Strong pairing from small Fermi surface:
possible application to bilayer nickelate

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Outline

(I) introduction to Nickelate $La_3Ni_2O_7$

(II) Small Fermi surface in a bilayer model

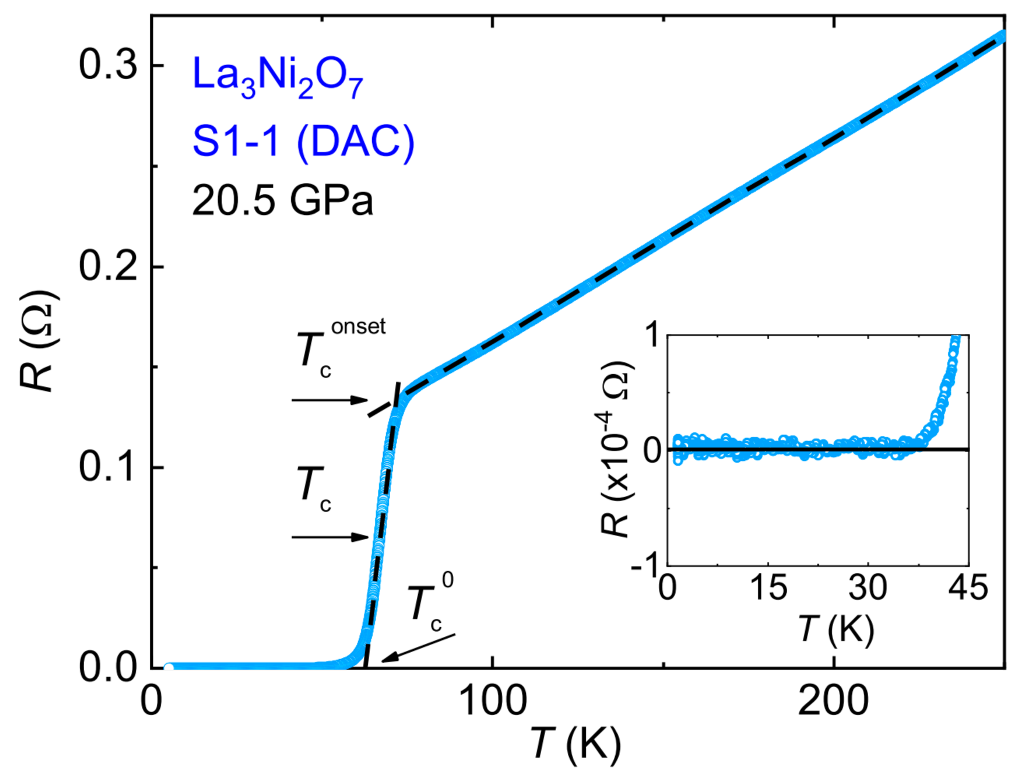
(III) Superconductivity from Feshbach resonance

