zaanen, NJP 2012

Hardcore bosons on a lattice

First: forget about the spin background

Do hardcore bosons on a lattice $E^{+} = |1\rangle\langle 0|$

$$H = -t \sum_{\langle ij \rangle} \left(E_i^x E_j^x + E_i^y E_j^y \right) - \mu \sum_i E_i^z + V \sum_{\langle ij \rangle} E_i^z E_j^z$$

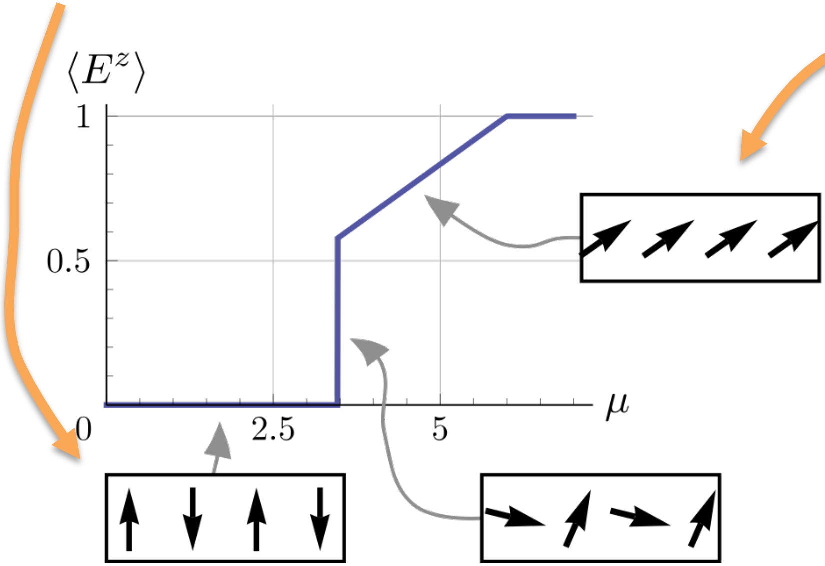
Ground state: variational wavefunction

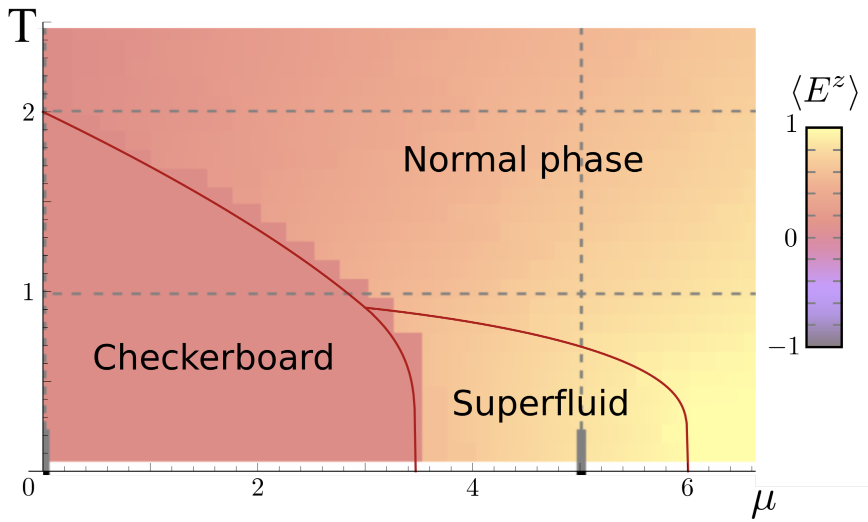
$$|\Psi\rangle = \prod_i \left(\cos\theta_i e^{i\psi_i} |1\rangle_i + \sin\theta_i |0\rangle_i \right)$$

Hardcore bosons on a lattice

Two phases:

