Phase Diagram of the Triangular *t-J-K* Model in the Doped-Mott Region:

Effects of Ring Exchange Interactions and the "Spin-Charge Separation"

Masao Ogata (Univ. of Tokyo)
Yuki Fuseya (Osaka Univ.)

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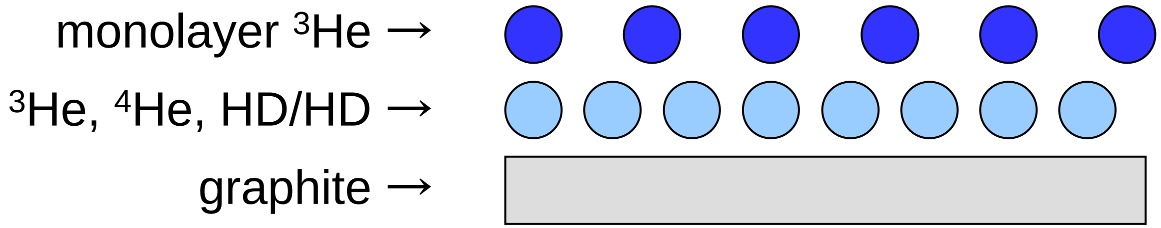
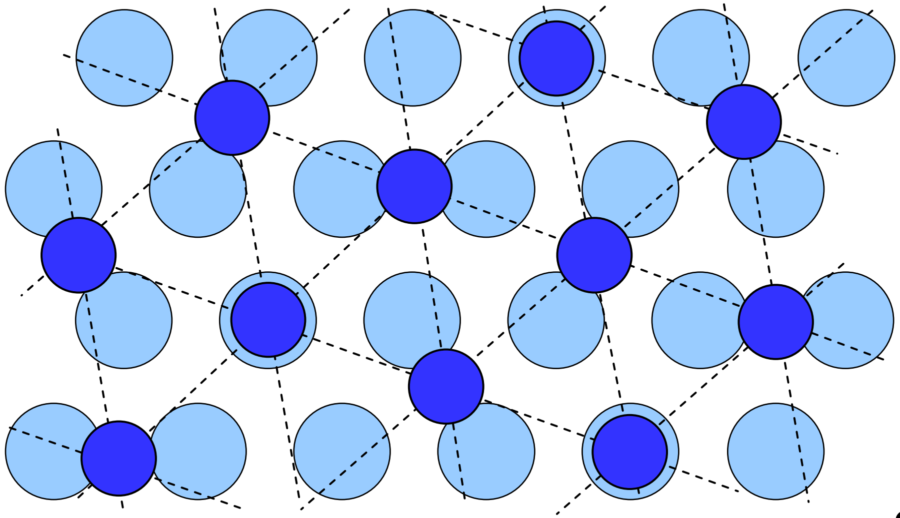
^{3}He adsorbed on graphite



Triangular lattice



"half-filling"

localization at

"4/7 phase"

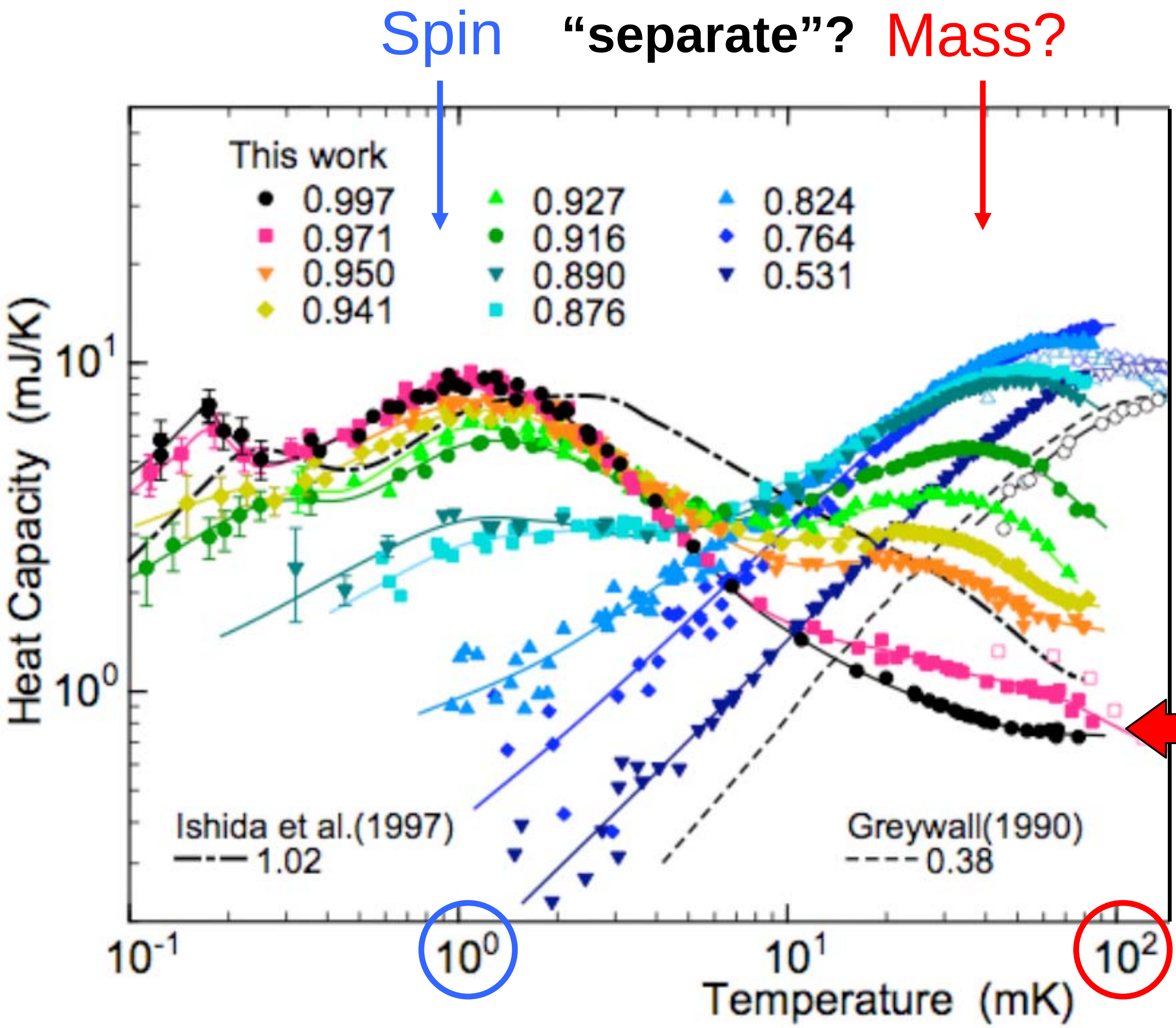
2D ^{3}He : underlayer

= 4 : 7

[Elser (1989)]

- Strongly correlated Fermion system
- Purely two-dimensional
- Super Clean

Double-peaked heat capacity



Spin degrees of freedom
+
Mass degrees of freedom

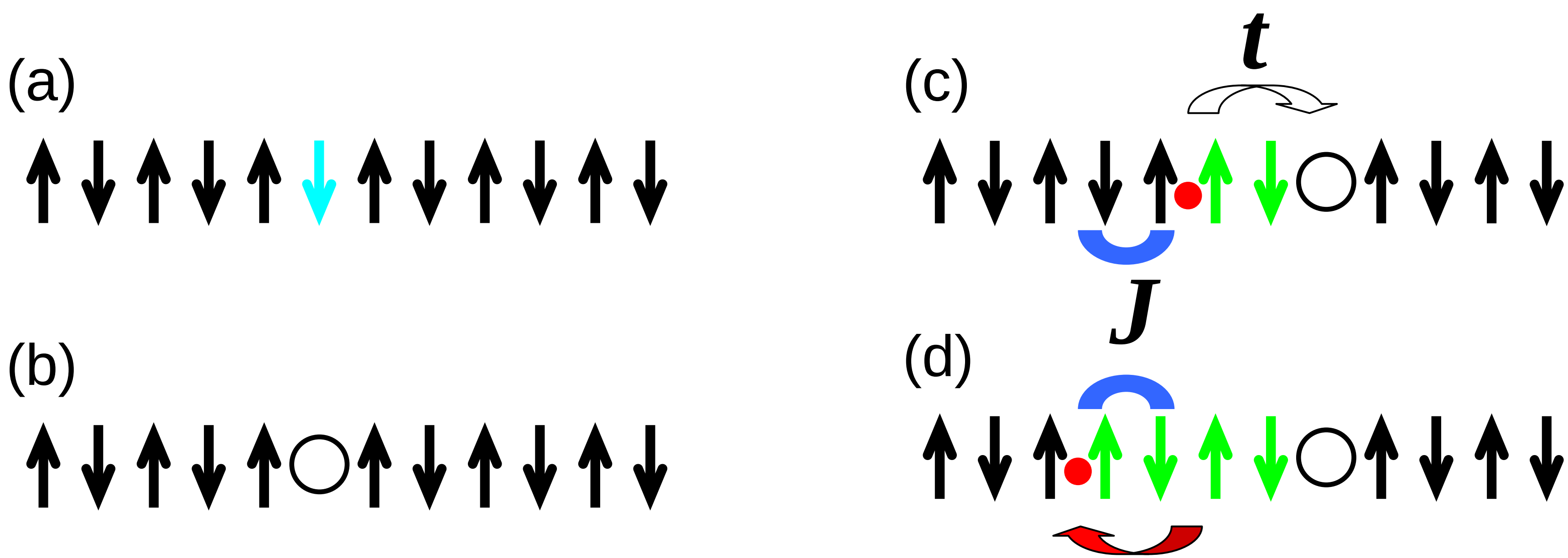
Spin-"Charge" separation

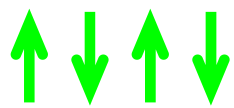
Localized 4/7 phase: half-filling

$^3He/^4He$/gr, [Matsumoto, et al. (2007)]

