The fate of the spin polaron in the 1D t-J model

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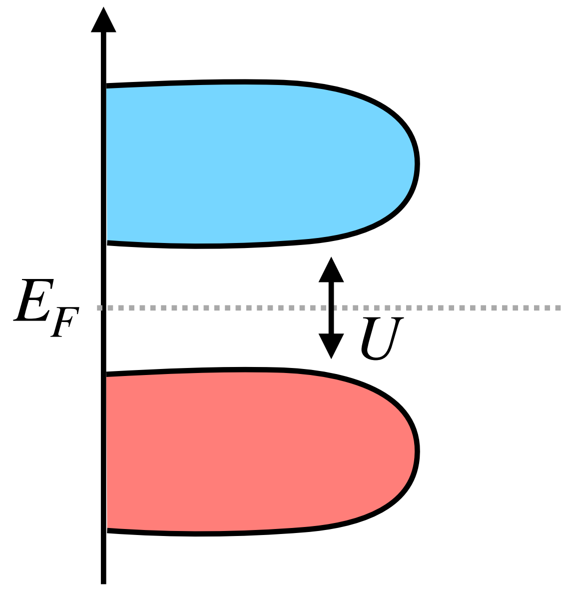
Outline

- Introduction
- 2D case: spin polaron
- 1D case: spin-charge separation
- Methods (1D case in polaronic description)
- Results
- Summary

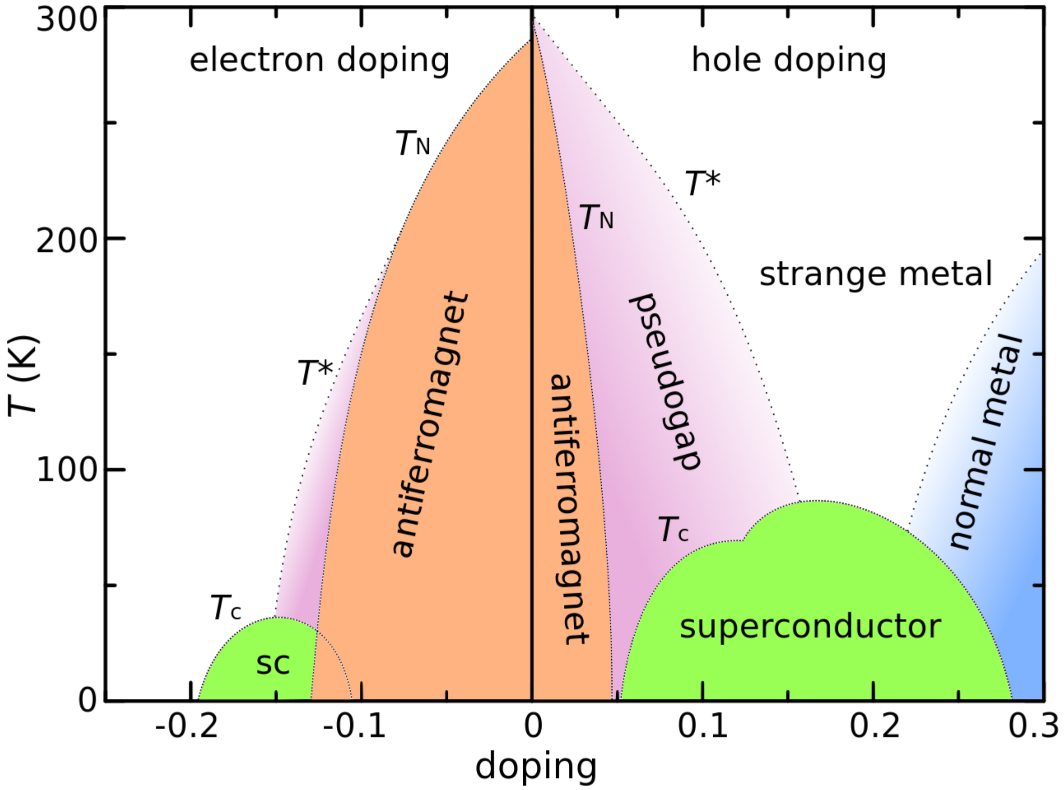
Introduction



Mott insulator

ENIGMA: how do we understand the doped Mott insulator?

example: Cuprates



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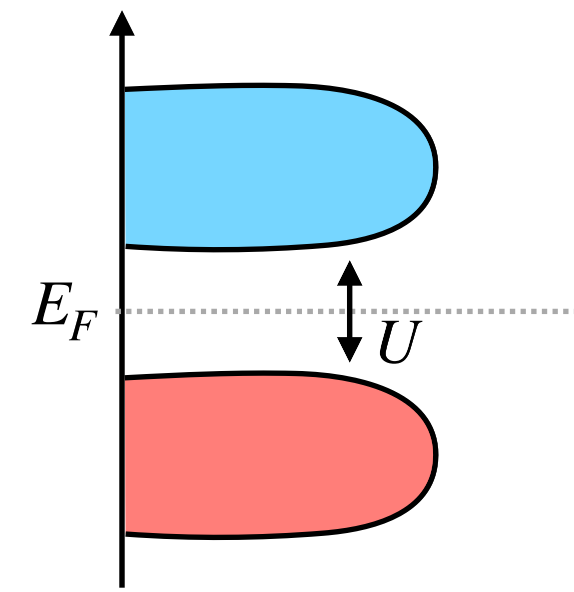
Introduction



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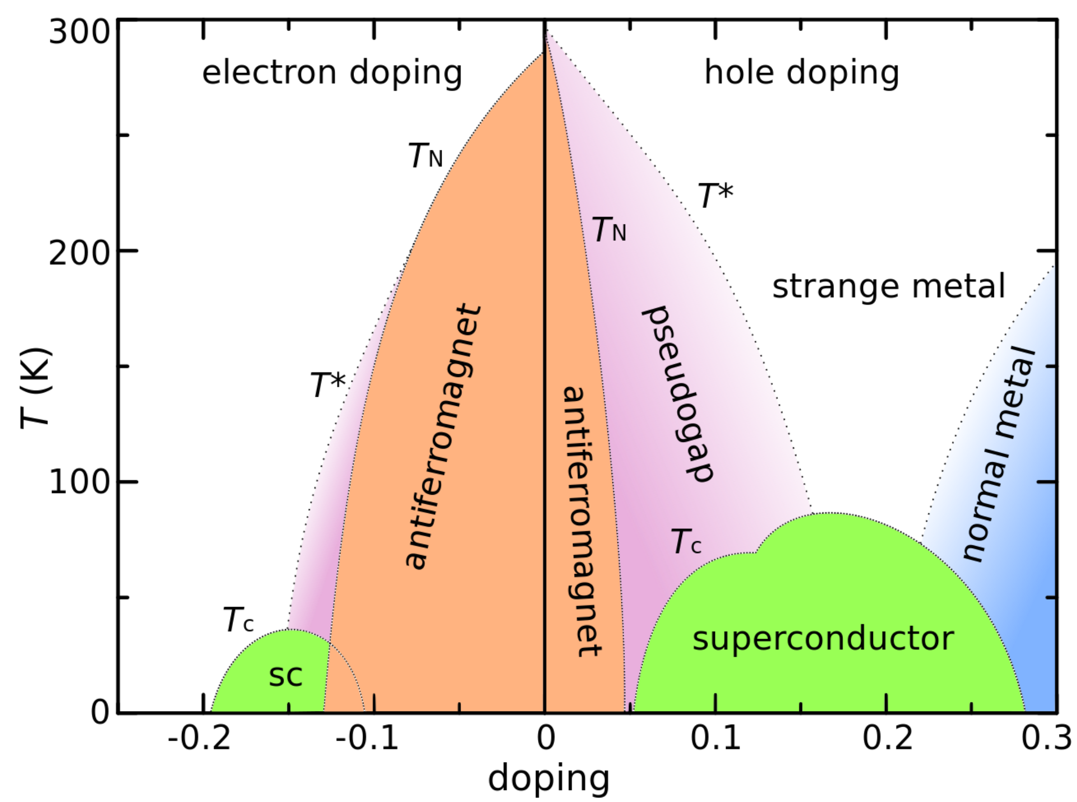

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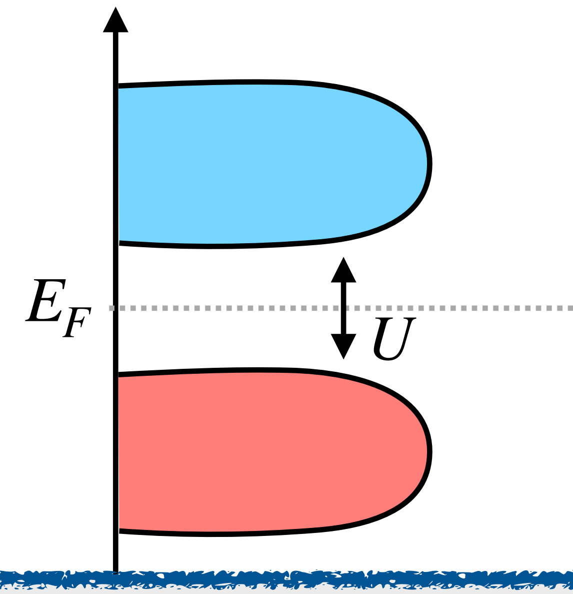
Only one case is well established: the single hole in a Mott insulator

Introduction

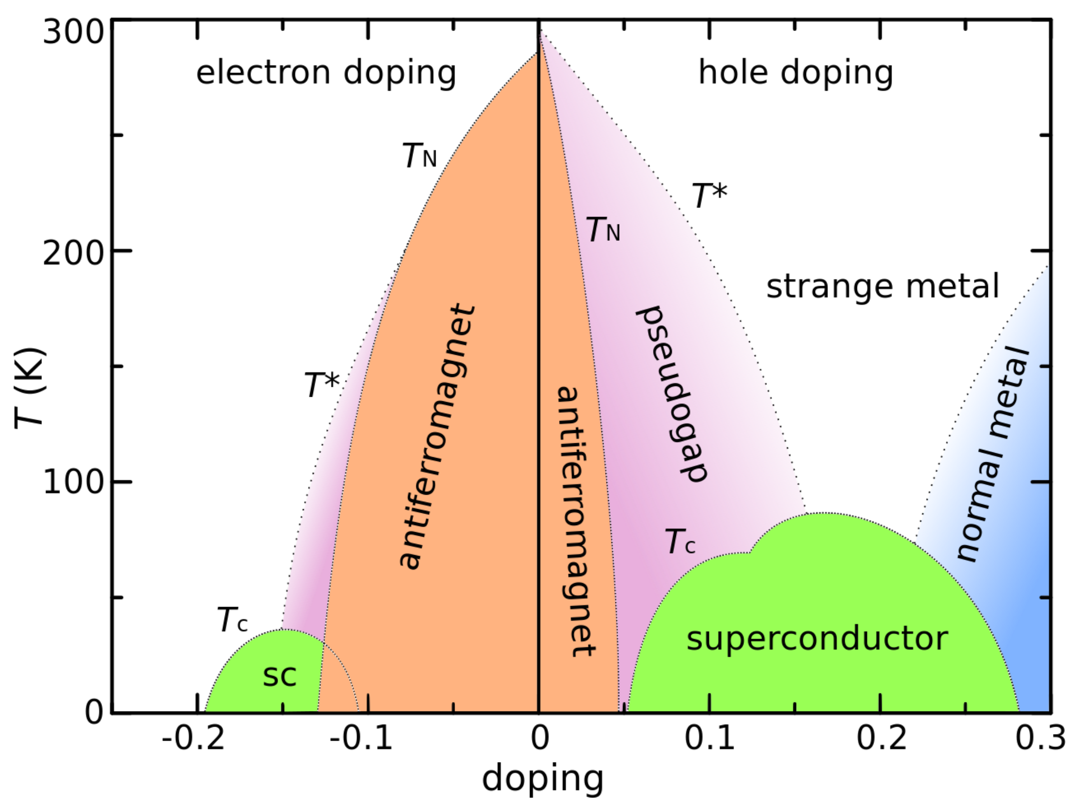


Mott insulator

We show that it still may not be completely understood

ENIGMA: h… Mott insulator?

example: Cuprates



Only one case is well established: the single hole in a Mott insulator

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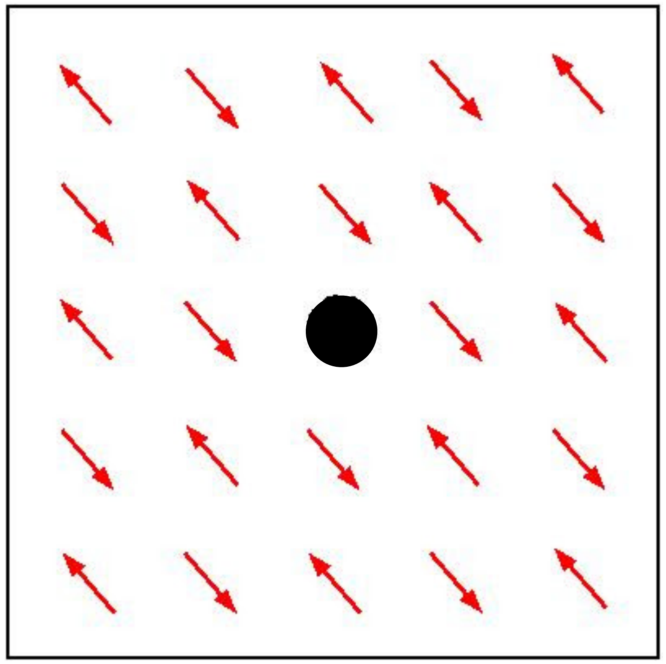
What do we know so far?