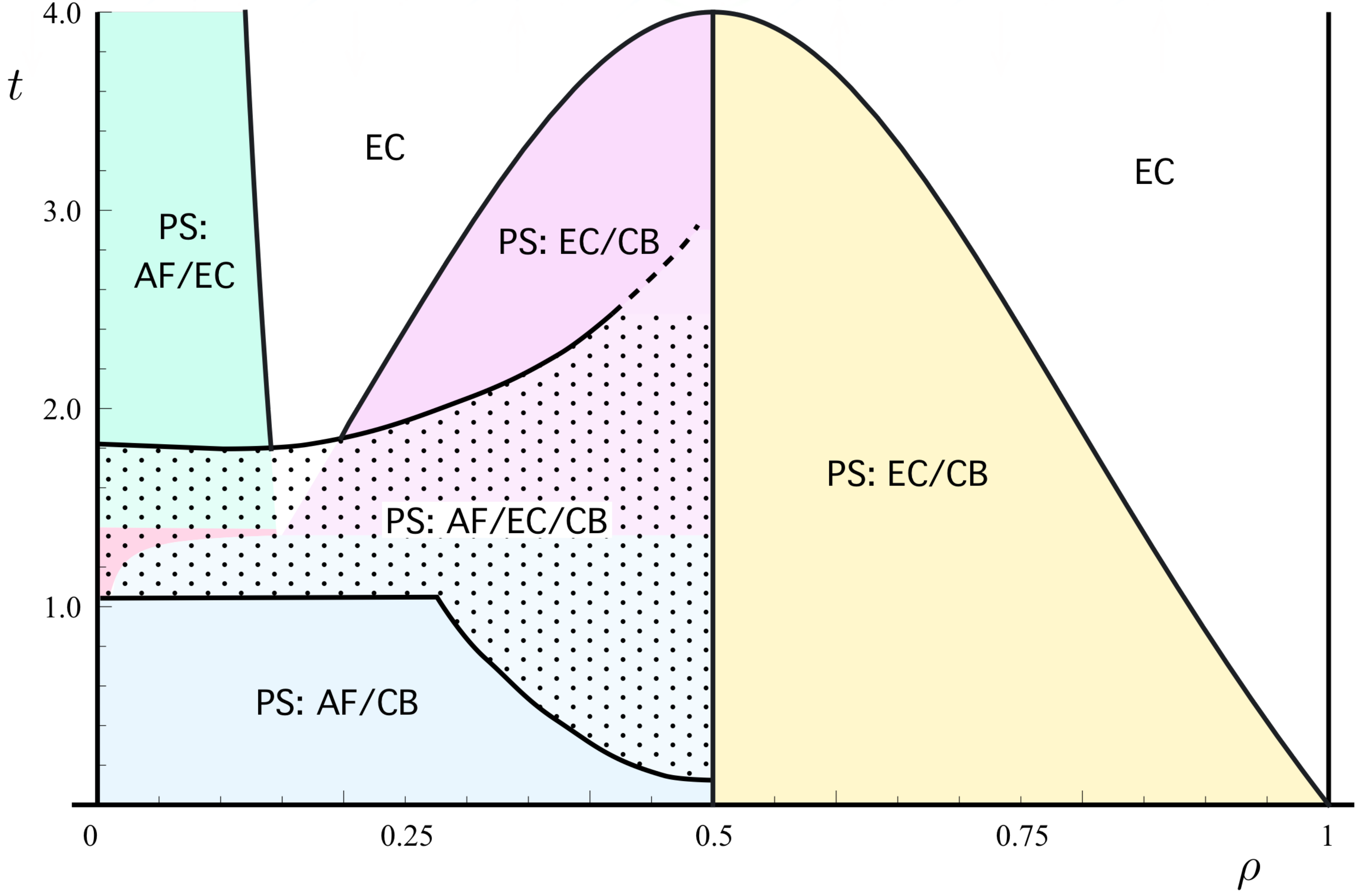
Checkerboard / solid and **Superfluid**