Spin-Charge separation in 1-dim

Tomonaga-Luttinger liquid



In 2-dim ---- movement of a hole leaves
trace of Unfovored spin states 

→ spin - charge binding
Fermi Liquid

t-J model as a model for ^{3}He

A model of monolayer ^{3}He in the doped case

Large U Hubbard model = t-J model

in a triangular lattice ------- Frustration

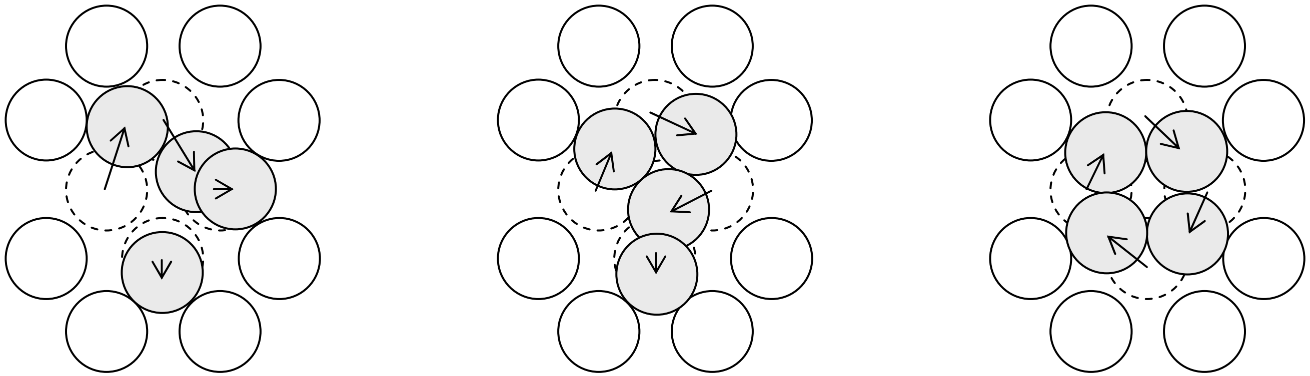
$$H = -t \sum_{i,j,\sigma} \left(\tilde{c}^{\dagger}_{i\sigma} \tilde{c}_{j\sigma} + \mathrm{H.c.} \right) + J \sum_{i,j} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{4} n_i n_j \right)$$

However, no spin-charge separation was observed in the triangular t-J model. (Koretsune-Ogata, PRL 89, 116401 (2002))

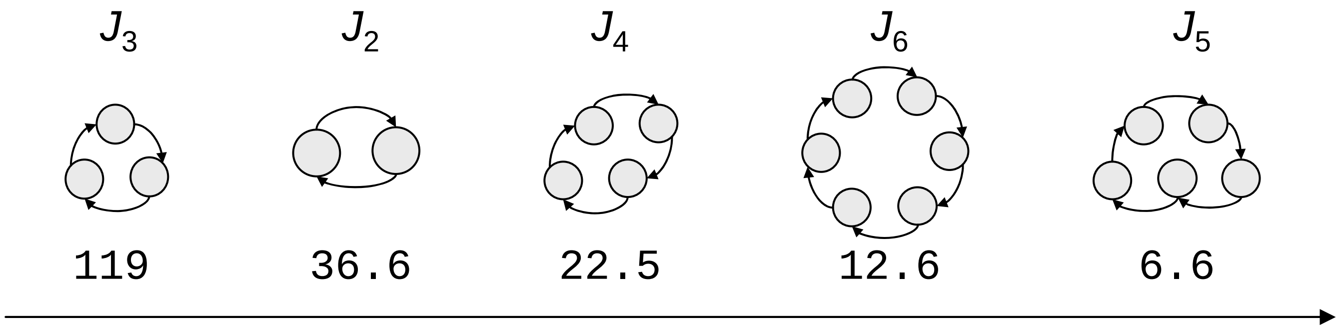
Multiple Spin Exchange

MSE is relevant in a hard-core quantum solid

--- Thouless (1965)



$$H = \sum_n (-1)^n J_n \left(P_n + P_n^{-1} \right)$$



[Bernu et al. (1992)]

t-*J*-*K* model

As a minimum model of monolayer ^{3}He, we use

t-*J*-*K* model

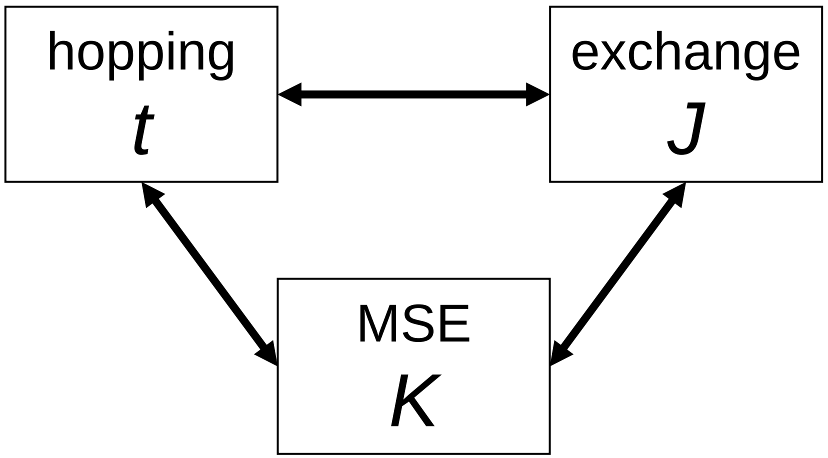
$J = J_2 - 2J_3$

(J can be ferro. for large J_3)

$$H = -t \sum_{i,j,\sigma} \left(\tilde{c}^{\dagger}_{i\sigma} \tilde{c}_{j\sigma} + \mathrm{H.c.} \right)$$

$$+ J \sum_{i,j} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{4} n_i n_j \right) + K \sum_{i,j,k,l} \left(P_4 + P_4^{-1} \right)$$