2D: spin polaron

Adding a single hole in a 2D antiferromagnet



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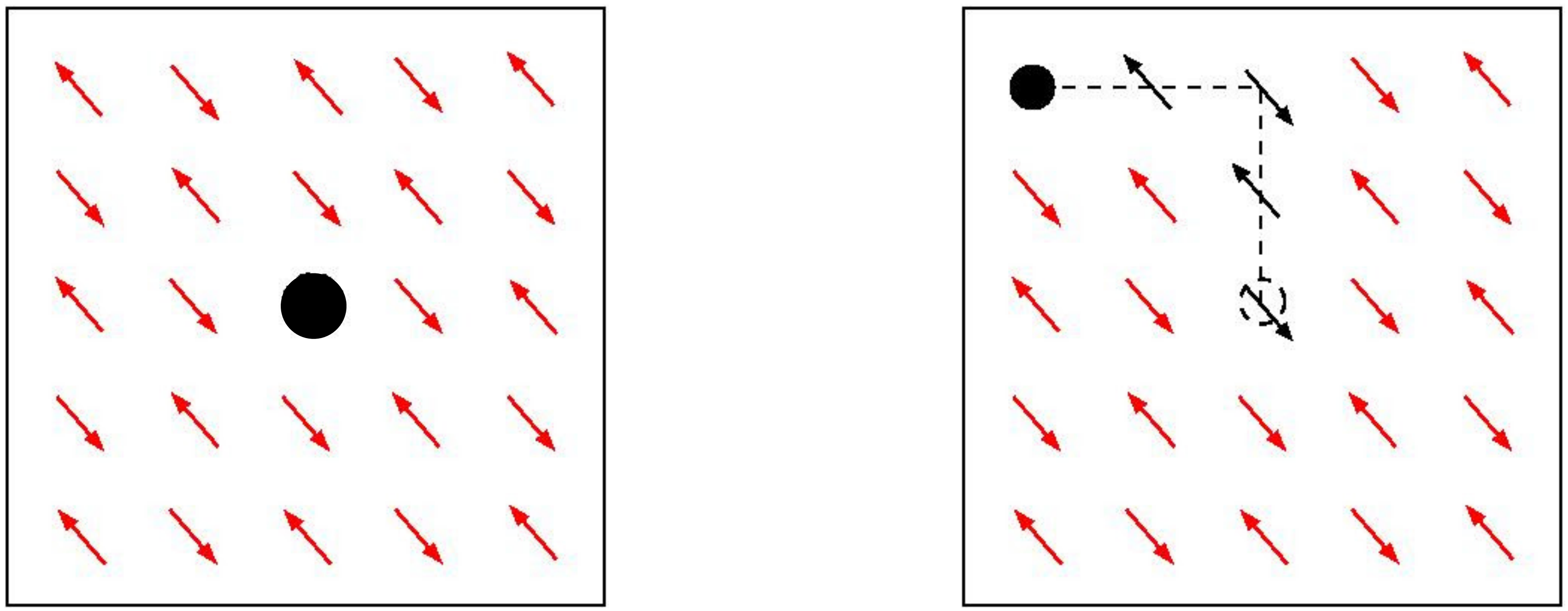

Ingredients

mobile hole:

→ overturns spins = creates magnons

→ after *each* hop *a* magnon with energy E → hole in a discrete linear (string) potential

nearest neighbor spin flips present in Hubbard or t-J:

→ may overturn "back" the spins in AF = annihilates magnons

2D: spin polaron

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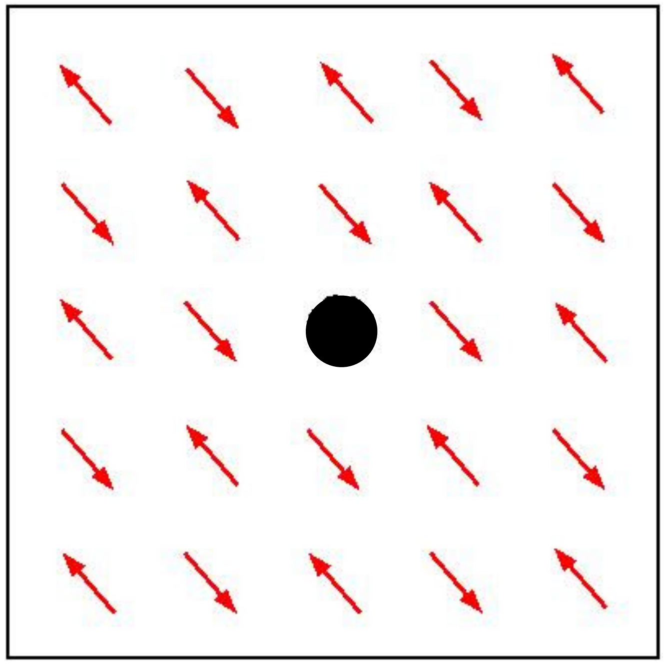

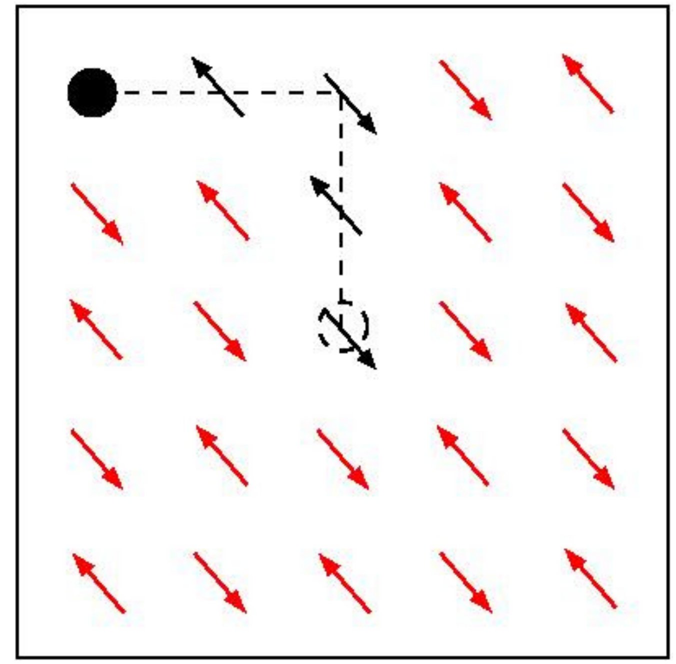

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Result

→ hole may form a *weakly* mobile quasiparticle in 2D AF = spin polaron

2D: spin polaron

Adding a single hole in a 2D antiferromagnet

Very well established concept:

- L. N. Bulaevskii, E. L. Nagaev, and D. I. Khomskii, JETP **27**, 836 (1968)
- C. L. Kane, P. A. Lee, and N. Read, Phys. Rev. B **39**, 6880 (1989)
- G. Martinez & P. Horsch, PRB **44**, 317 (1991)

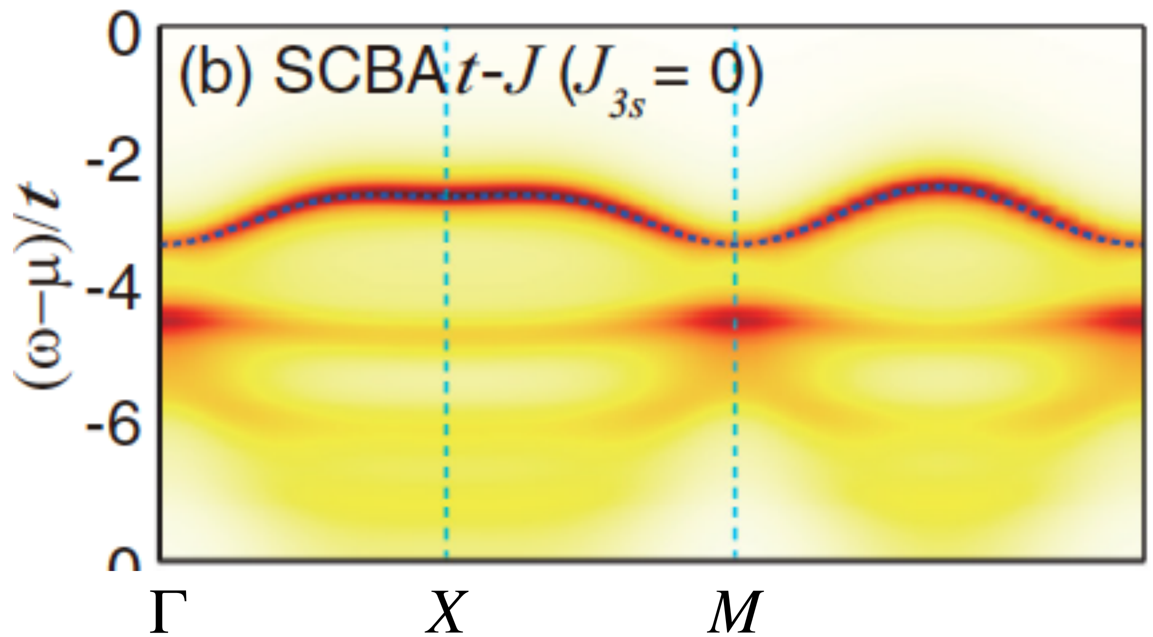
& several other papers from the 90's

2D: spin polaron

Adding a single hole in a 2D antiferromagnet

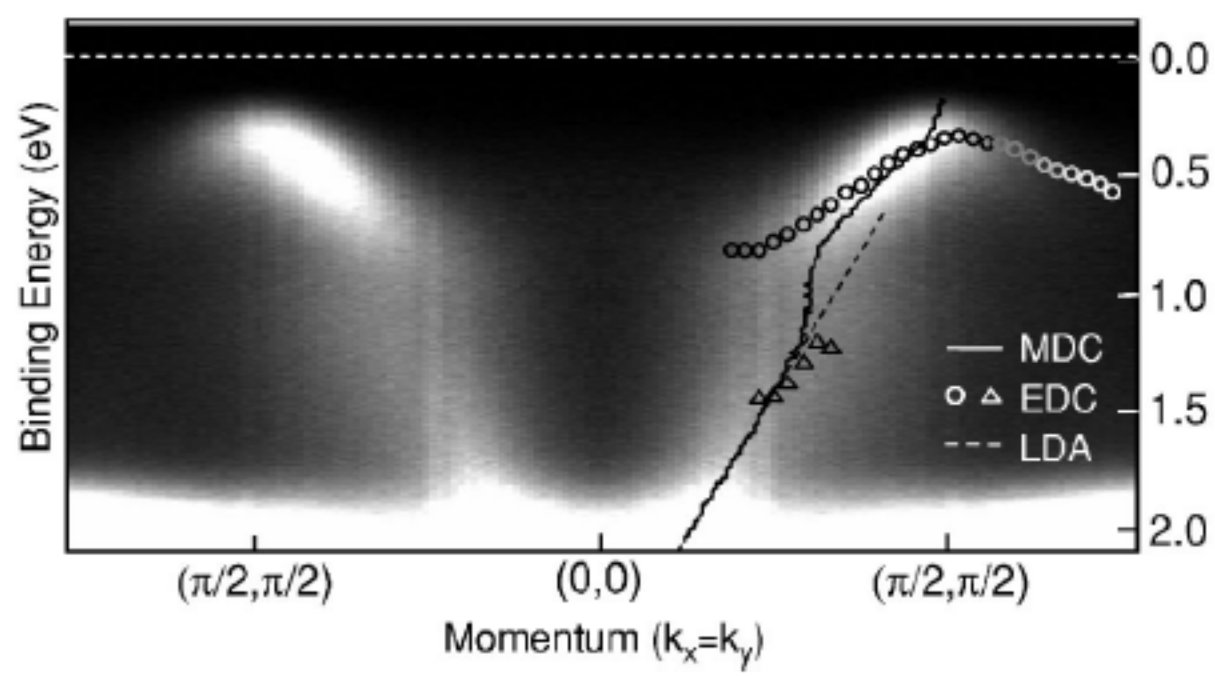
This concept works very well for understanding ARPES results

Theory: A(**k**, ω) / 2D *t*-*J* model



*[n=1; J=0.4t ; PRB **92**, 075119 (2015)]*

Experiment: ARPES / $Ca_2CuO_2Cl_2$



*[PRB **71**, 094518 (2005)]*

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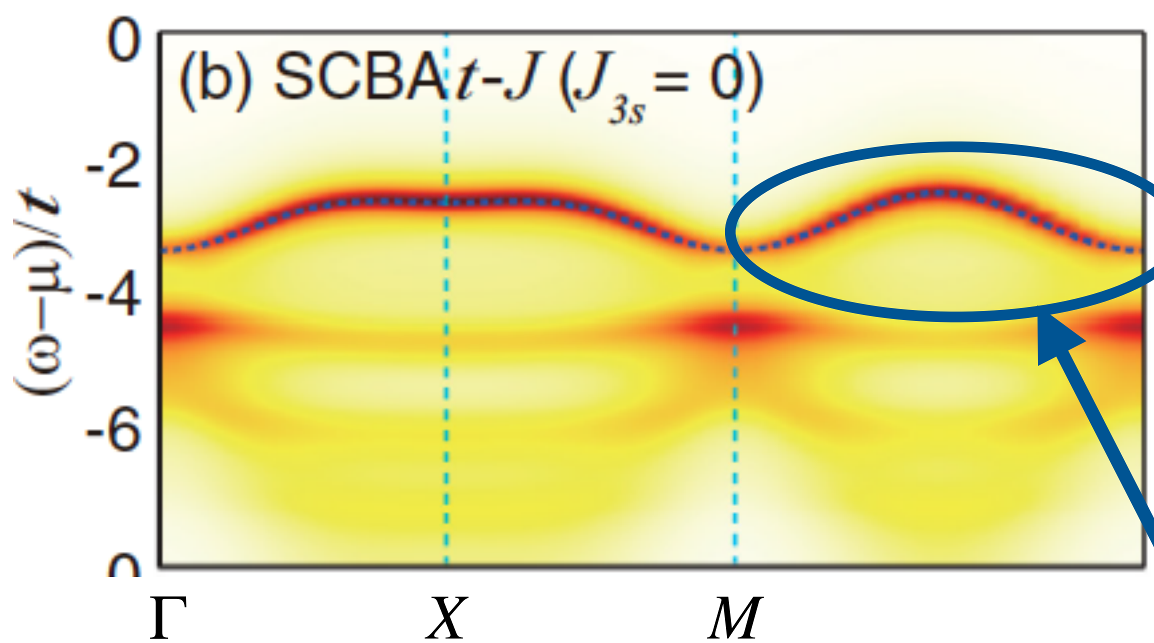