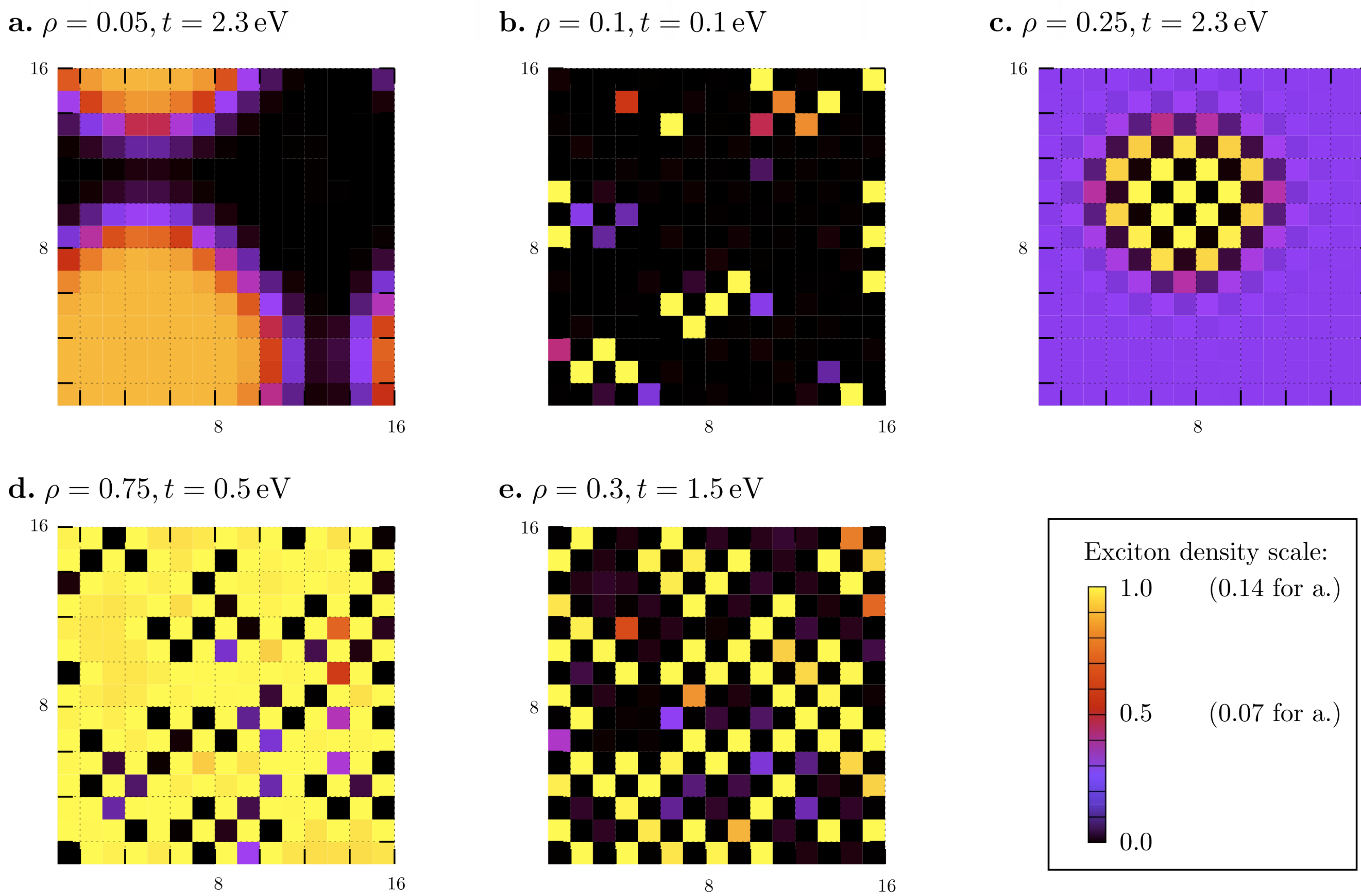


Separated by 1st order transition ('spin-flop')