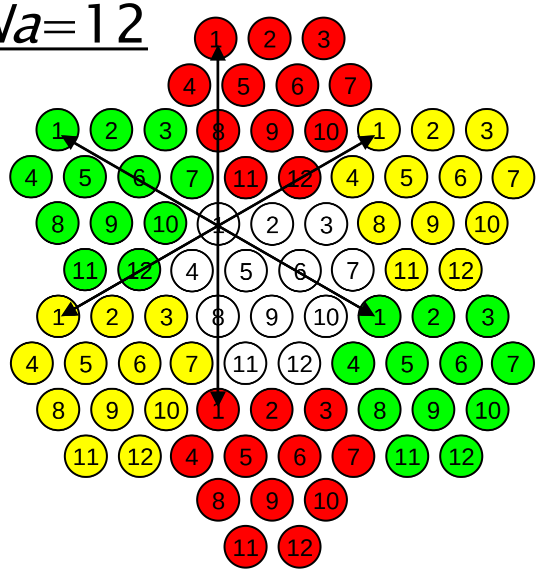
$$(J = J_2 - 2J_3)$$



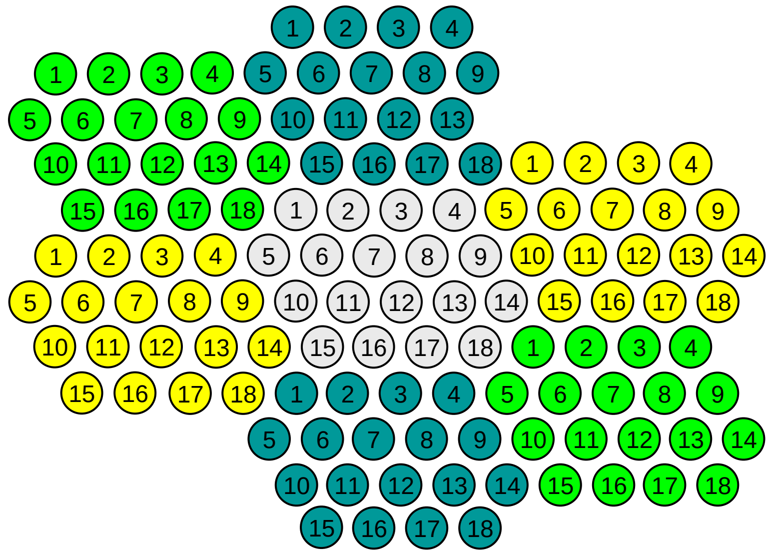
Cluster

Exact diagonalization

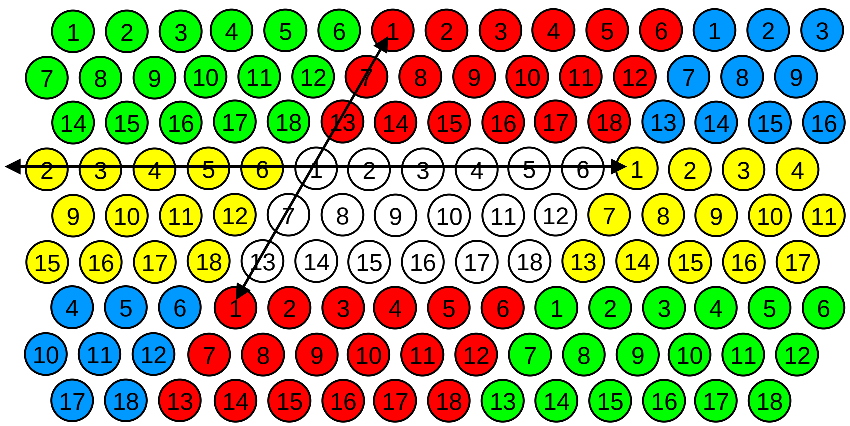
Na=12



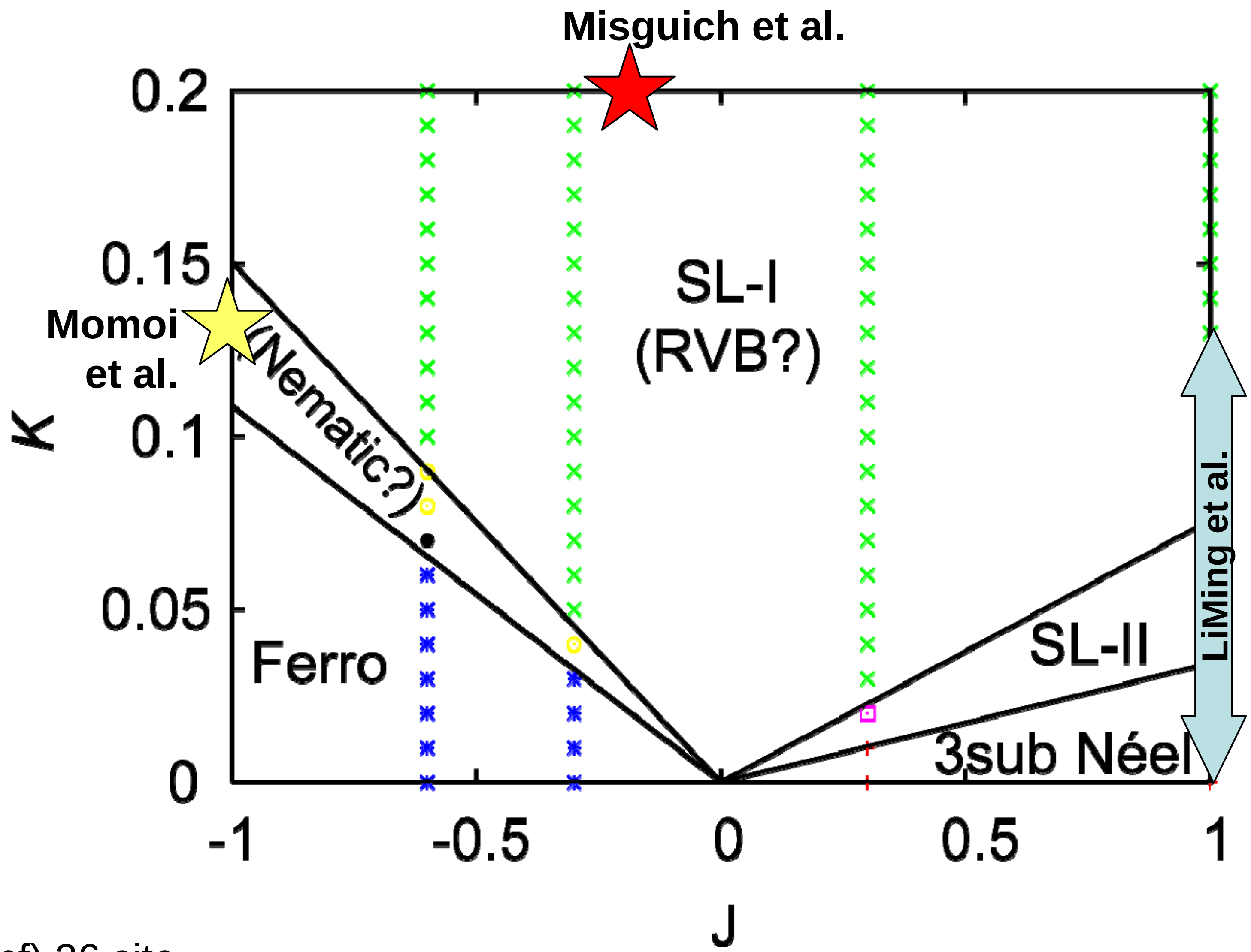
Na=18b



Na=18a



Half filling (n=1.0)



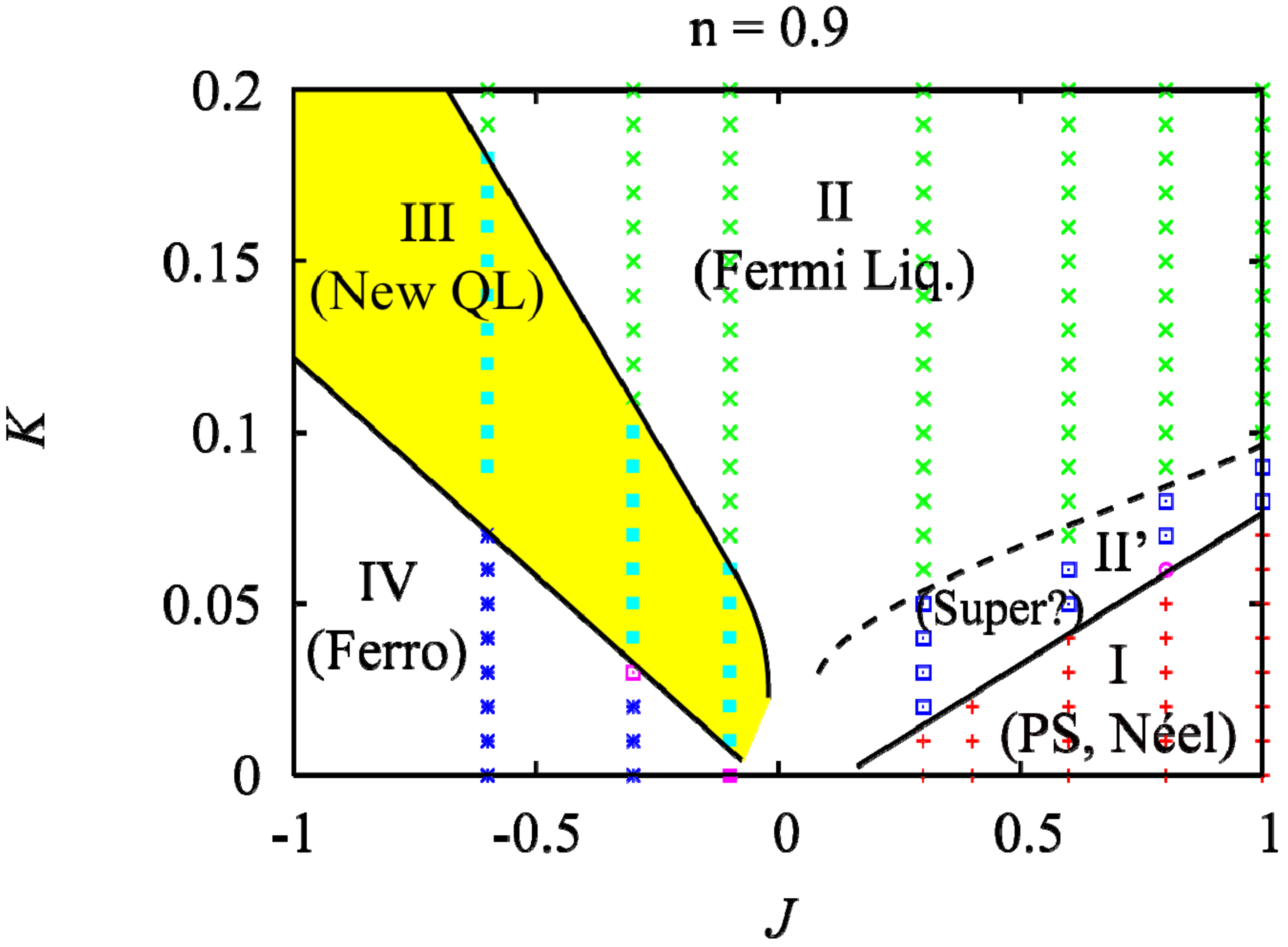
- N=12,18,20
- Cluster shape
- Boundary
- E-level
- Δ_s
- κ (comp.)
- S(q), N(q)

cf) 36 site

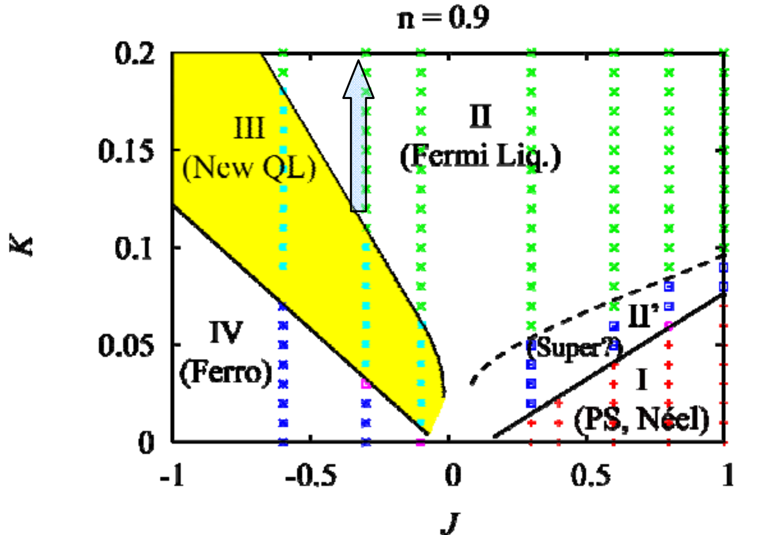
Misguich, et al (1999)