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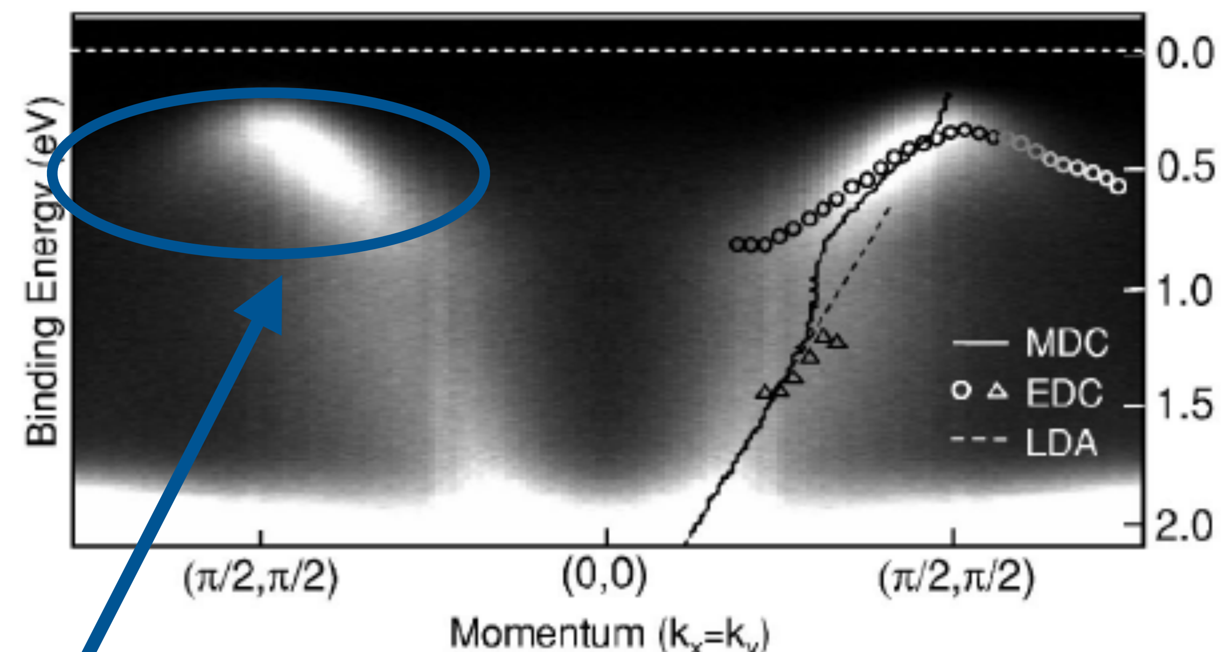
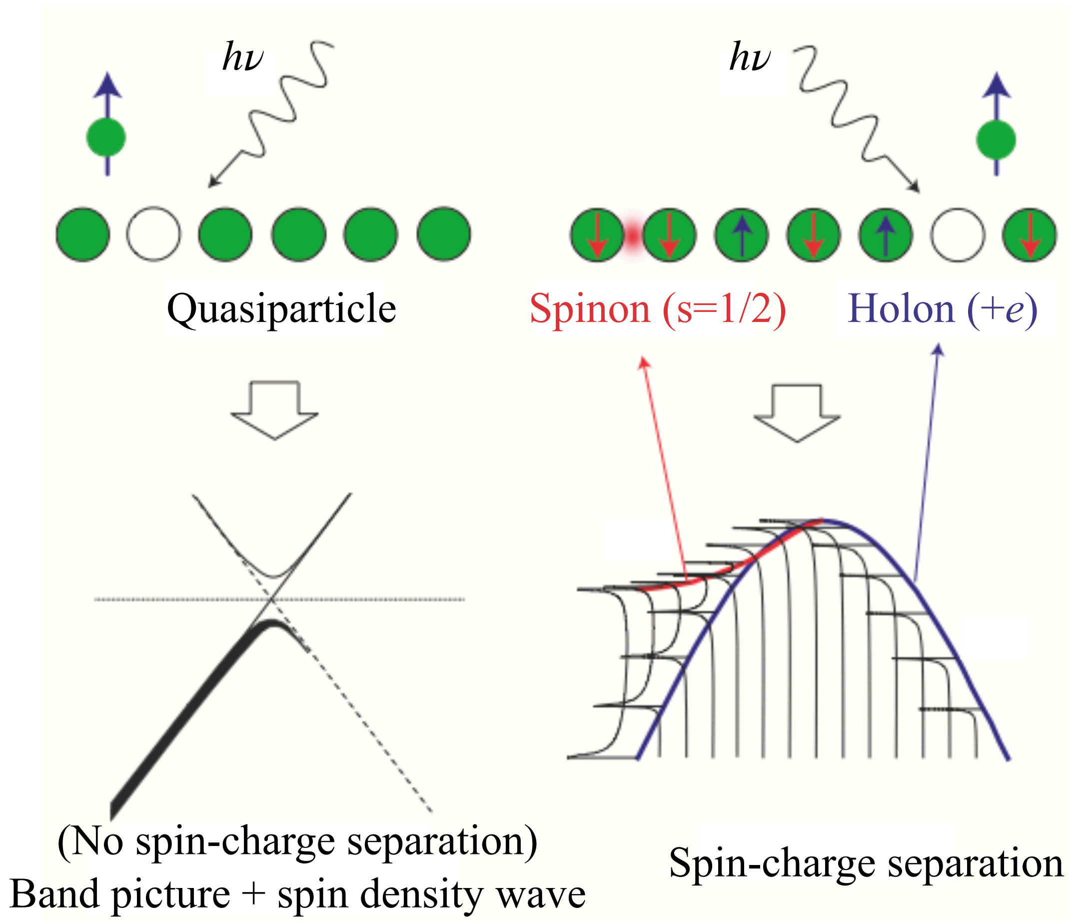


*[PRB **71**, 094518 (2005)]*

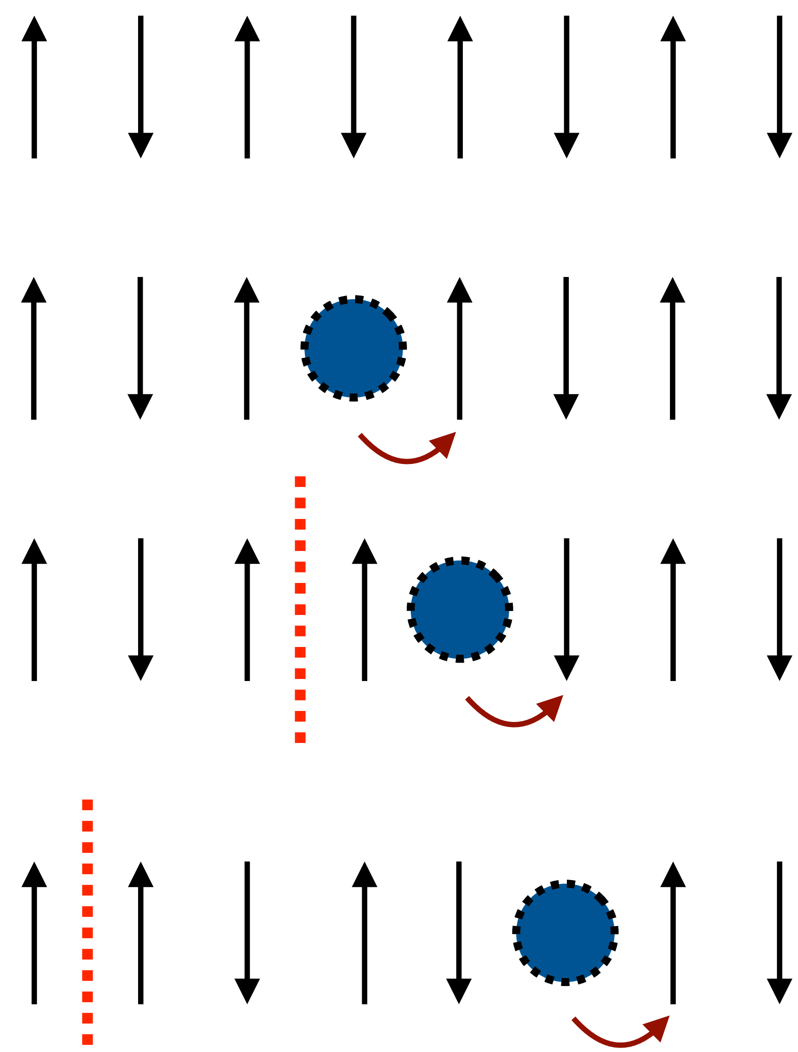
Spin polaron dispersion in model $A(\mathbf{k},\omega)$ and in ARPES/undoped cuprates

1D: spin-charge separation

Adding a single hole in a 1D antiferromagnet



[Nat. Phys. ***2****, 397 (2006)]*



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Adding a single hole in a 1D antiferromagnet

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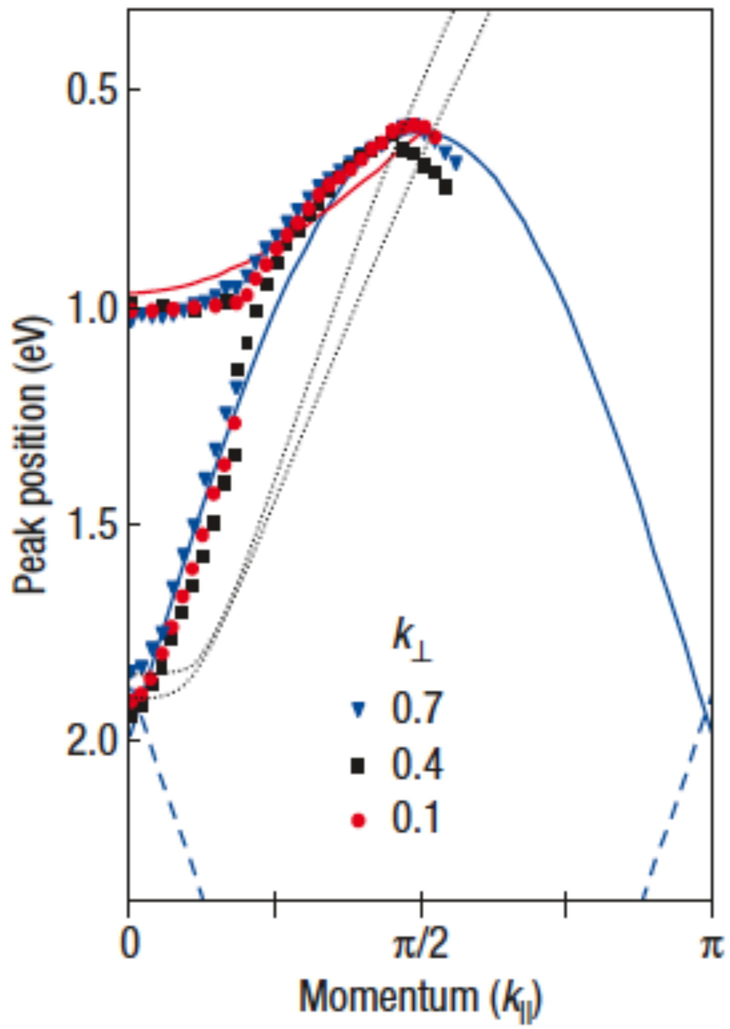
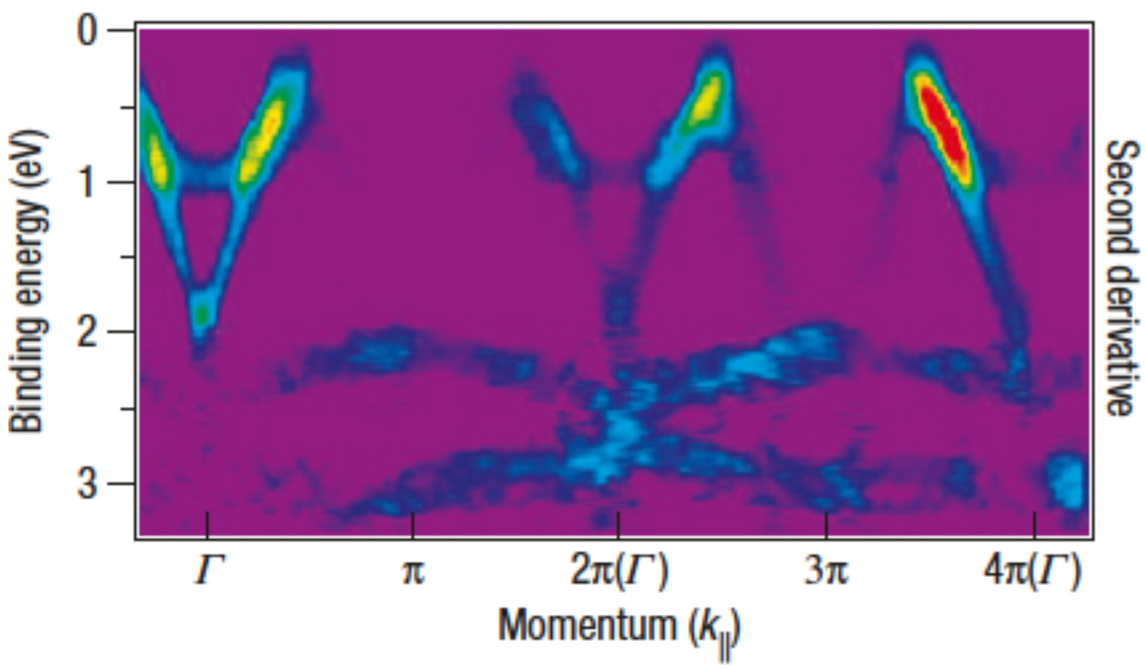
Theory: A(**k**, ω) of 1D AF