Ground state phase diagram



Phase separation: Monte Carlo results



The exciton superfluid

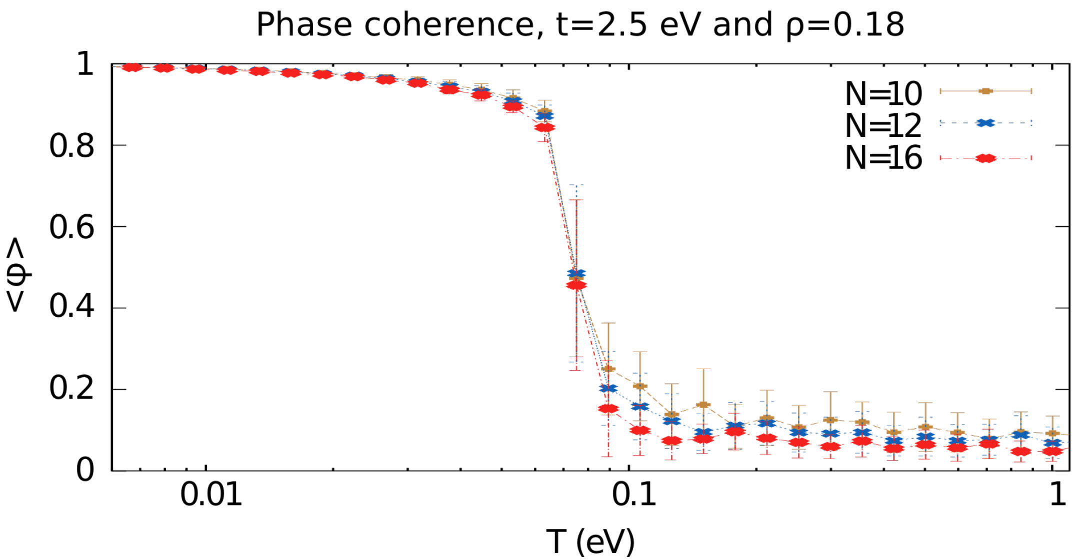
Ground state wavefunction

$$|\Psi\rangle = \prod_i \left(\sqrt{\rho}|E_i\rangle + \sqrt{1-\rho}|0\ 0\rangle_i\right)$$

Anomalous interlayer tunneling

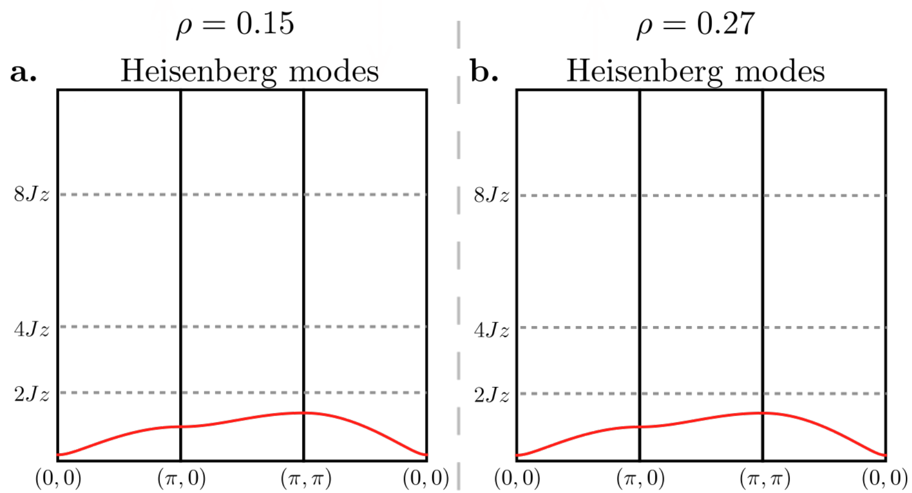
$$\langle \sum_\sigma c^\dagger_{i1\sigma} c_{i2\sigma} \rangle = \sqrt{2\rho(1-\rho)}$$

Kosterlitz-Thouless transition:



Exciton-spin dynamics in the superfluid

- Superfluid = **quantum paramagnet**
- So: propagating triplet excitations
- Strong exciton-spin coupling shown in **renormalization of triplet bandwidth**



Why does triplet kinetic energy increases?