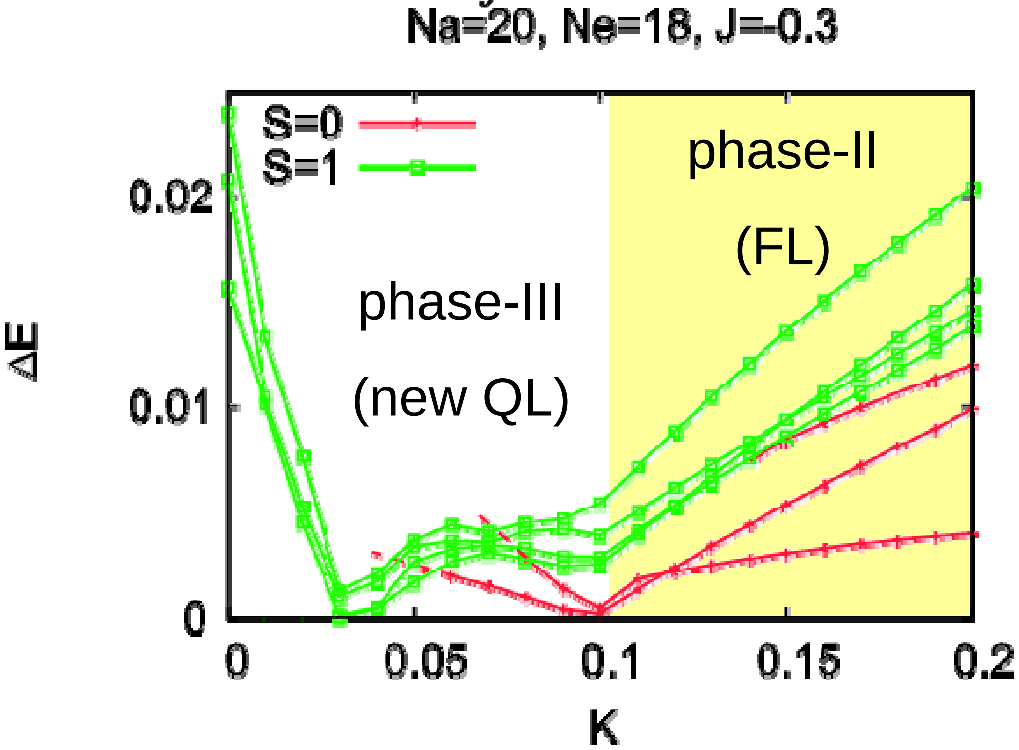
LiMing, et al (2000) Momoi et al (2006)

Doped region (n=0.9)

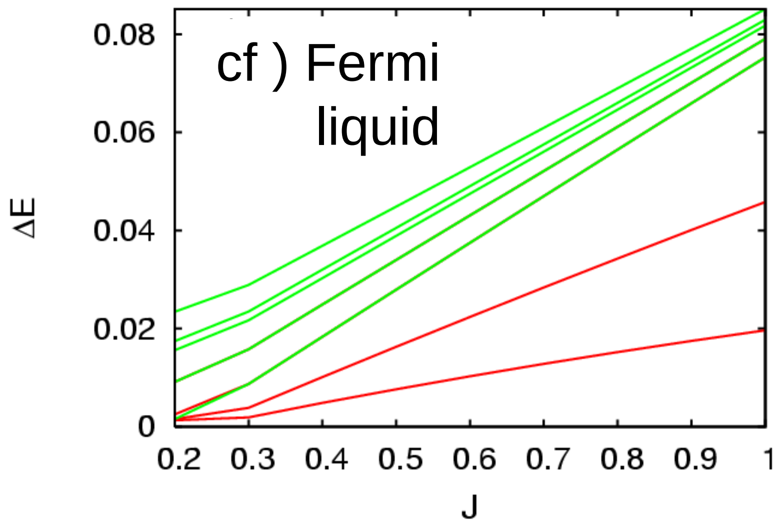


Excitation energy





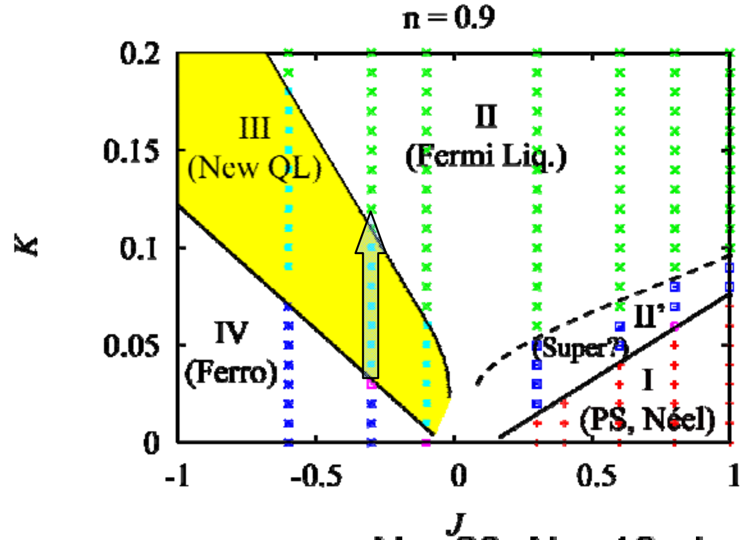
ordinary

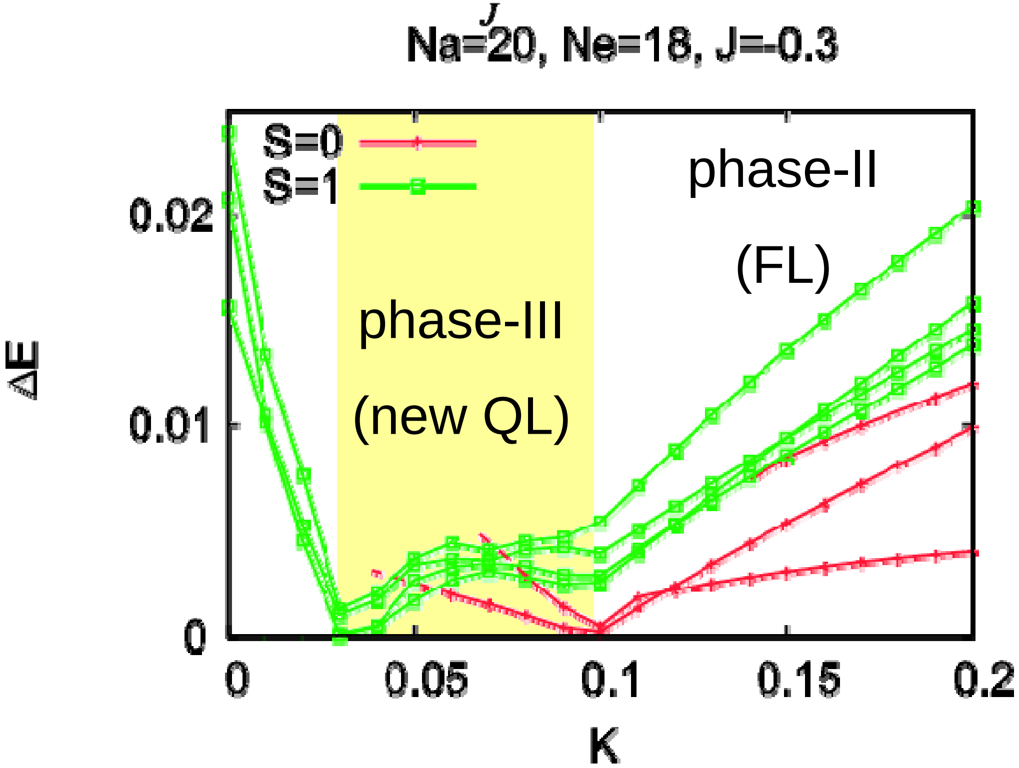


Fermi Liquid region

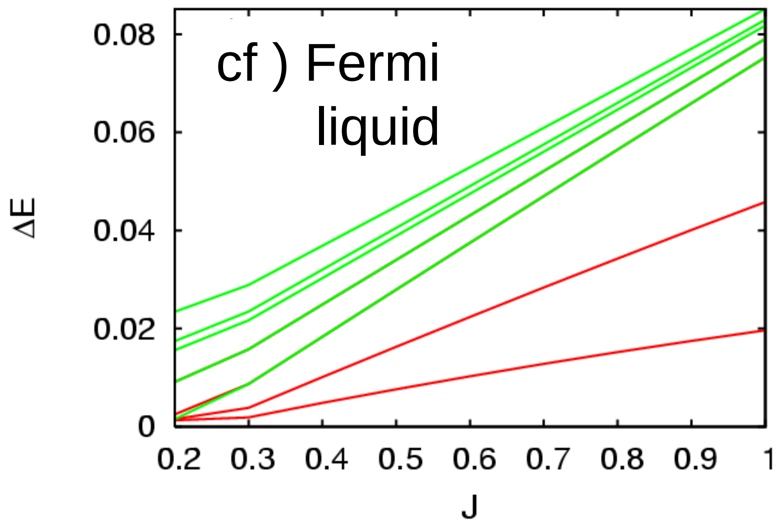
S(q) and N(q) are
consistent with Fermi surface