[Nat. Phys. **2***, 397 (2006)]*

Experiment: ARPES on 1D cuprate ($SrCuO_2$)



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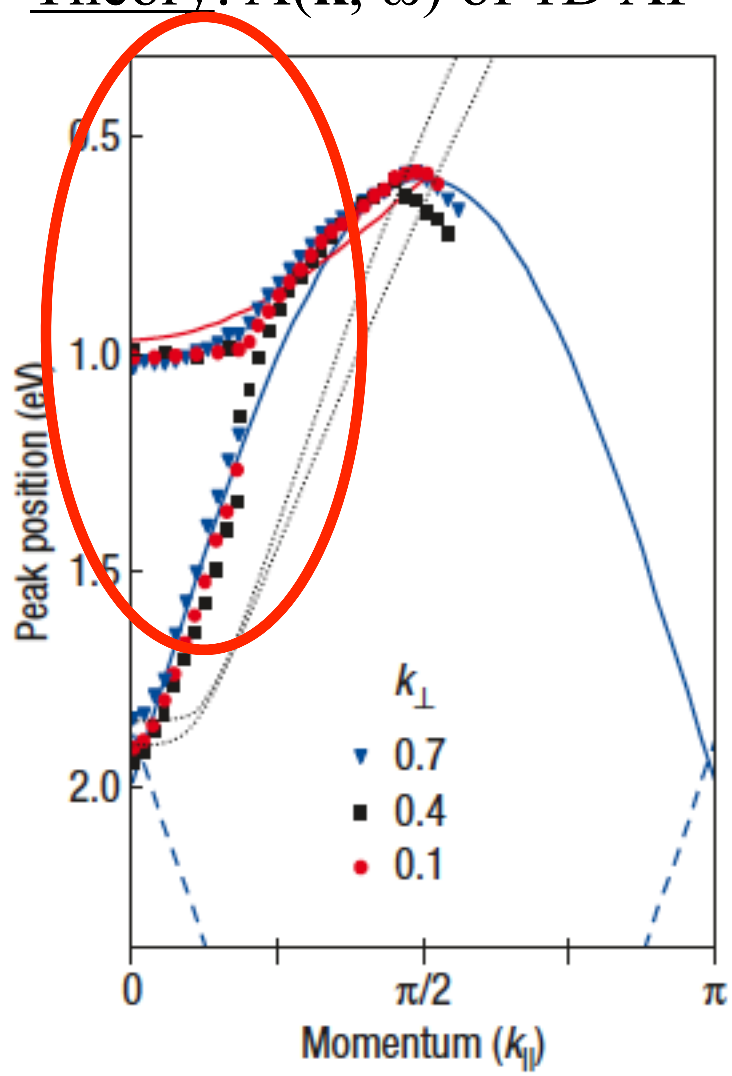

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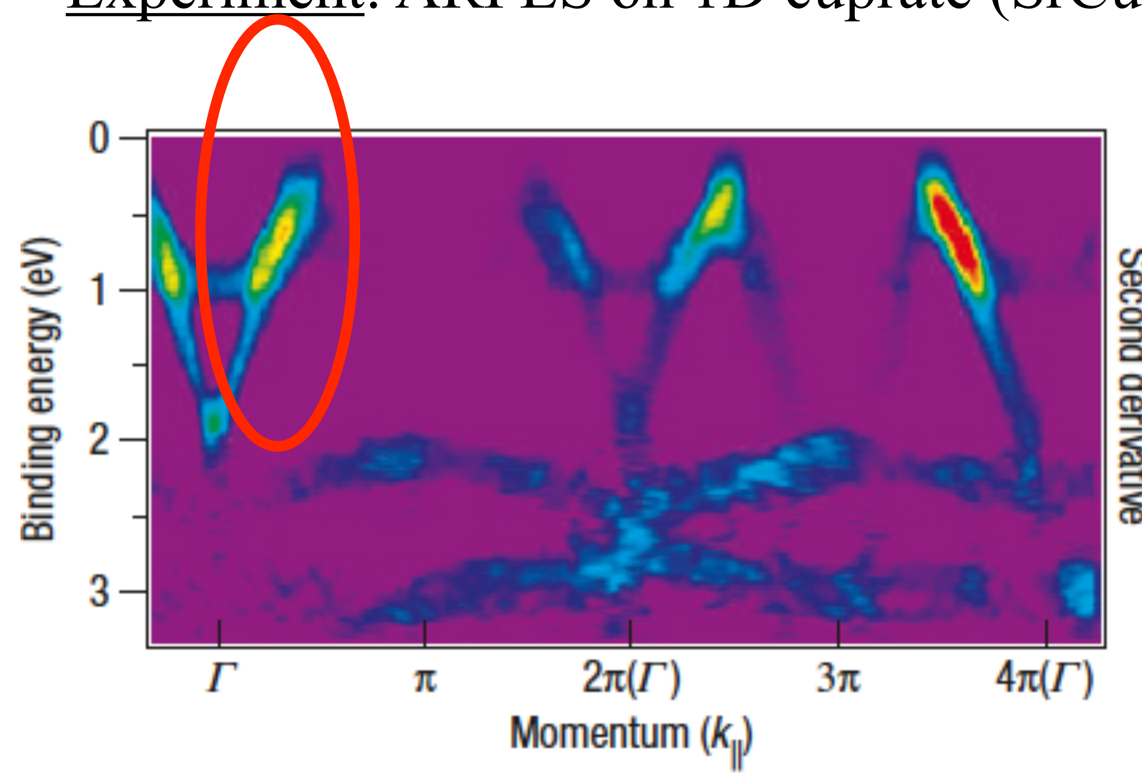


*[Nat. Phys. **2**, 397 (2006)]*

the spin and charge of the holon fractionalize into partons: spinon and holon

The 1D problem in the 2D language

t-J → interacting magnons and a hole

→ t-J model

$$\boxed{H = -t \sum_{\langle i,j \rangle} (\tilde{c}^\dagger_{i,\sigma} \tilde{c}_{j,\sigma} + h.c.) + J \sum_{\langle i,j \rangle} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{4} \tilde{n}_i \tilde{n}_j \right)}$$

→ Rotate one sublattice & introduce **bosons** a via Dyson-Maleev transformation

$$S_i^+ = a_i \tilde{n}_i \qquad S_i^- = a_i^\dagger P_i \tilde{n}_i \qquad S_i^z = \left(\frac{1}{2} - a_i^\dagger a_i \right) \tilde{n}_i$$

$$P_i = 1 - a_i^\dagger a_i, \quad \tilde{n}_i = 1 - h_i^\dagger h_i$$

→ Introduce **holes** h via slave-fermion transformation

$$\tilde{c}^\dagger_{i\uparrow} = h_i, \qquad \tilde{c}_{i\uparrow} = h_i^\dagger P_i,$$

$$\tilde{c}^\dagger_{i\downarrow} = h_i a_i^\dagger, \qquad \tilde{c}_{i\downarrow} = h_i^\dagger a_i,$$

The 1D problem in the 2D language

t-J → interacting magnons and a hole

→ t-J model

$$\boxed{H = H_t + H_{xy} + H_z}$$

$$H_t = t \sum_{\langle i,j \rangle} \left[h_i^\dagger h_j \left(a_i + a_j^\dagger P_i \right) + h_j^\dagger h_i \left(a_j + a_i^\dagger P_j \right) \right]$$

$$H_{xy} = \frac{J}{2} \sum_{\langle i,j \rangle} h_i h_i^\dagger \left[a_i a_j + a_i^\dagger a_j^\dagger P_i P_j \right] h_j h_j^\dagger ,$$

$$H_z = \frac{J}{2} \sum_{\langle i,j \rangle} h_i h_i^\dagger \left[a_i^\dagger a_i + a_j^\dagger a_j - 2 a_i^\dagger a_i a_j^\dagger a_j + 1 \right] h_j h_j^\dagger$$

Exact mapping!

The 1D problem in the 2D language

t-J → interacting magnons and a hole

→ t-J model

$$\boxed{H = H_t + H_{xy} + H_z}$$

We introduce a tuning parameter for the magnon-magnon interaction

$$\boxed{\lambda a_i^\dagger a_i a_j^\dagger a_j}$$

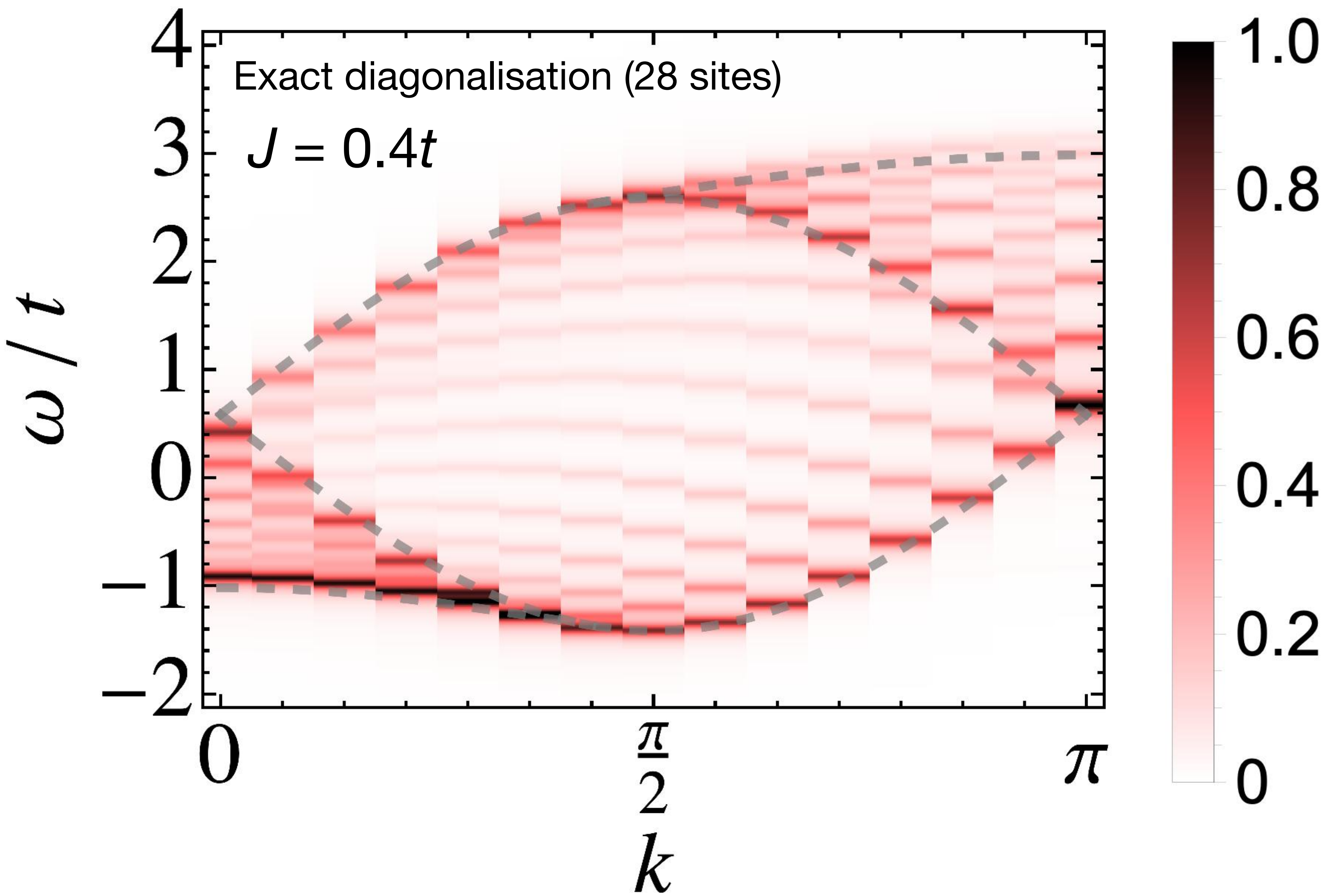
$$H_z = \frac{J}{2} \sum_{\langle i,j \rangle} h_i h_i^\dagger \left[a_i^\dagger a_i + a_j^\dagger a_j - 2 a_i^\dagger a_i a_j^\dagger a_j + 1 \right] h_j h_j^\dagger$$

Exact mapping!