(IV) Deconfined Fermi liquid to Fermi liquid transition

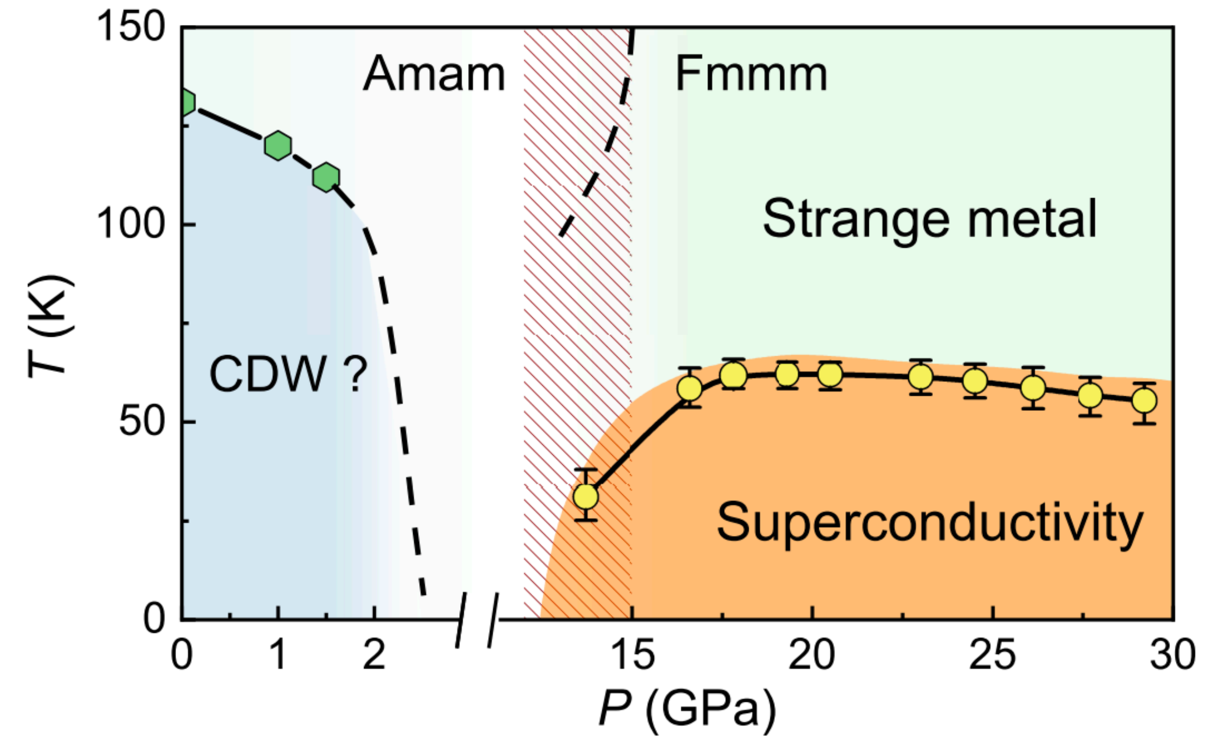
Bilayer nickelate $La_3Ni_2O_7$

80K superconductor under pressure

H. Sun, et.al, Meng Wang, Nature (2023)



Y.Zhang, et.al, Huiqiu Yuan, arxiv:2307.14819



Superconductor emerges after a structure phase transition

My assumption: pressure is not essential other than stabilizing the crystal

Bilayer model for La3Ni2O7

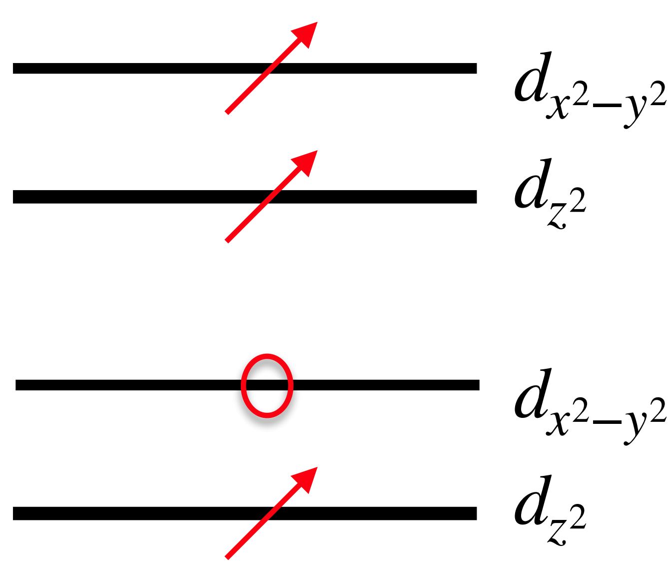
Bilayer square lattice

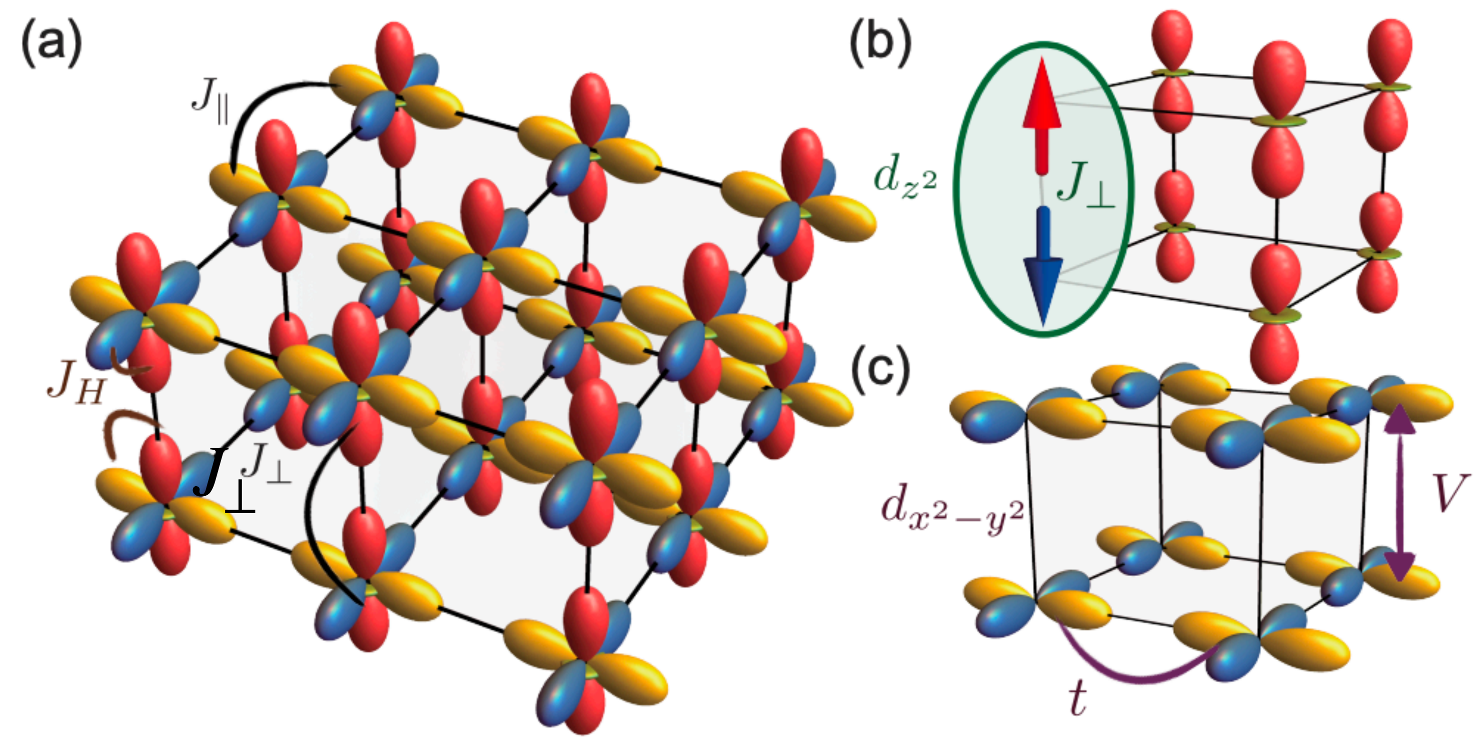
density per site (per layer): $3d^{8-x}$, x=0.5

$$H_{d_{z^2}} = J_\perp \sum_i . \vec{S}_{i;t} \cdot \vec{S}_{i;b}$$

x=0:

x=1:





d_{z^2} is Mott localized and form rung singlet!

We only care about d_{x^2-y^2} orbital; Hund's rule transmit the $J_\perp$

For d_{x^2-y^2}: strong $J_\perp$, but negligible $t_\perp$

Effective model for $d_{x^2-y^2}$ orbital

Bilayer t-J model **(Ignorance of d_{z^2} is quantitatively not appropriate)**

$$H = -t \sum_{l,\sigma,\langle ij \rangle} P c^{\dagger}_{i;l;\sigma} c_{j;l;\sigma} P + J_{\parallel} \vec{s}_{i;l} \cdot \vec{s}_{i;l}$$

$$+ J_{\perp} \sum_{i} \vec{s}_{i;t} \cdot \vec{s}_{i;b} + V \sum_{i} n_{i;t} n_{i;b}$$