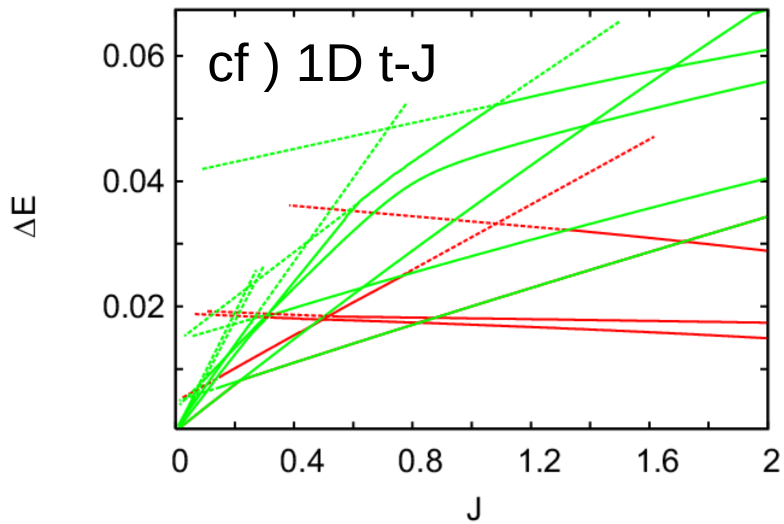
Excitation energy





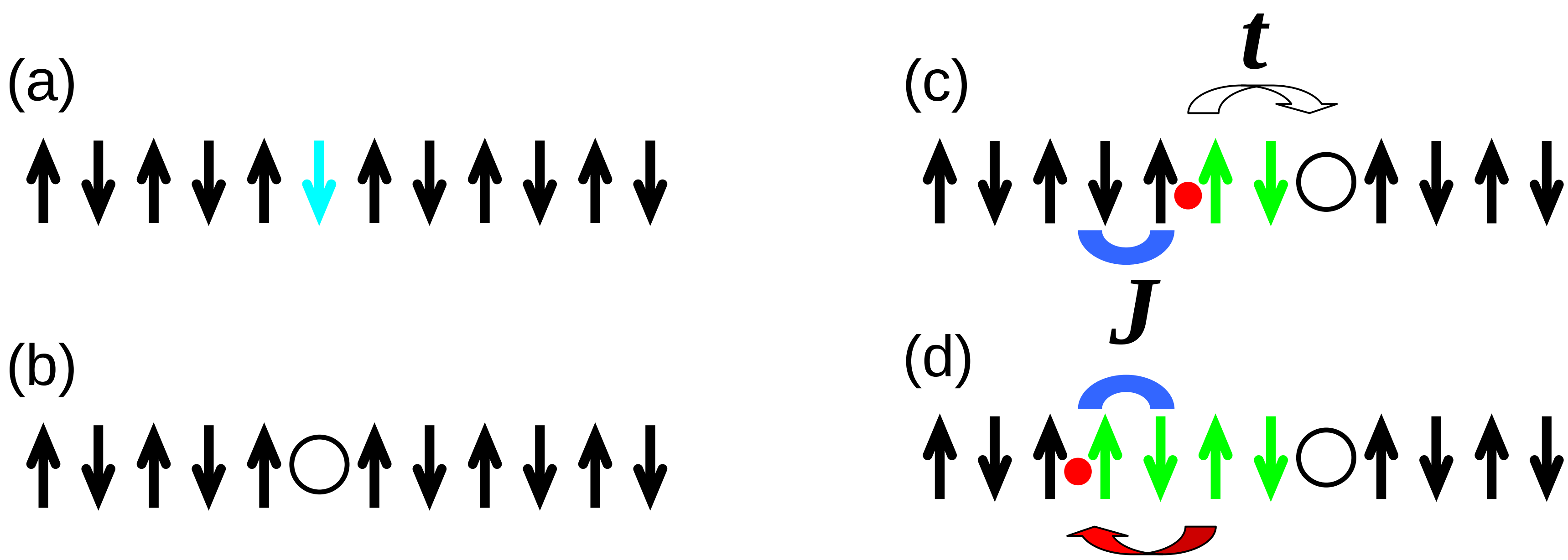
ordinary





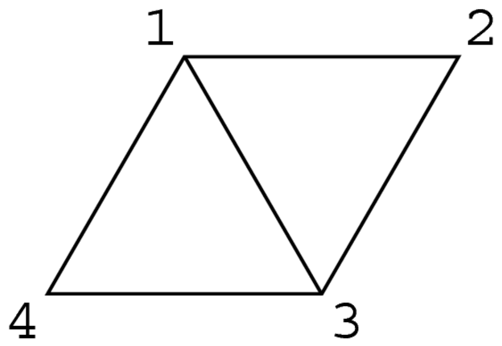
Spin-Charge separation in 1-dim

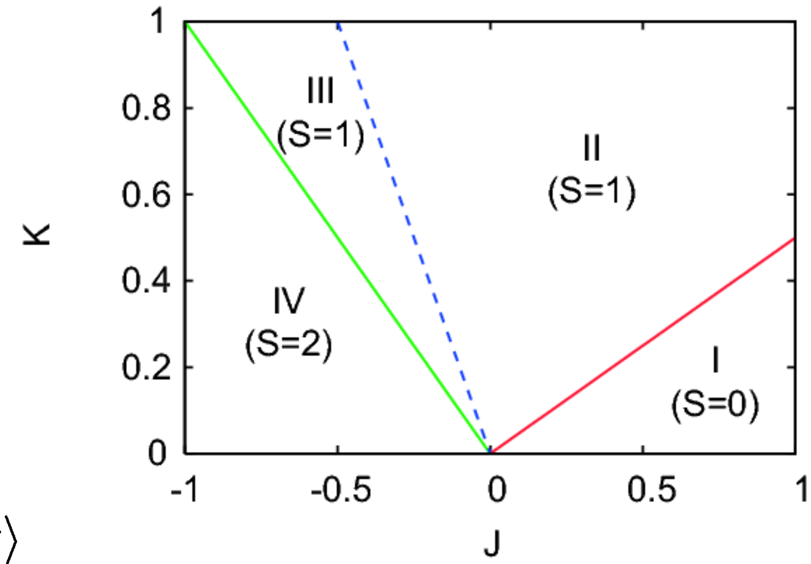
Tomonaga-Luttinger liquid



Similar situation can be considered in the *t*-*J*-*K* model !

4-site cluster





S=0

$$-J + 2K \quad |\uparrow\uparrow\downarrow\downarrow + \downarrow\downarrow\uparrow\uparrow + \uparrow\downarrow\downarrow\uparrow + \downarrow\uparrow\uparrow\downarrow - 2\,\uparrow\downarrow\uparrow\downarrow - 2\,\downarrow\uparrow\downarrow\uparrow\rangle$$

S=1

$$J \quad |\uparrow\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow\uparrow\rangle$$

$$3J \quad |\uparrow\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow\uparrow\rangle$$

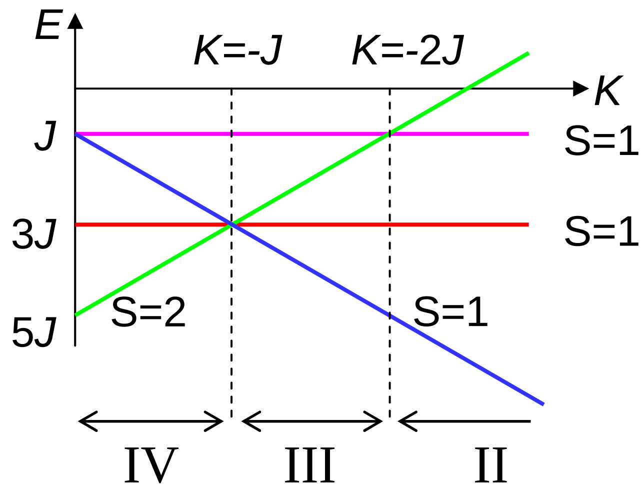
$$J - 2K \quad |\uparrow\uparrow\uparrow\downarrow - \uparrow\uparrow\downarrow\uparrow + \uparrow\downarrow\uparrow\uparrow - \downarrow\uparrow\uparrow\uparrow\rangle$$

S=2

K (ring) dominant case

$$5J + 2K \quad |\uparrow\uparrow\uparrow\uparrow\rangle$$

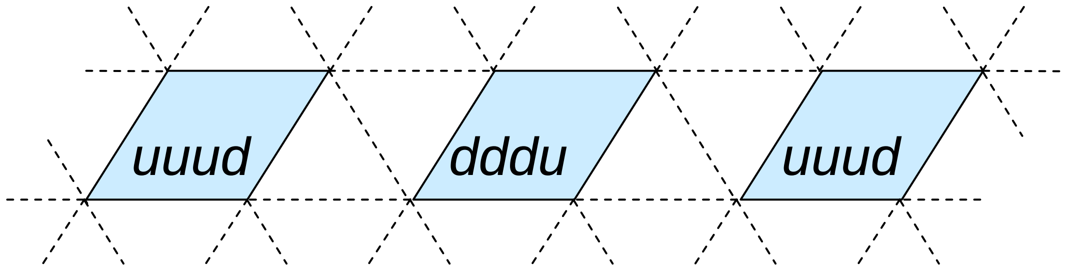
J (<0) dominant case (Ferro)

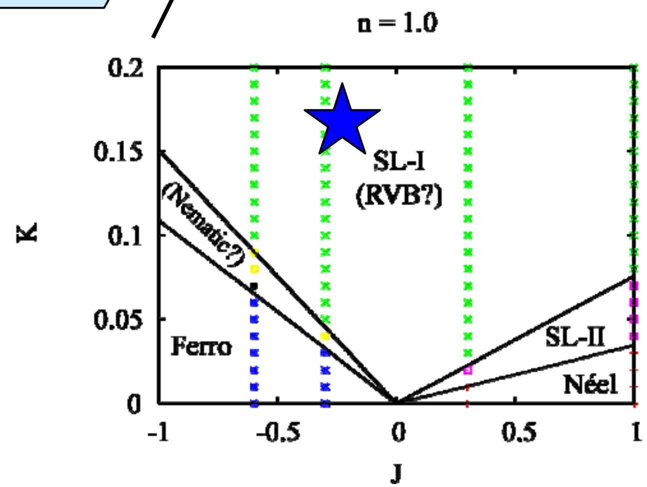


Plaquette approximation

***K*-dominant case** $|\uparrow\uparrow\uparrow\downarrow - \uparrow\uparrow\downarrow\uparrow + \uparrow\downarrow\uparrow\uparrow - \downarrow\uparrow\uparrow\uparrow\rangle$ $J - 2K$