Results

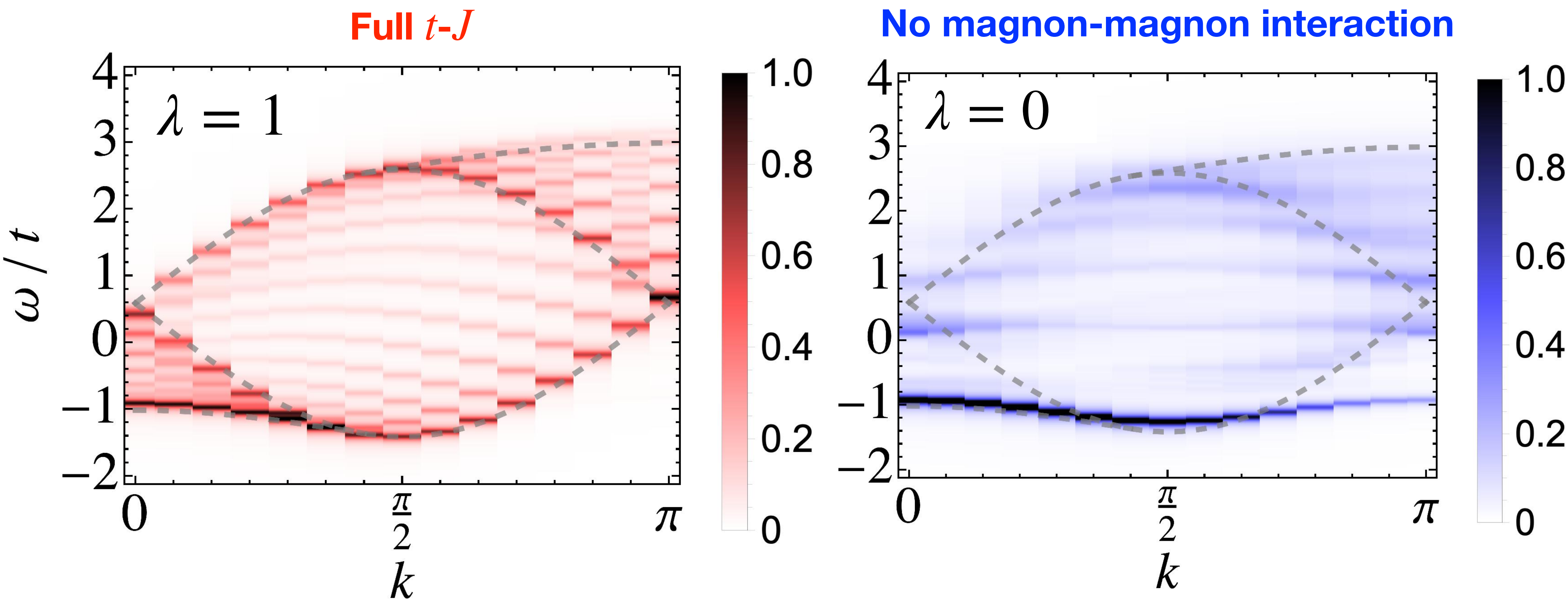
Benchmarking

$A(k, \omega)$ on 1D t-J



- spinon and holon branches clearly visible
- no quasiparticle

Results

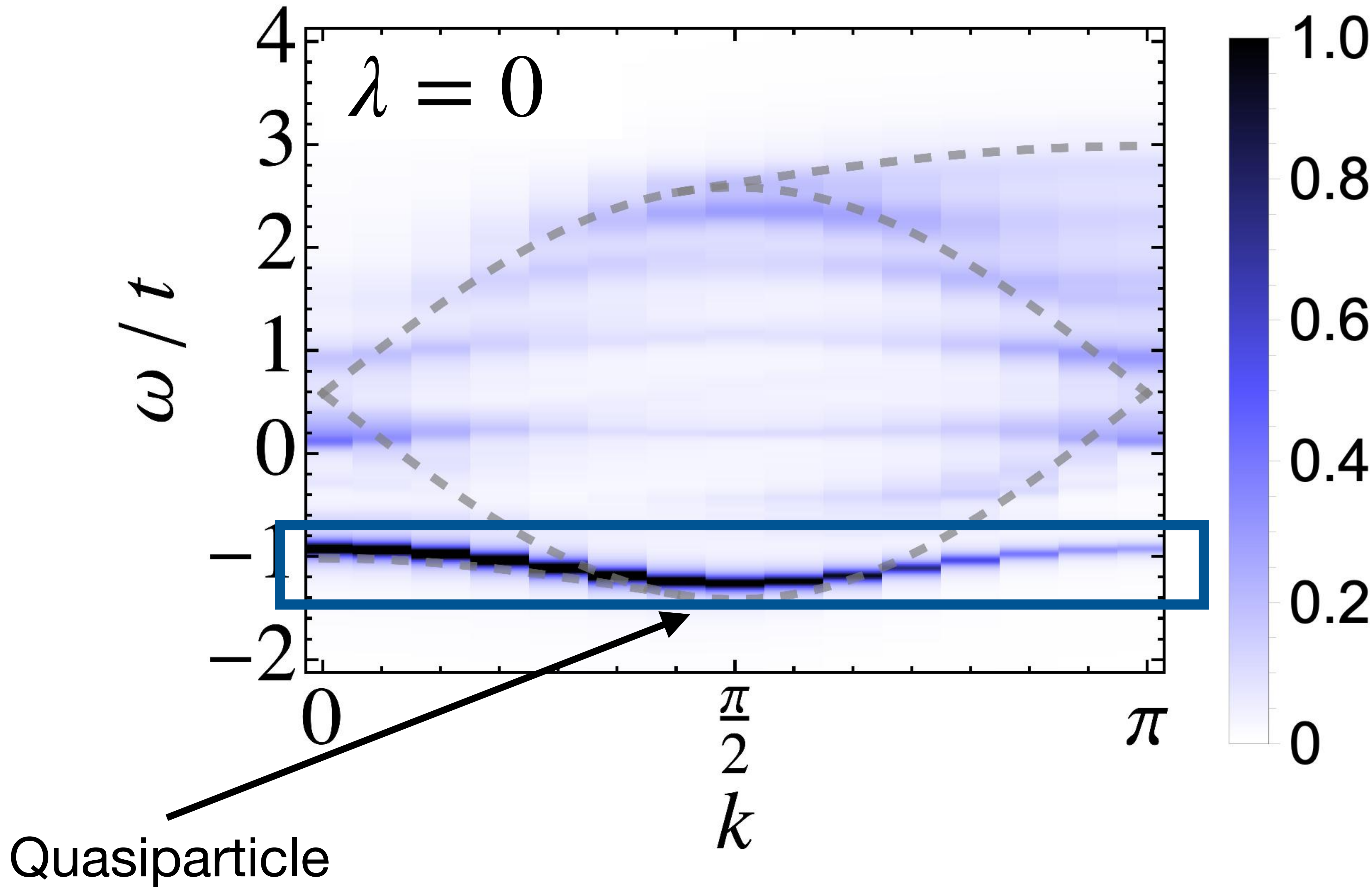


For $\lambda = 0$

- Persistence of "asymmetric eye"
- energy gap
- additional branch from $\pi/2$ to π

$$\boxed{\lambda a_i^\dagger a_i a_j^\dagger a_j}$$

$\lambda = 0$

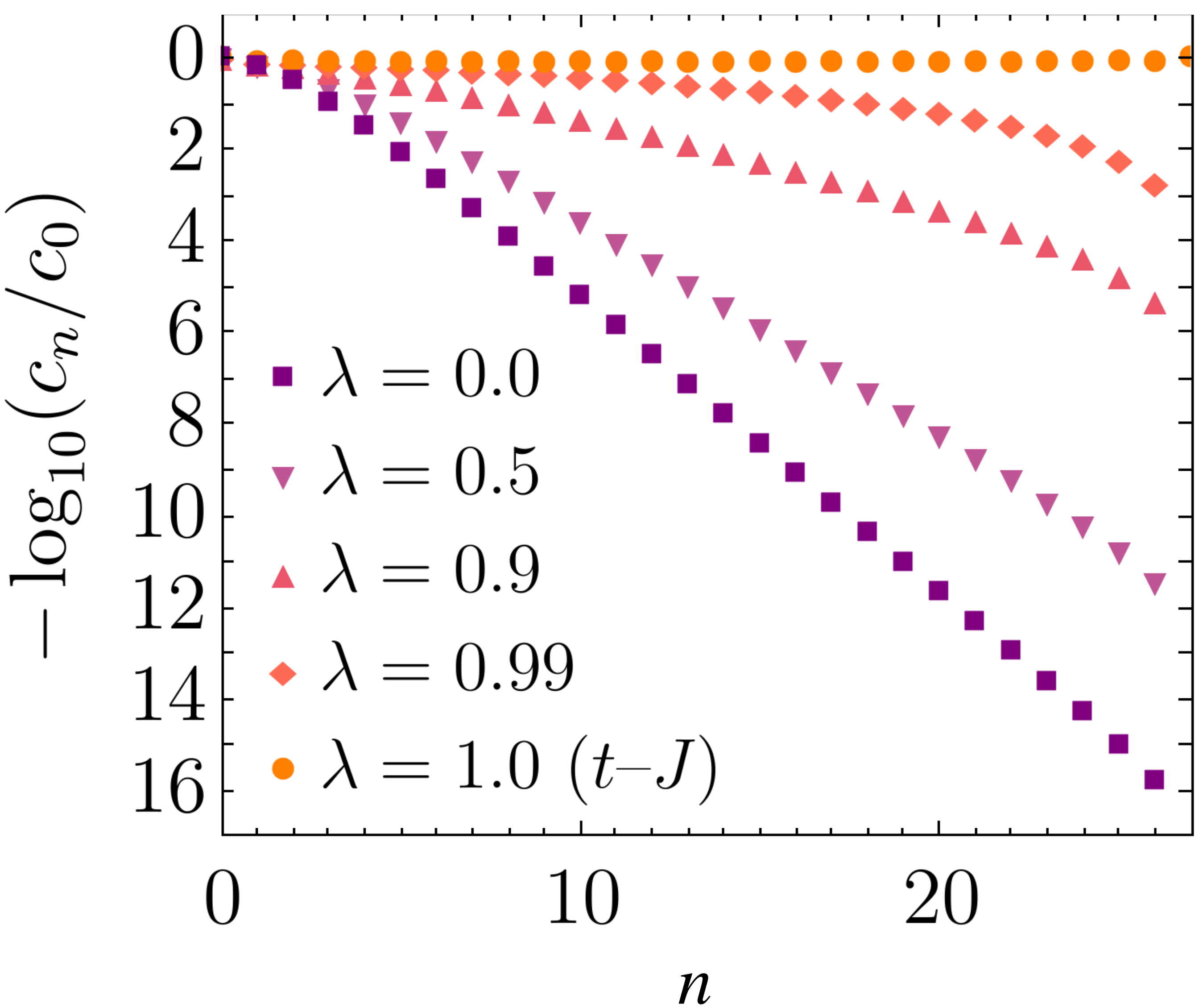


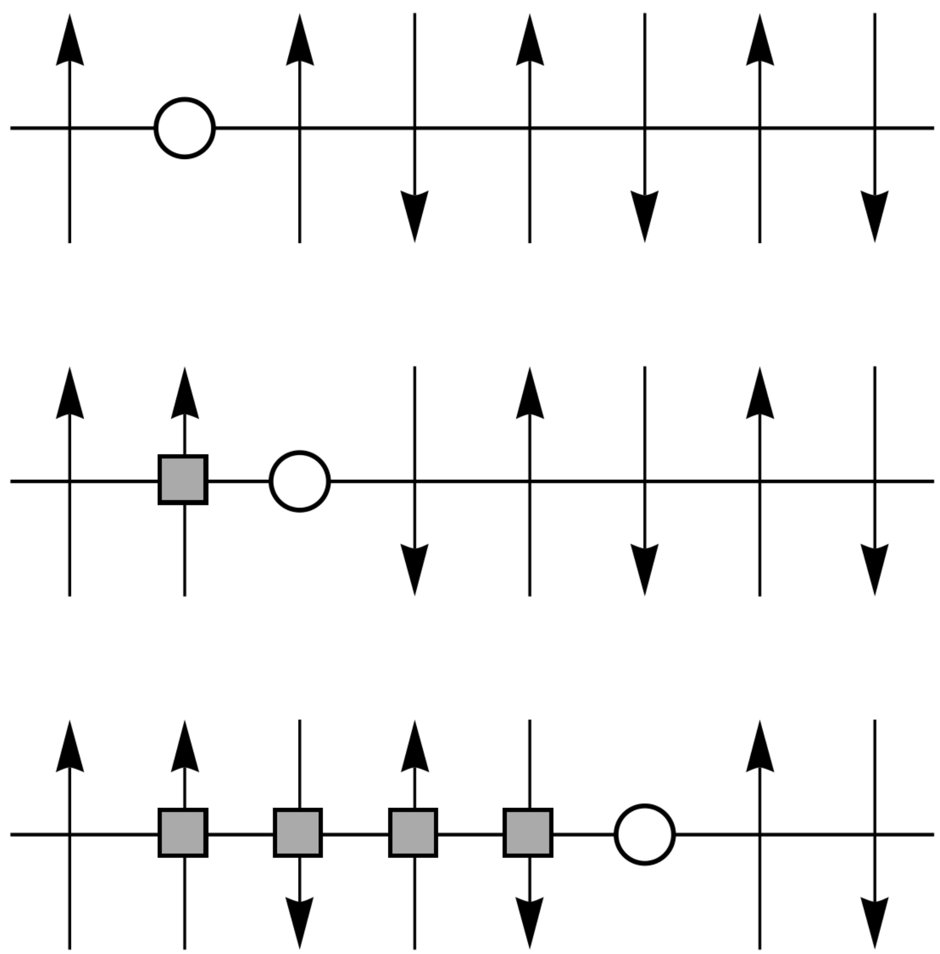
$\lambda = 0$
4
3
2
1
0
-1
-2
ω / t
0
$\frac{\pi}{2}$
π
k
1.0
0.8
0.6
0.4
0.2
0
Quasiparticle

Spin polaron or spin-charge separation?