Heisenberg 'hopping' of triplets

$$J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j \rightarrow -J \sum_{\langle ij \rangle} t_i^\dagger t_j$$

Exciton hopping

$$\langle e^\dagger \rangle \rightarrow \sqrt{\rho_{\mathrm{SF}}}$$

$$-t \sum_{\langle ij \rangle} e_j^\dagger e_i t_i^\dagger t_j$$

Energy scales: $J \sim \dfrac{t_e^2}{U}$ $\quad t \sim \dfrac{t_e^2}{V}$ $\quad U > V \rightarrow t > J$

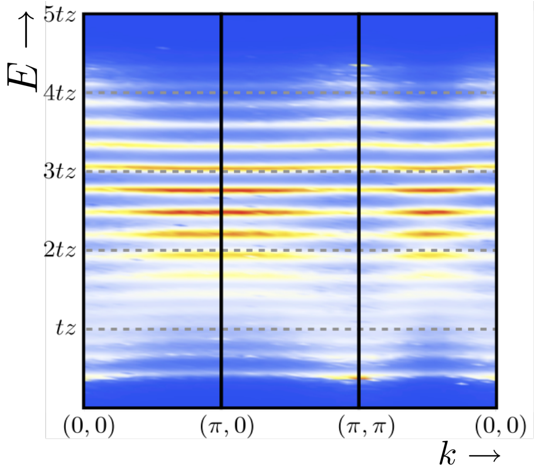
Thus enhancement…

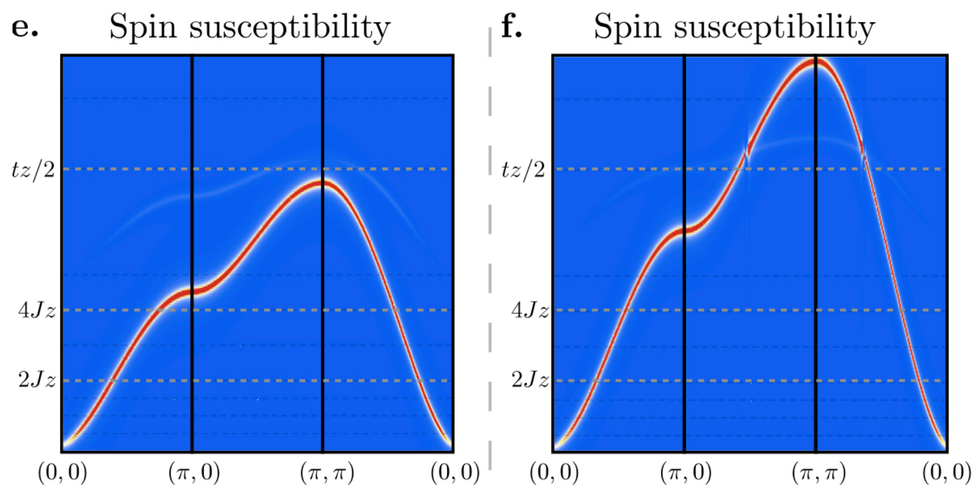
Summary

Magnetic order **prevents** motion of exciton

Exciton condensation **helps** motion of triplets

Ref: Rademaker, Wu, Zaanen & Hilgenkamp, EPL 2012; Rademaker, Wu, Zaanen, NJP 2012





But: **phase separation** is all around!

thank you for your attention!