SL-I RVB: | *uuud* *dddu* − *dddu* *uuud* ⟩

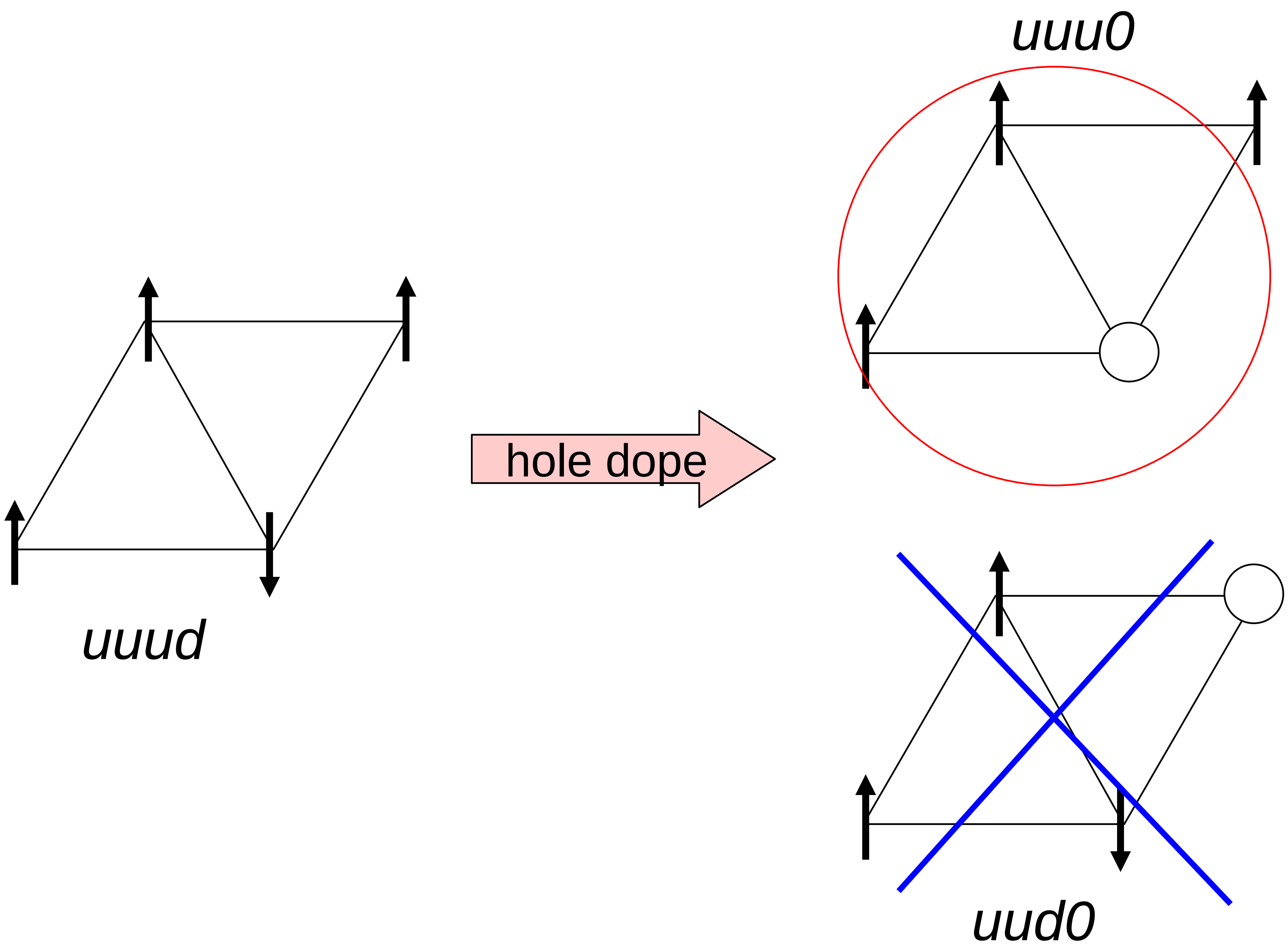




$|\uparrow\uparrow\uparrow\downarrow - \uparrow\uparrow\downarrow\uparrow + \uparrow\downarrow\uparrow\uparrow - \downarrow\uparrow\uparrow\uparrow\rangle$ = *uuud*

u3d1 state

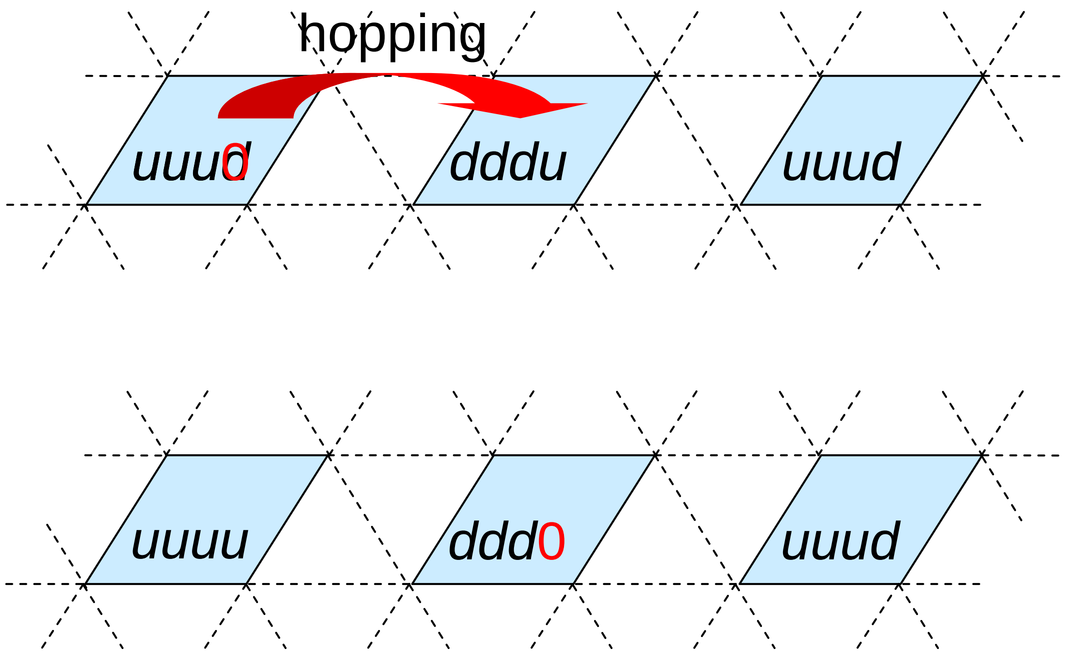
Hole-doped plaquette

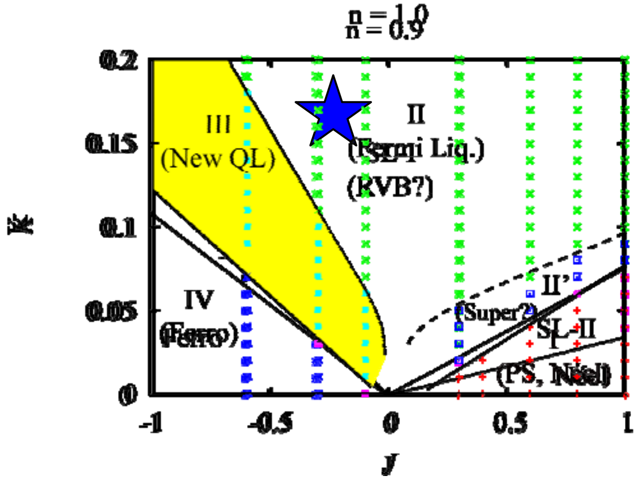


Plaquette approximation

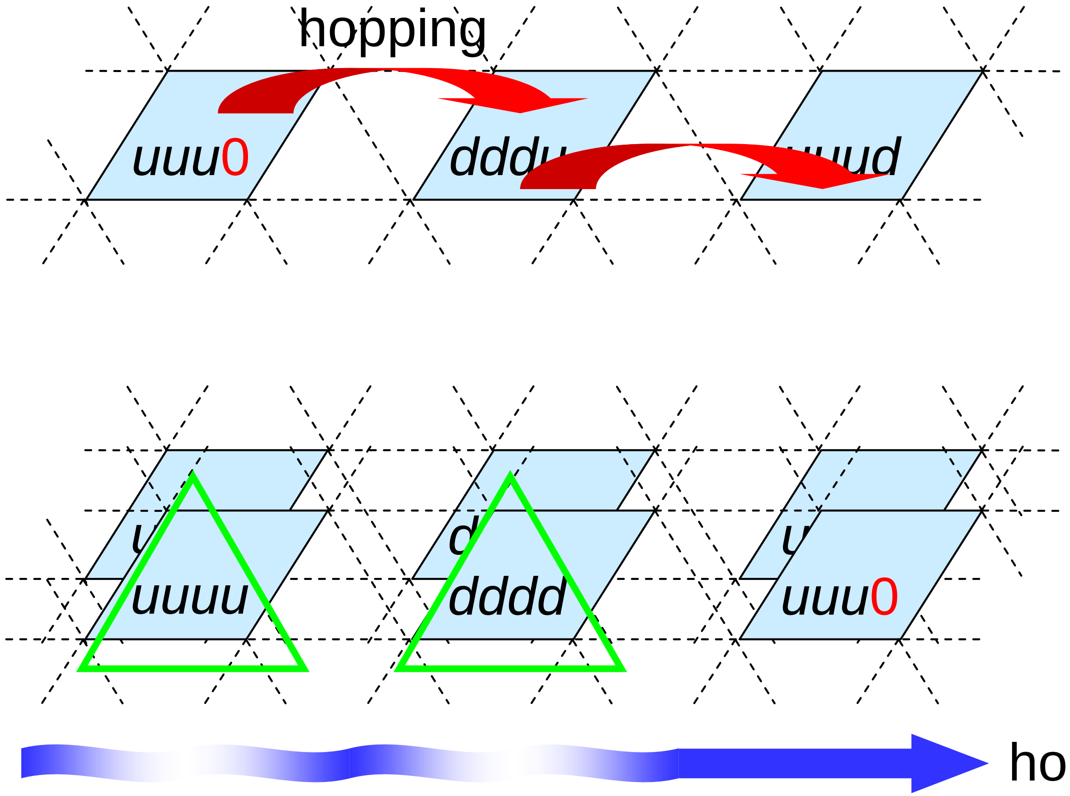
***K*-dominant case** $|\uparrow\uparrow\uparrow\downarrow - \uparrow\uparrow\downarrow\uparrow + \uparrow\downarrow\uparrow\uparrow - \downarrow\uparrow\uparrow\uparrow\rangle$ $J - 2K$