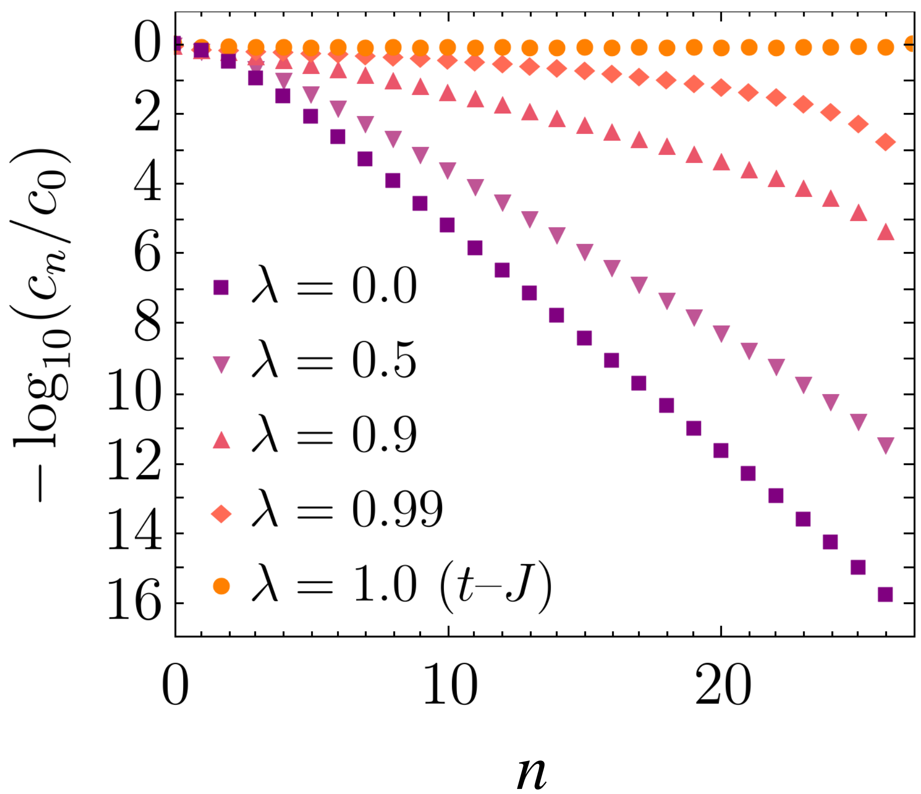
c_n — coefficient of state with:

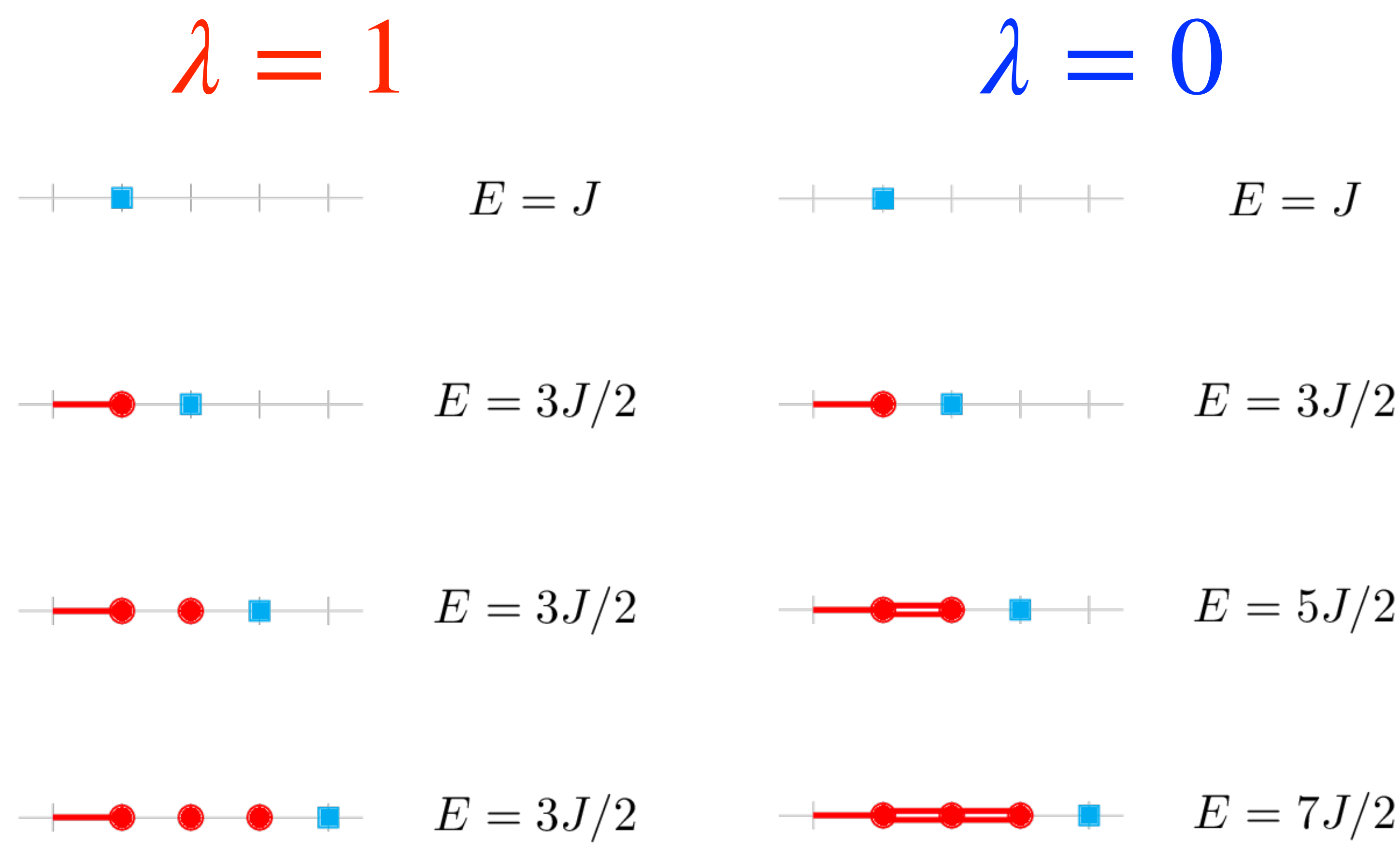
→ chain of n magnons attached to the hole





Spin polaron or spin-charge separation?





SciPost Phys. **7**, *066 (2019)*

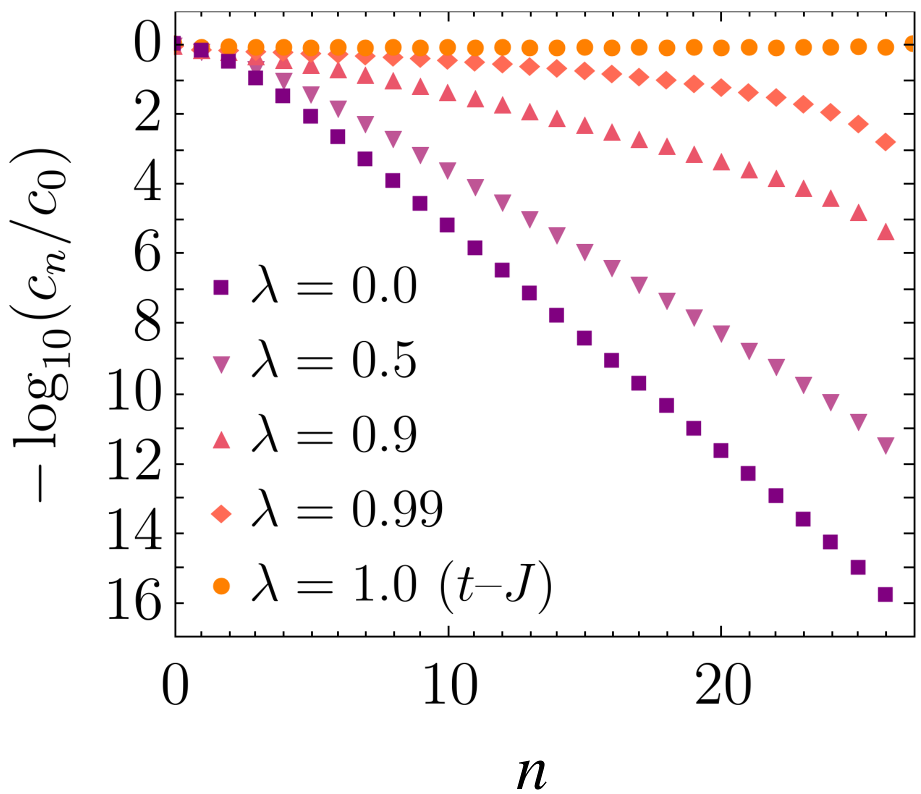
Magnons do **not cost** energy ($\lambda = 1$) ⟶ any number of magnons possible

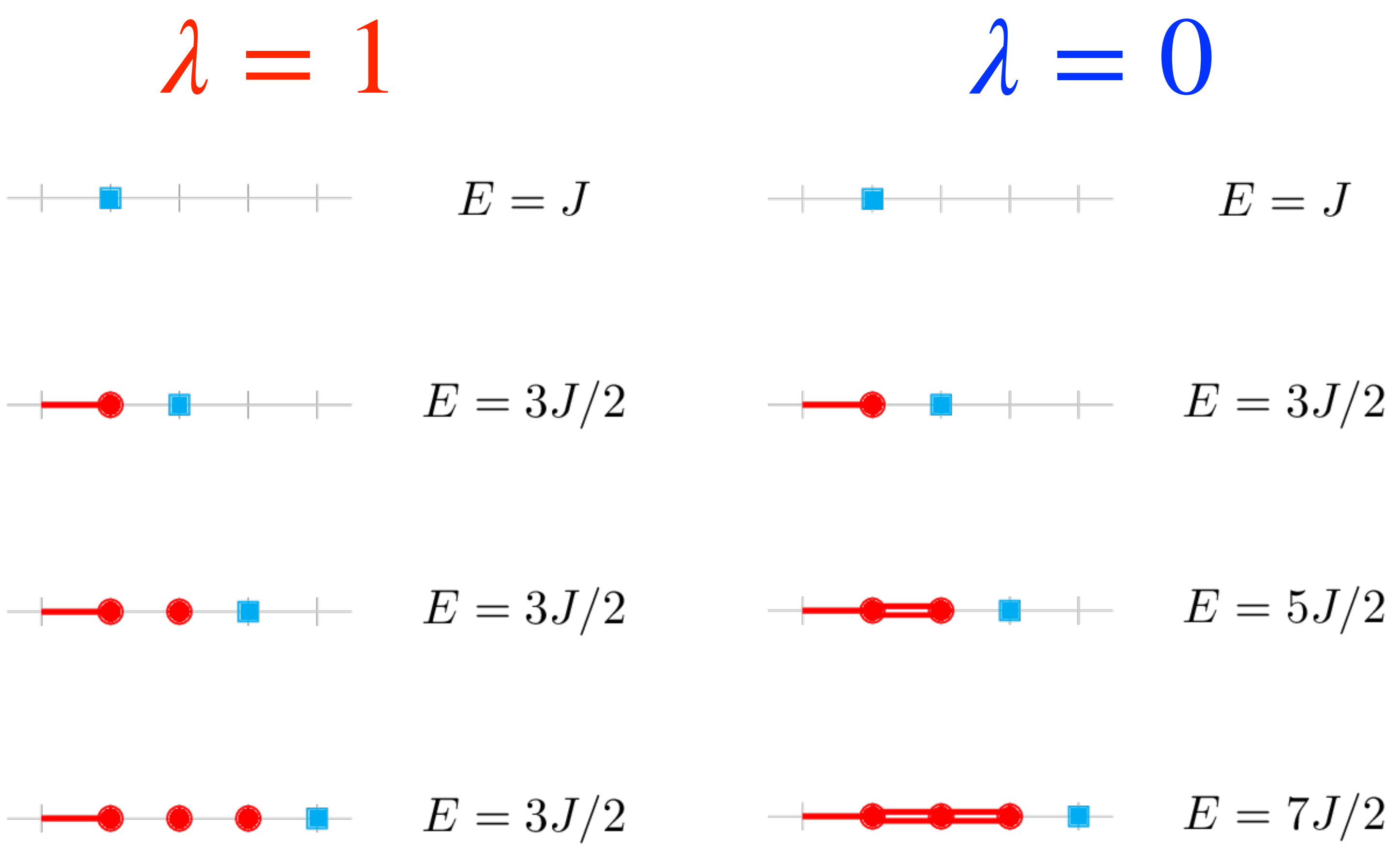
→ **spin-charge separation**

Magnons **cost** energy ($\lambda = 0$) ⟶ limited number of magnons possible

→ **spin polaron**

Spin polaron or spin-charge separation?