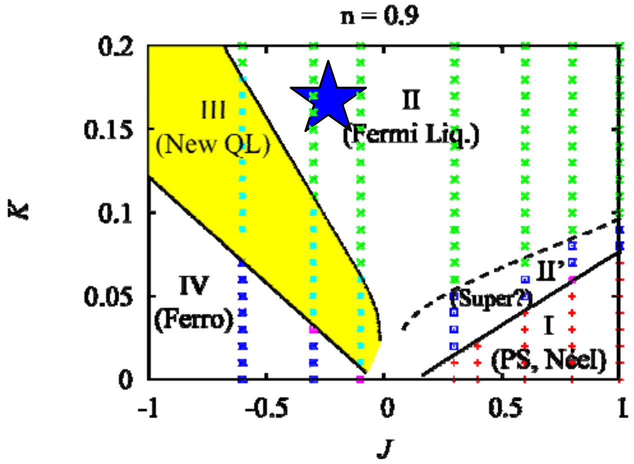
Hole doping





Plaquette approximation





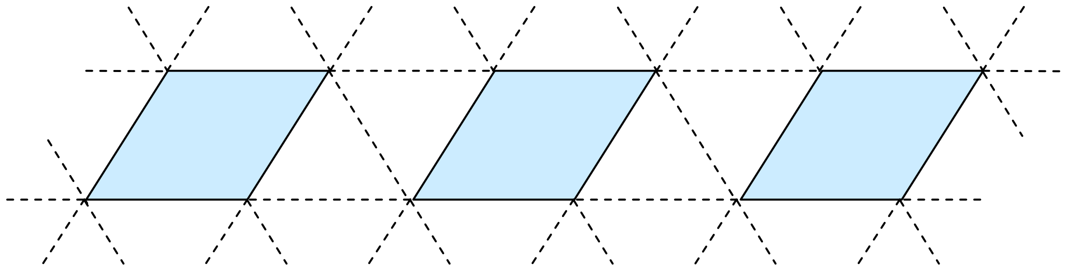
Unfavored spin states remains. ⇨ spin-charge binding: Fermi liquid

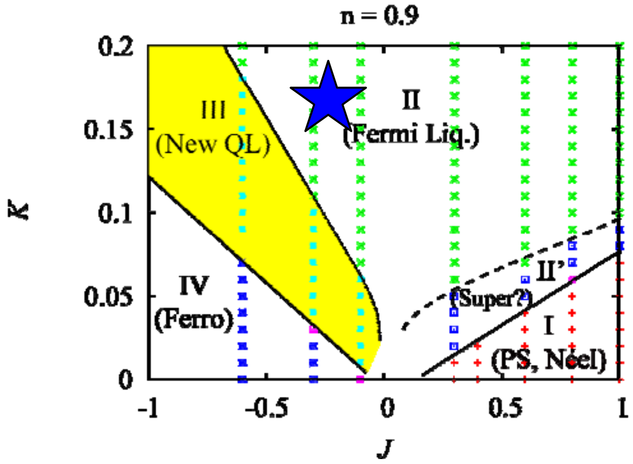
Plaquette approximation

***J*-*K*-competing case** $|\uparrow\uparrow\uparrow\downarrow - \uparrow\uparrow\downarrow\uparrow + \uparrow\downarrow\uparrow\uparrow - \downarrow\uparrow\uparrow\uparrow\rangle$ *uuud*

almost degenerate $|\uparrow\uparrow\uparrow\uparrow\rangle$ *uuuu*

Hole doping





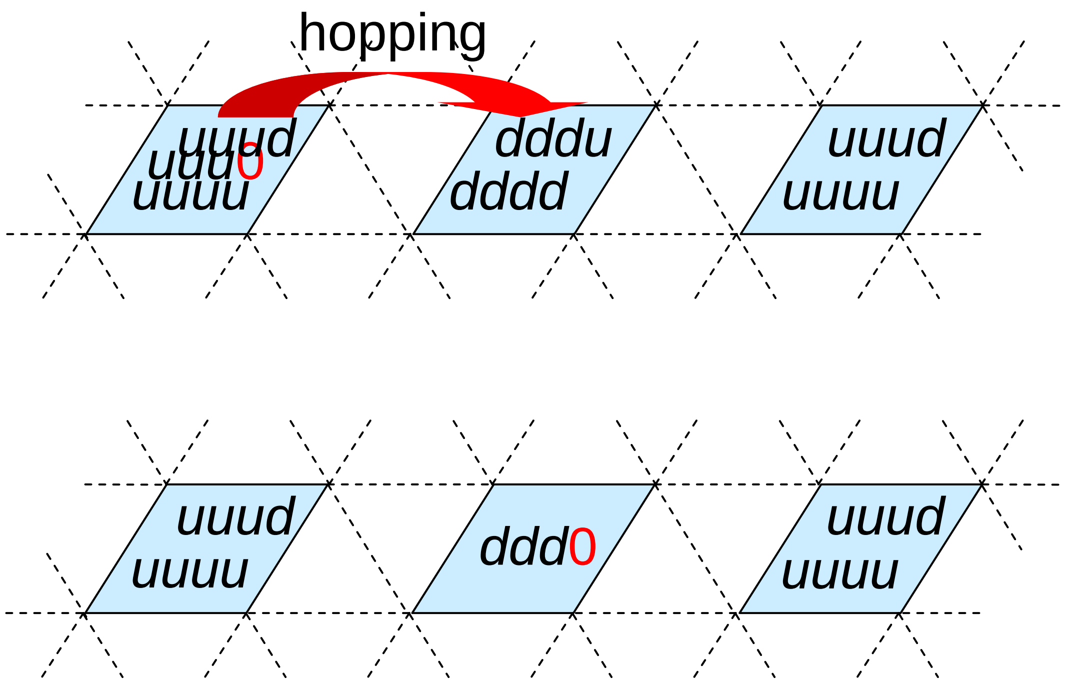
Plaquette approximation

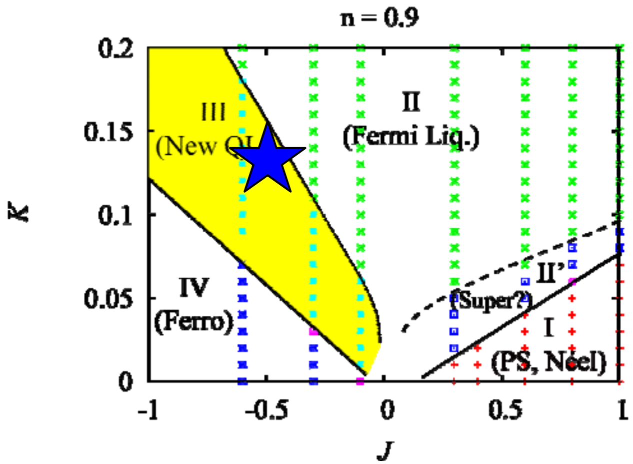
***J*-*K*-competing case**

$|\uparrow\uparrow\uparrow\downarrow - \uparrow\uparrow\downarrow\uparrow + \uparrow\downarrow\uparrow\uparrow - \downarrow\uparrow\uparrow\uparrow\rangle$ *uuud*

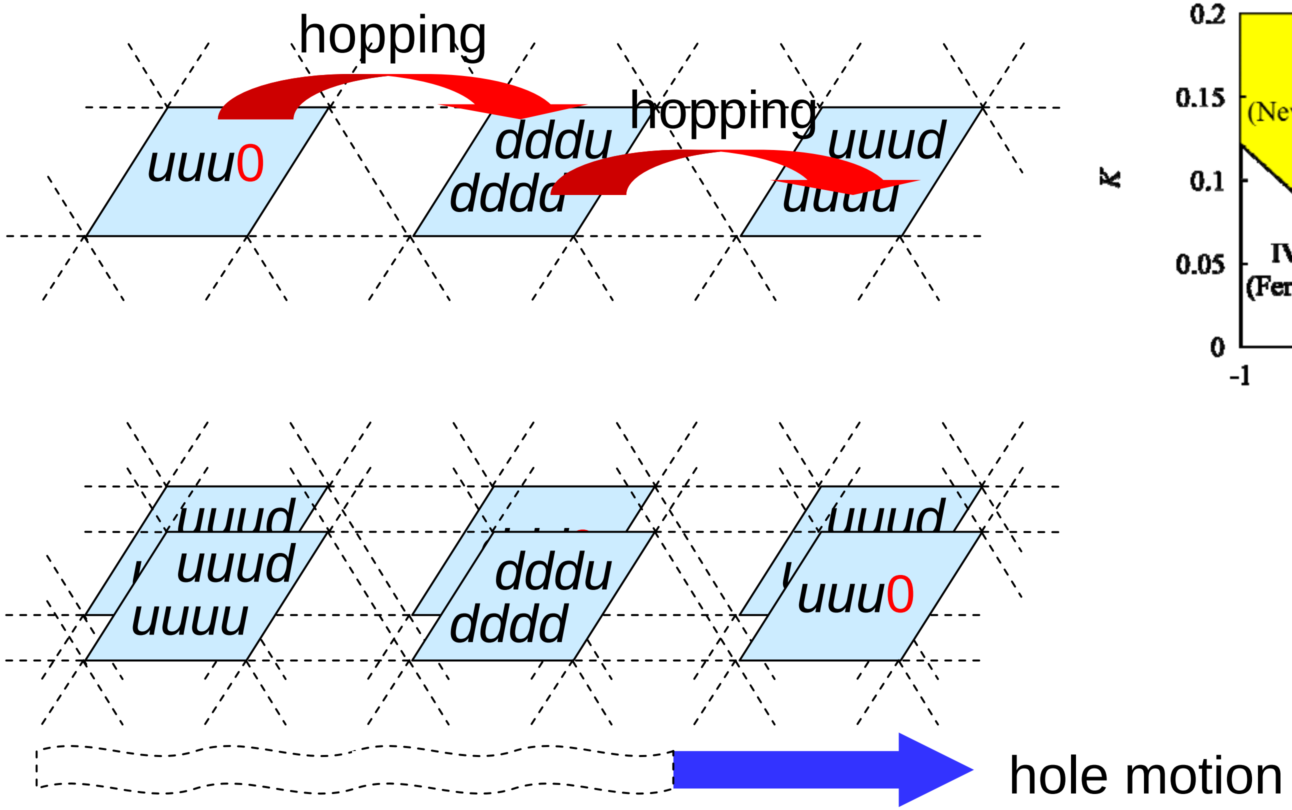
$|\uparrow\uparrow\uparrow\uparrow\rangle$ *uuuu*

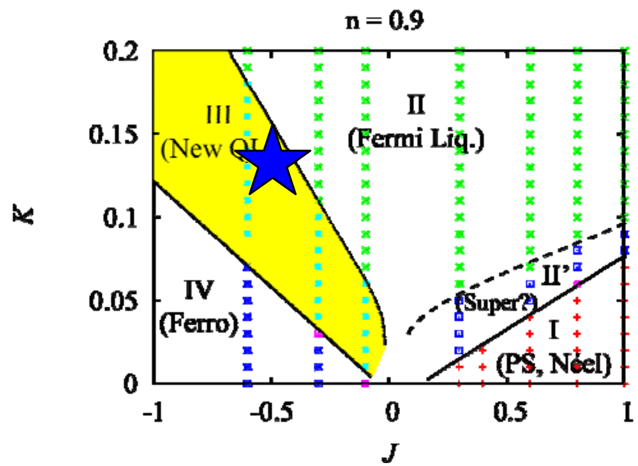
Hole doping





Plaquette approximation

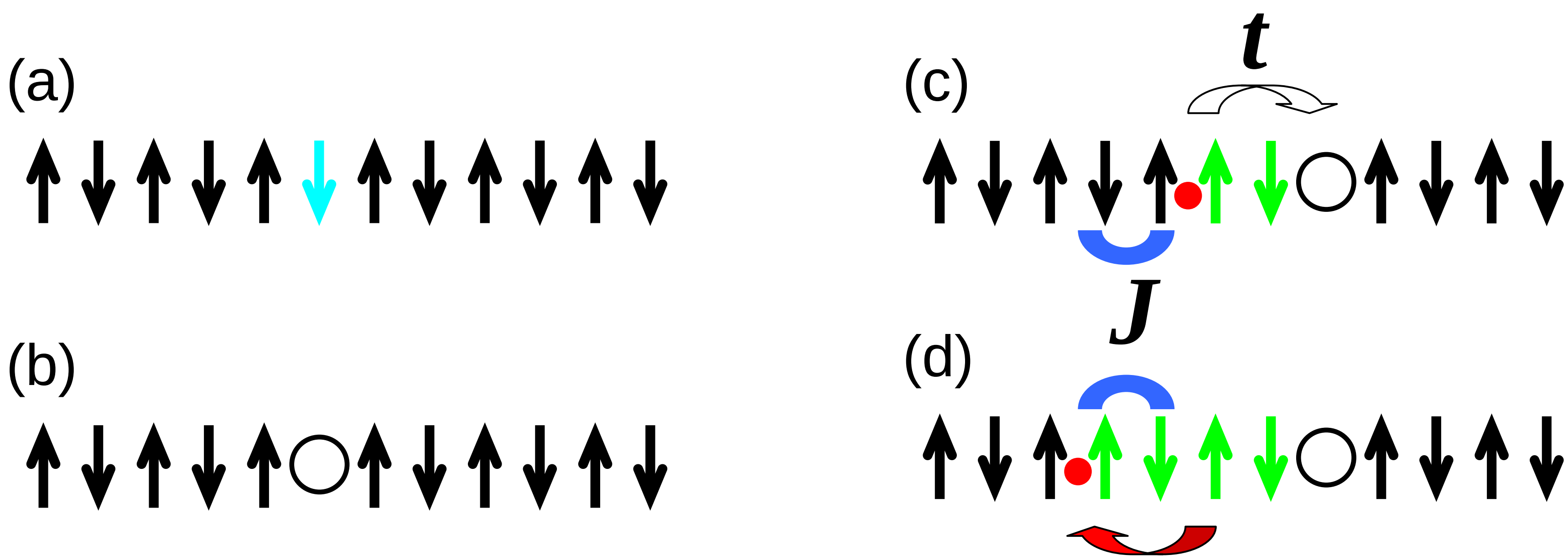




No trace of spin ⇨ spin-charge separation as in 1-dim : new state

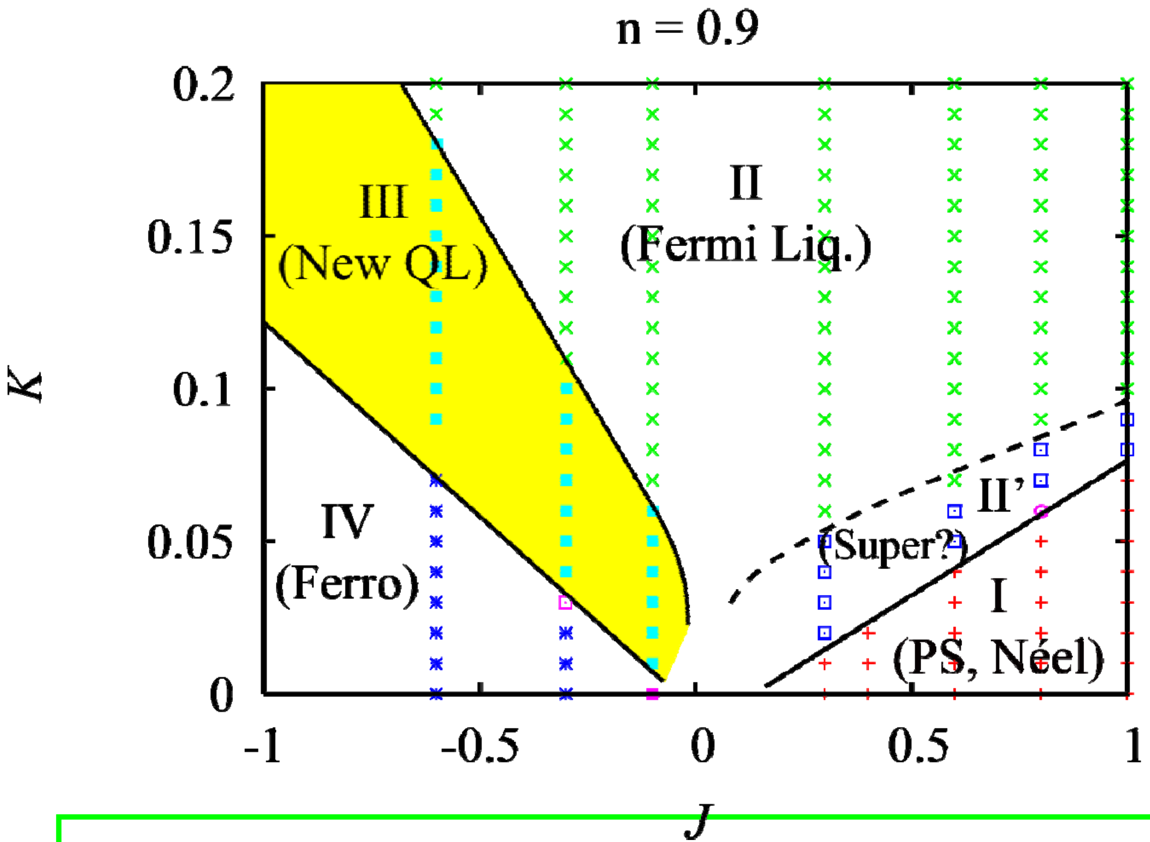
Spin-Charge separation in 1-dim

Tomonaga-Luttinger liquid



Similar situation in the *t*-*J*-*K* model

Summary



Fuseya-Ogata:
arXiv: 0804.4329
(JPSJ 78, 013601 (2009))

Doping dependence will be OK.

- **Triangular *t-J-K* model** (exact diagonalization, up to 20 site)
- **New state** (between Ferro and Fermi liquid)
- **Spin-charge separation** (*J* vs. *K*, consistent with 2D ^{3}He double peak in C)