SciPost Phys. ***7****, 066 (2019)*

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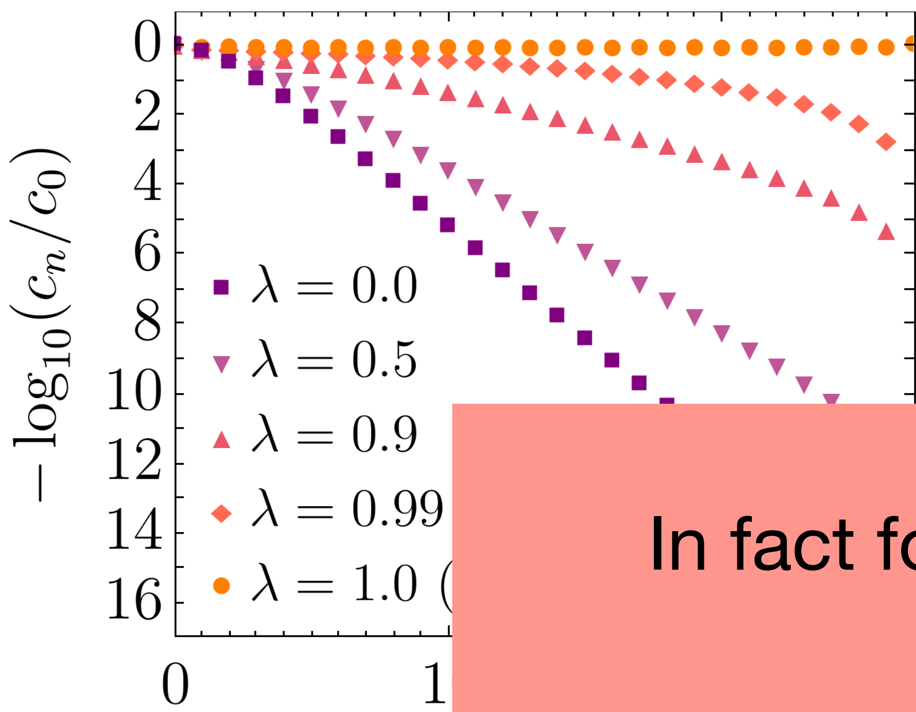
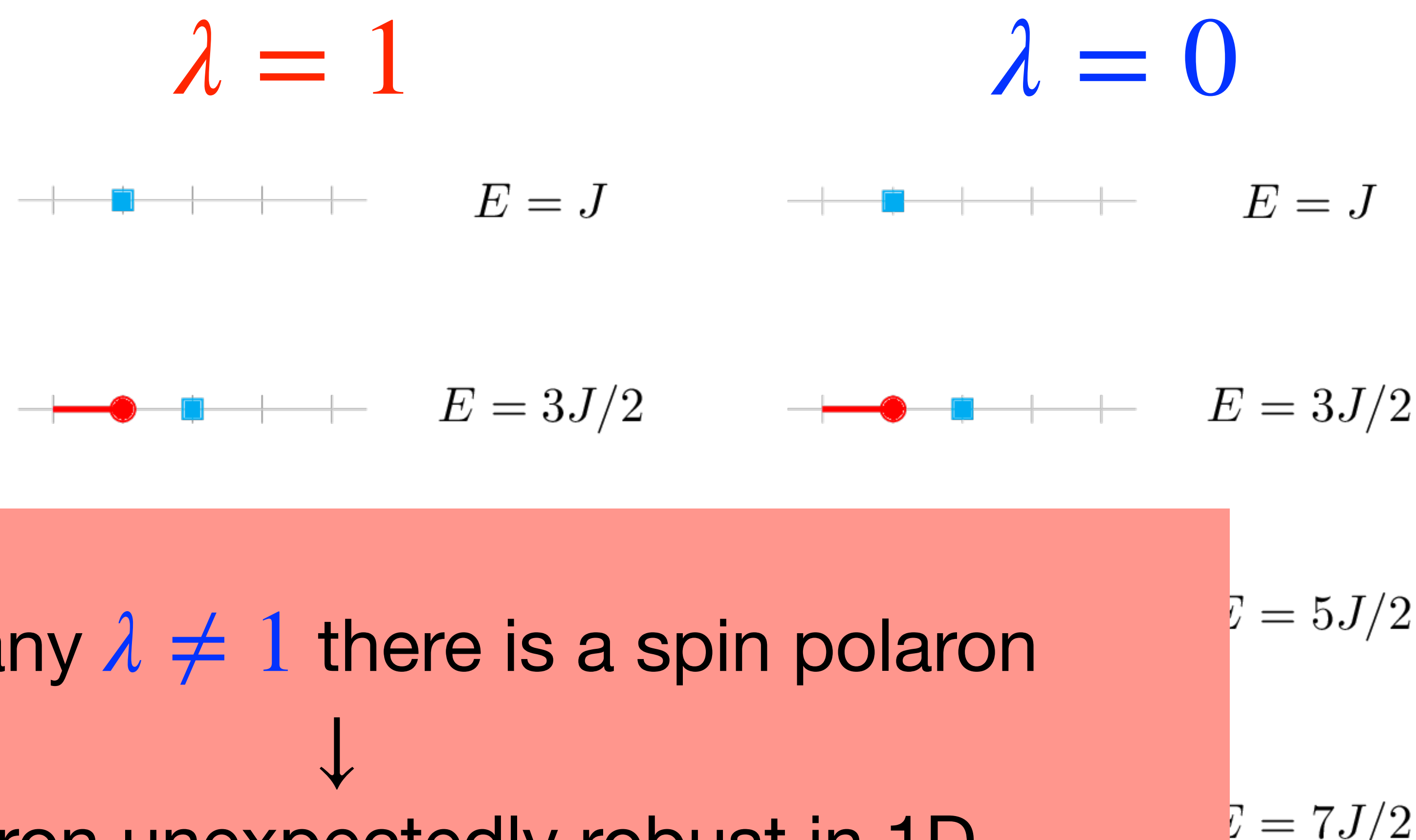
$\rightarrow$ **spin-charge separation**

Magnons **cost** energy ($\lambda = 0$) $\longrightarrow$ limited number of magnons possible

$\rightarrow$ **spin polaron**

Spin polaron or spin-charge separation?





In fact for any $\lambda \neq 1$ there is a spin polaron

$\downarrow$

spin polaron unexpectedly robust in 1D

ys. ***7****, 066 (2019)*

Magnons do **not cost** energy ($\lambda = 1$) $\longrightarrow$ any number of magnons possible

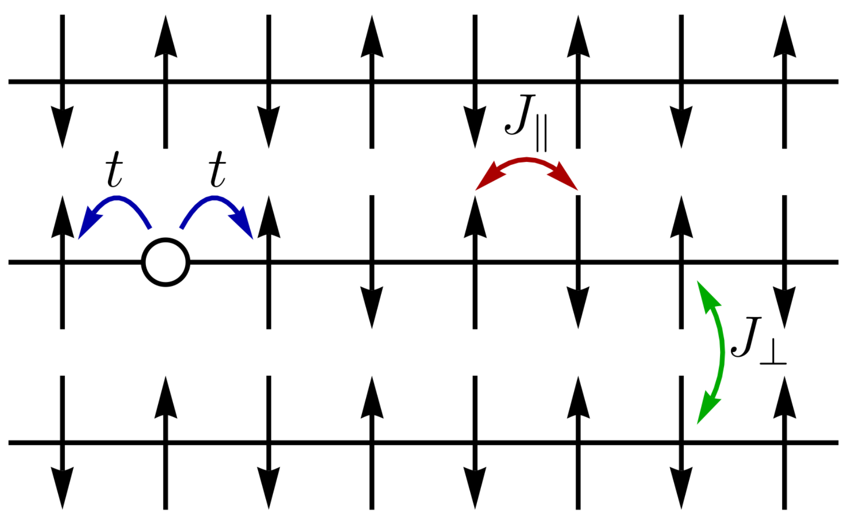
$\rightarrow$ **spin-charge separation**

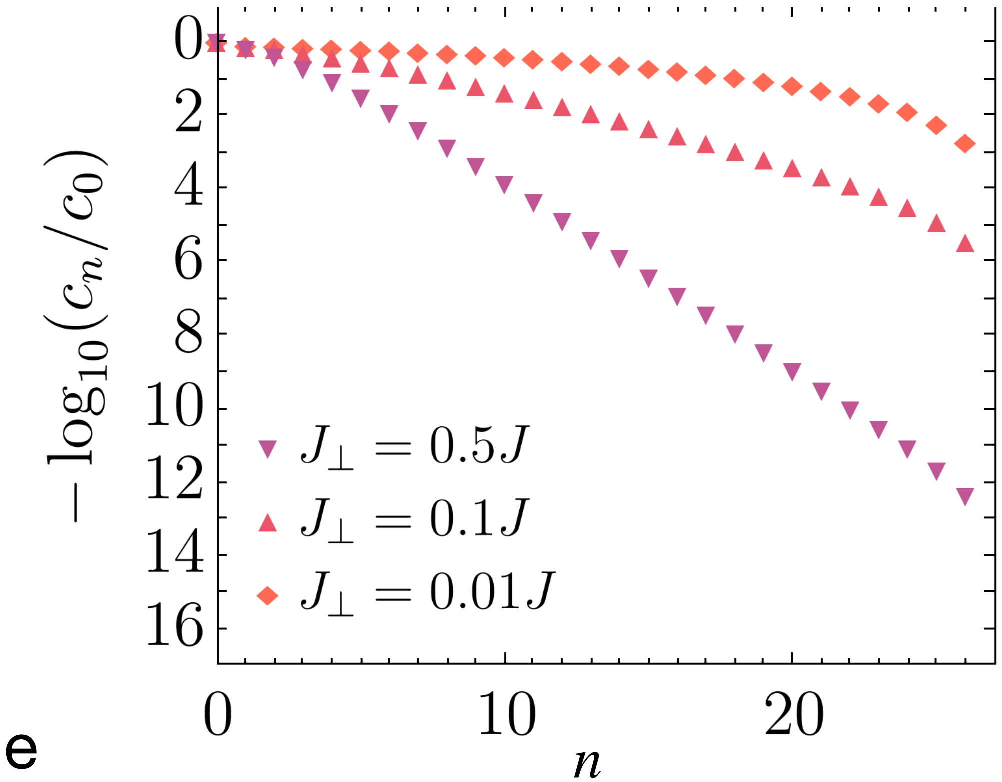
Magnons **cost** energy ($\lambda = 0$) $\longrightarrow$ limited number of magnons possible

$\rightarrow$ **spin polaron**

Quasi-1D cuprates

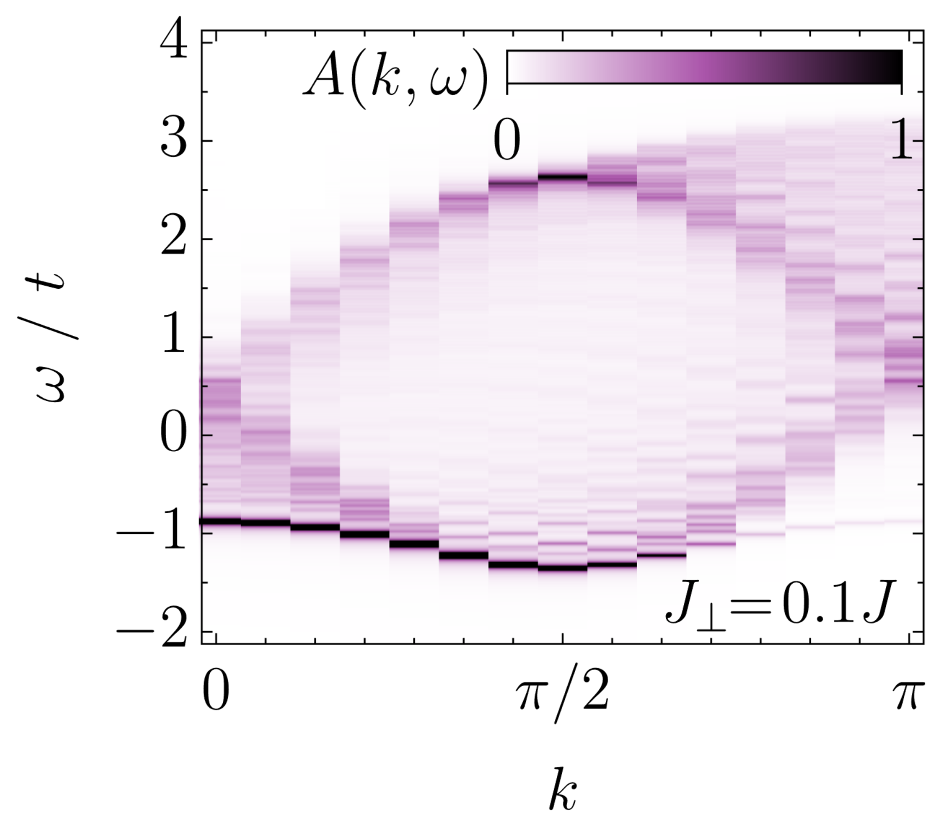
Weakly **coupled t-J chains** $(J_\perp \neq 0)$





staggered field $\rightarrow$ $\lambda \neq 1$ $\rightarrow$ spin polaron stable

ARPES for $J_\perp \sim 0 - 0.1 J_\parallel$
agrees with experiments



$\rightarrow$ ARPES on quasi-1D cuprates
well-understood in the spin polaron picture

Summary

- t-J is actually a special case

  Spin-charge separation in 1D only when the value of the magnon-magnon interactions is critical

- spin polaron stable and robust in quasi-1D cuprates

- ARPES on quasi-1D cuprates agrees with spin polaron picture

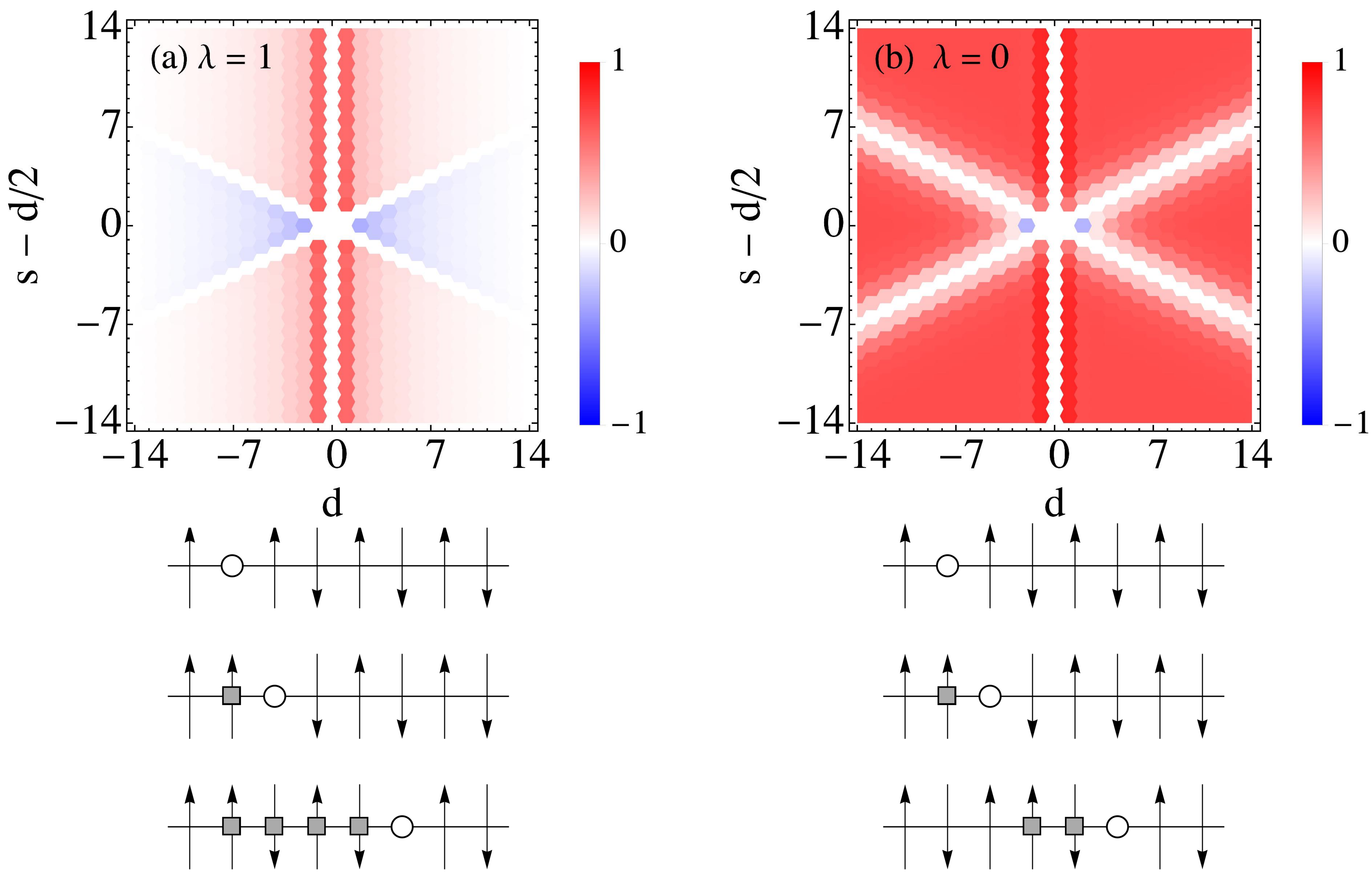
- in fact ARPES on 1D and 2D cuprates is quite similar

Spin-charge saperation vs. spin polaron

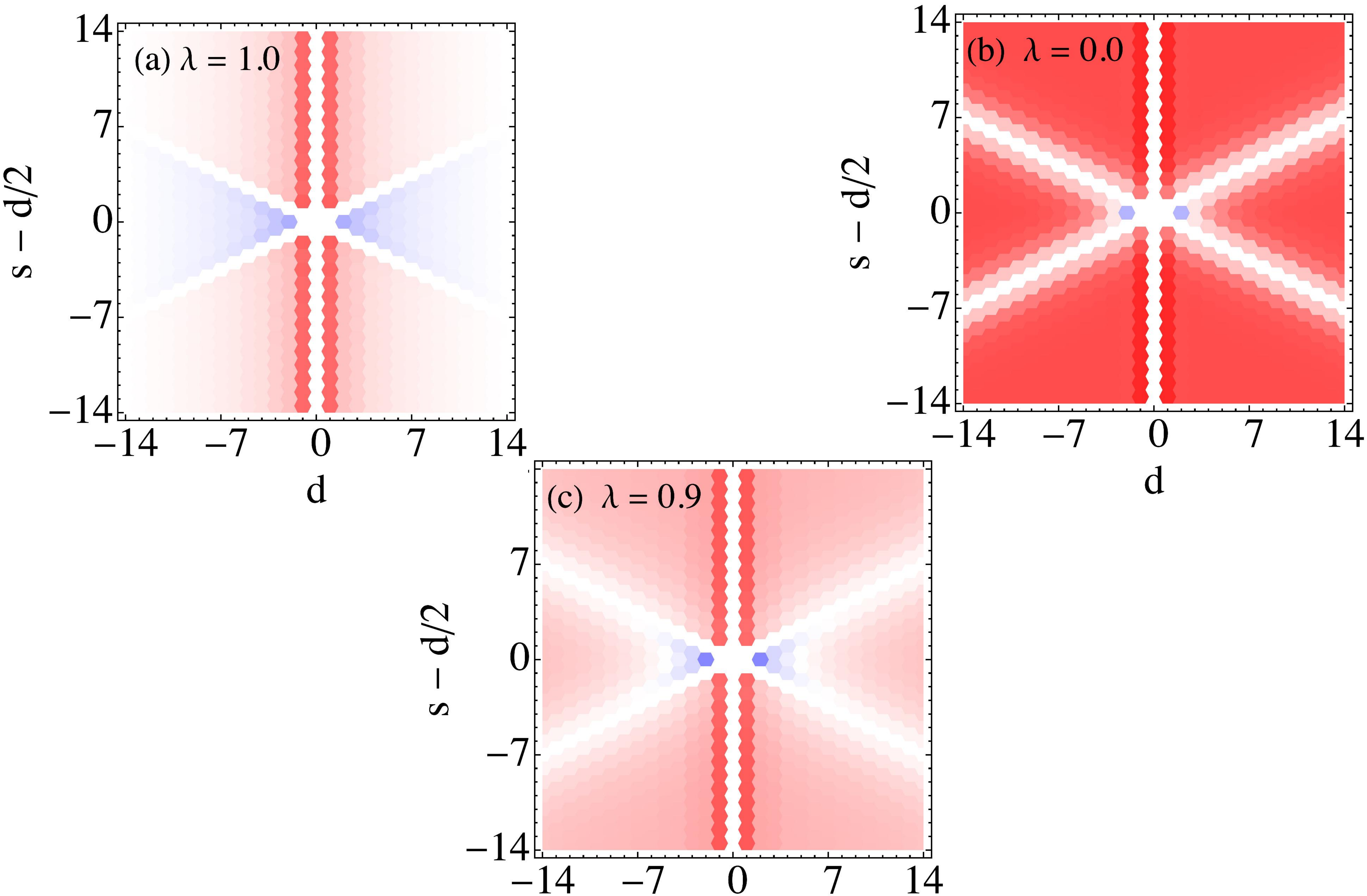
$$C^{str}_{SH}(d,s) = 4\langle S^z_i \prod_{j=1,j\neq s}^{d-1} (-1)^{1-n_{i+j}} S^z_{i+d}\rangle_{\bullet_i \circ_{i+s} \bullet_{i+d}}$$

Rectified correlator: $(-1)^d C^{str}_{SH}(d, s-d/2)$

Science ***357***, *484 (2017)*



Summary: $\lambda = 1$ is special



Thank you

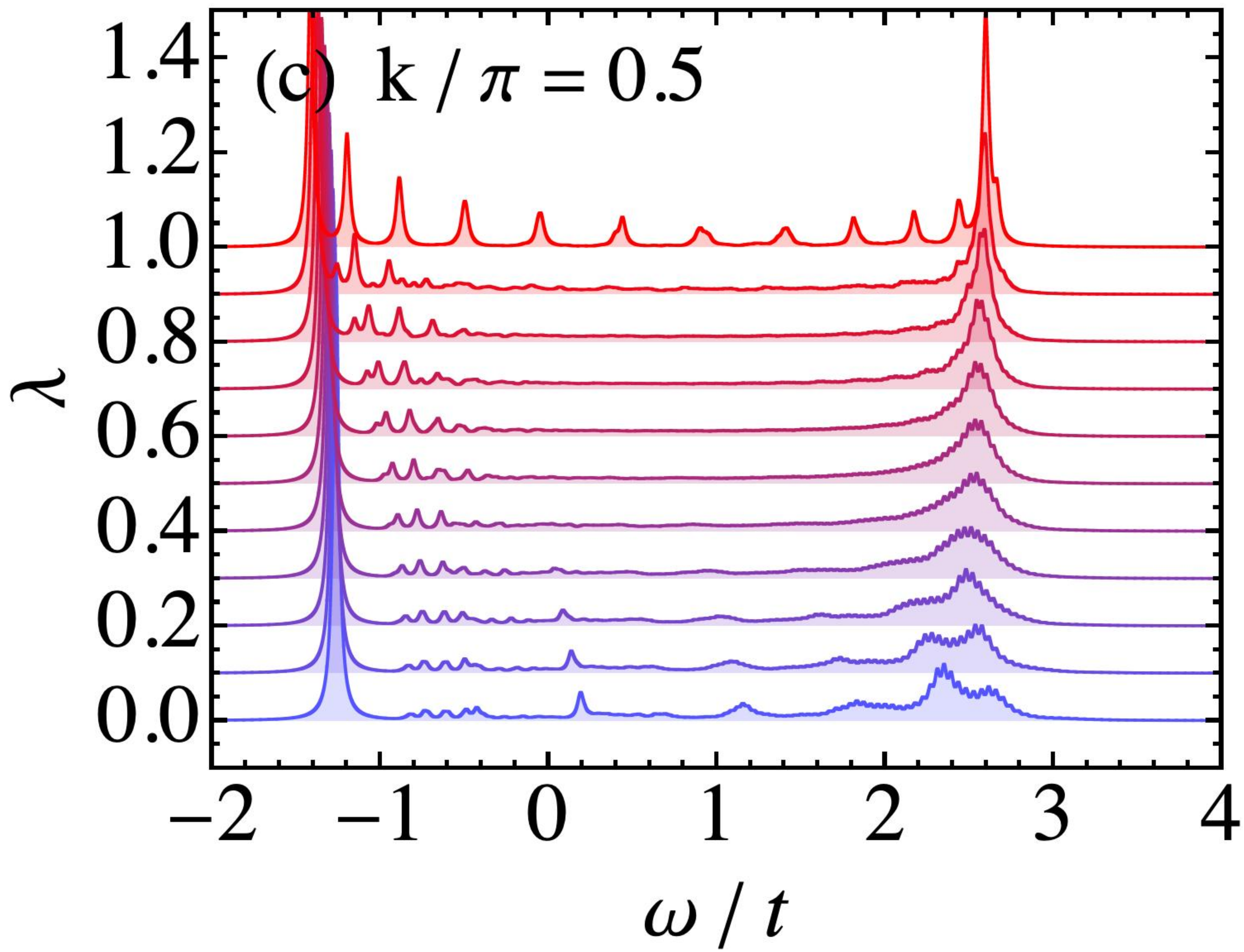
Understanding λ

$$H = -t \sum_{\langle i,j \rangle} \left(\tilde{c}^{\dagger}_{i\sigma} \tilde{c}_{j\sigma} + H.c. \right) + J \sum_{\langle i,j \rangle} \left(S_i S_j - \frac{1}{4} \tilde{n}_i \tilde{n}_j + \right.$$

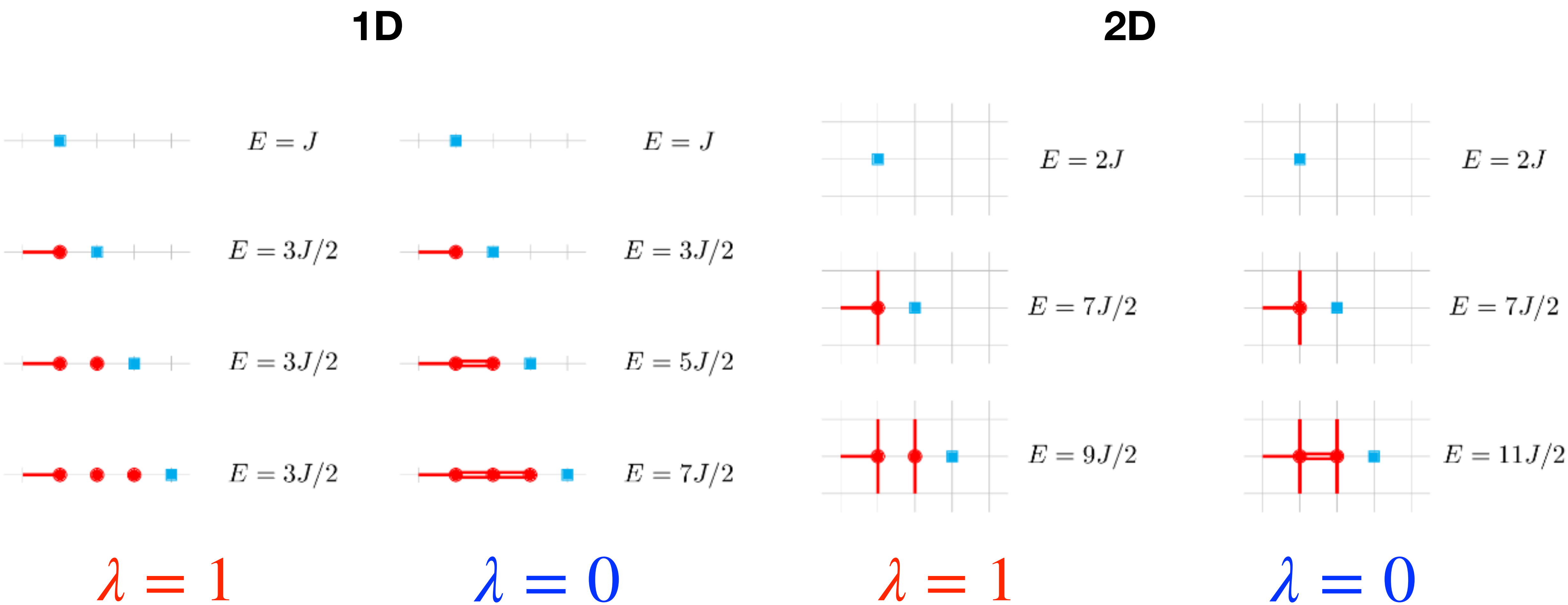
$$\left. +(\lambda - 1) \left(S_i^z S_j^z - \frac{1}{4} \tilde{n}_i \tilde{n}_j + \frac{1}{2} \left(\xi_i^{\mathscr{A}} S_i^z + \xi_j^{\mathscr{A}} S_j^z \right) \tilde{n}_i \tilde{n}_j \right) \right).$$

$\xi^{\mathscr{A}} = -1$ when i is in sublattice $\mathscr{A}$

Possible experimental measurement



why is $\lambda = 1$ special?



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What is p?

$$H_{rot}|\psi_{rot}\rangle = \mathscr{Z}_{\mathscr{A}} H \mathscr{Z}^{\dagger}_{\mathscr{A}} \mathscr{Z}_{\mathscr{A}} |\psi\rangle = \mathscr{Z}_{\mathscr{A}} H |\psi\rangle$$

Consider the translation operators that simply shift the whole system by one site. We denote them by T_s for spin language and T_m for magnon language.

$$T_m|\varnothing\rangle = |\varnothing\rangle$$

$$T_m = \mathscr{M}\mathscr{Z}_{\mathscr{B}} T_s \mathscr{Z}^{\dagger}_{\mathscr{A}} \mathscr{M}^{\dagger} = \mathscr{M} T_s \mathscr{M}^{\dagger}$$

translation followed by rotation of all the spins

$$[T_s, \mathscr{H}] = 0 \ \ if \ \lambda = 1 \qquad\qquad [T_m, \mathscr{H}] = 0 \ \forall \ \lambda$$

$$|\varphi(p)\rangle = \frac{1}{\sqrt{N_\varphi}} \sum_{r=0}^{N-1} \mathrm{e}^{-ipr} T_m^r |\varphi\rangle$$