$n = 1 - x$

$J_{\perp} = V = 0$, two decoupled t-J model, no superconductor at x=0.5

We are interested in the strong $J_{\perp}$ regime

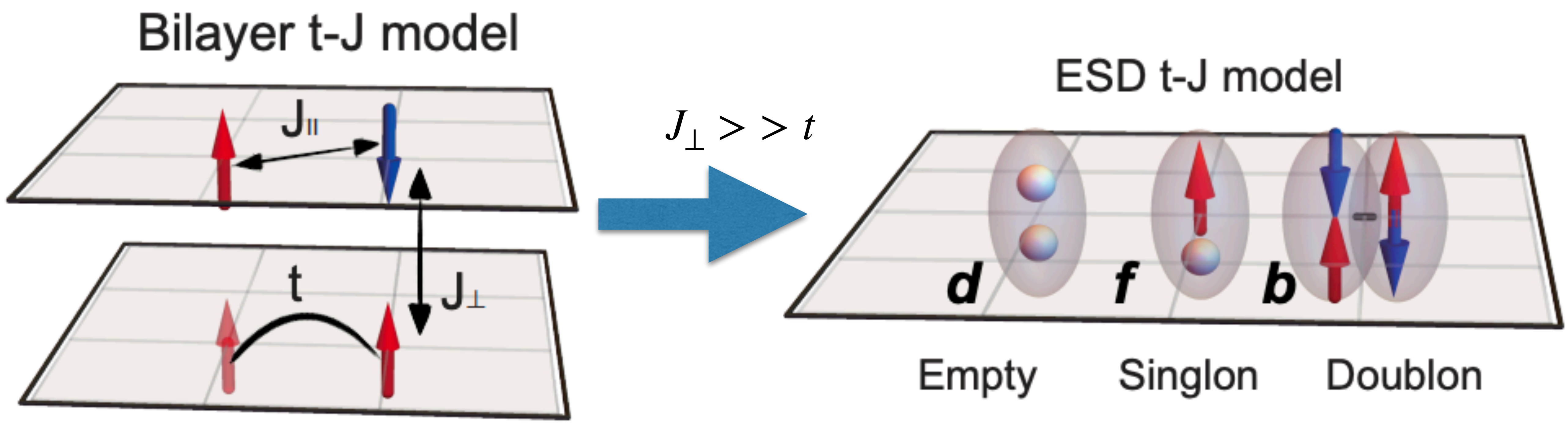
$$J_{\perp} \gtrsim t,\ V \gtrsim J_{\perp}$$

We add V so the net interaction is still repulsive.

ESD t-J model at large $J_\perp >> t$

Six states per rung:

Strong coupling approach!



Empty	Singlon	Doublon
$n_T = 0$	$n_T = 1$	$n_T = 2$
$S = 0$	$S = 1/2$	$S = 0$

$|d> = d_i^\dagger |0>$ $\quad$ $|b> = b_i^\dagger |0>$

$|l, \sigma> = f_{i;l\sigma}^\dagger |0>$

Projected electron operator:

(Generalized slave boson)

$$c_{i;l,\uparrow} = d_i^\dagger f_{i;l,\uparrow} + \frac{1}{\sqrt{2}} f_{i,\bar{l},\downarrow}^\dagger b_i,$$

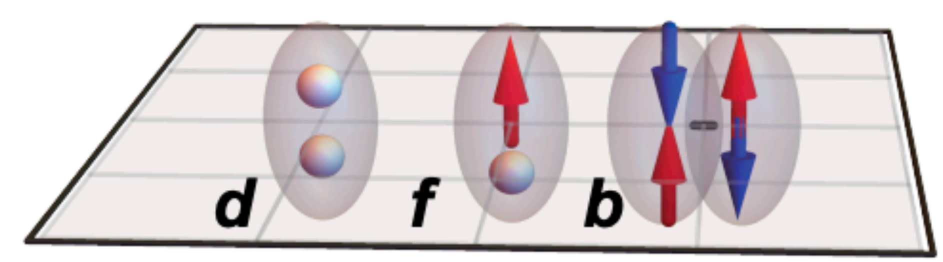
$$c_{i;l\downarrow} = d_i^\dagger f_{i;l,\downarrow} - \frac{1}{\sqrt{2}} f_{i;\bar{l},\uparrow}^\dagger b_i,$$

Generalized slave boson theory

$$H = -t \sum_{l;\langle ij\rangle} P c^{\dagger}_{i;l;\sigma} c_{j;l;\sigma} P + \sum_i \epsilon (n_{d;i} + n_{b;i}),$$

$$\epsilon = \frac{V - \frac{3}{4} J_{\perp}}{2}$$

ESD t-J model



Empty Singlon Doublon

One single parameter ϵ / t, we focus on $\epsilon > 0$

Substituting the electron operator:

$$H = -t \sum_{l,\langle i,j\rangle} \left[f^{\dagger}_{i,l,\uparrow} d_i + \frac{b^{\dagger}_i f_{i,\bar{l},\downarrow}}{\sqrt{2}} \right] \left[d^{\dagger}_j f_{j;l,\uparrow} + \frac{f^{\dagger}_{j,\bar{l},\downarrow} b_j}{\sqrt{2}} \right]$$

$$+ \left[f^{\dagger}_{i,l,\downarrow} d_i - \frac{b^{\dagger}_i f_{i,\bar{l},\uparrow}}{\sqrt{2}} \right] \left[d^{\dagger}_j f_{j;l,\downarrow} - \frac{f^{\dagger}_{j,\bar{l},\uparrow} b_j}{\sqrt{2}} \right]$$

$$+ \sum_i \delta_f n_{f;i} + \delta_d n_{d;i} + \delta_b n_{b;i}.$$

Local constraint:

$$n_{i;b} + n_{i;d} + n_{i;f} = 1$$

Average density:

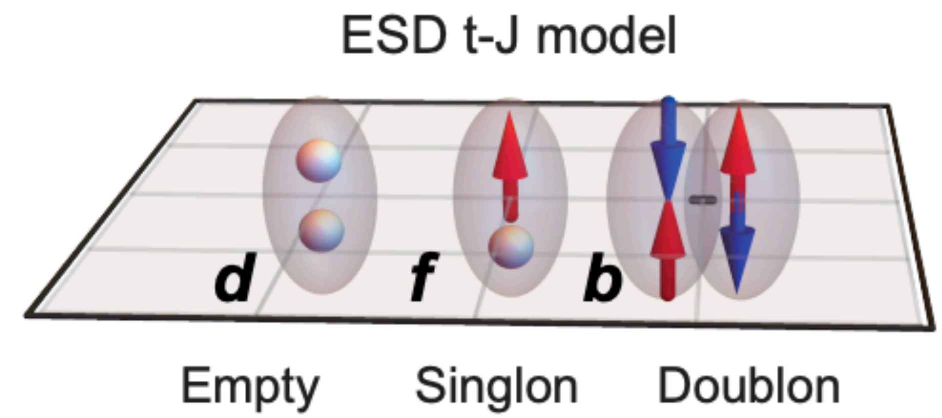
$$n_f + 2 n_d = 2x$$

Generalized slave boson mean field phase diagram

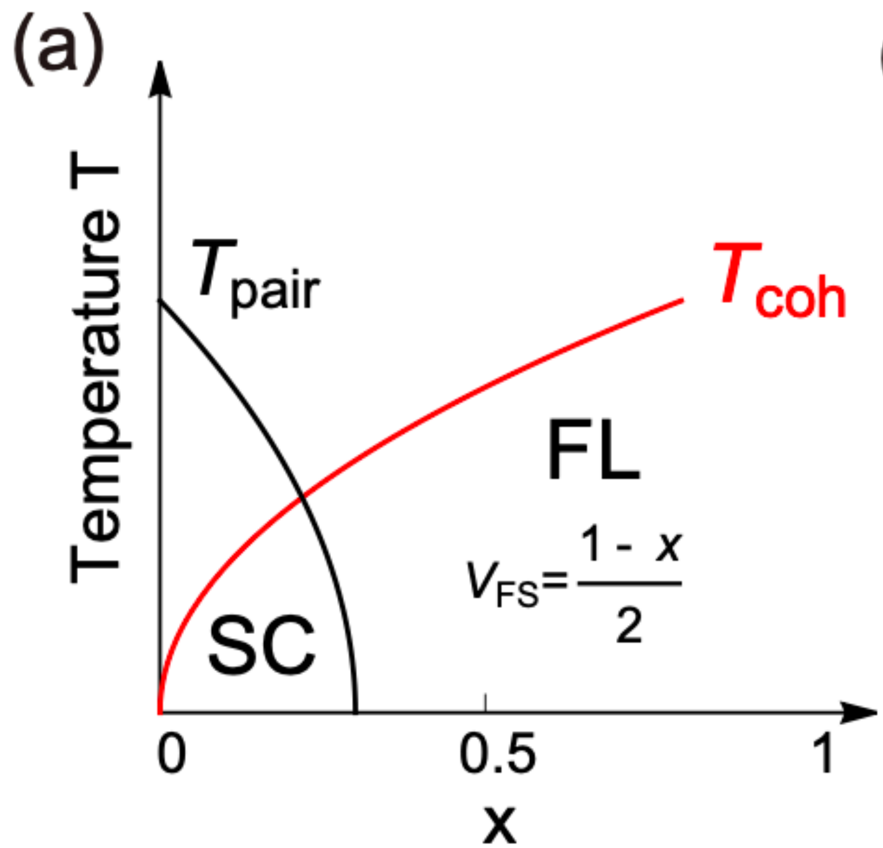
Mean field

$$H_M = H_b + H_d + H_f$$

$$H_f = -t_f \sum_{ij} f^\dagger_{i;l} f_{j;l} - \Delta_f \sum_{ij} \epsilon_{\sigma\sigma'} c_{i;t\sigma} c_{j;b\sigma'} + h.c.$$

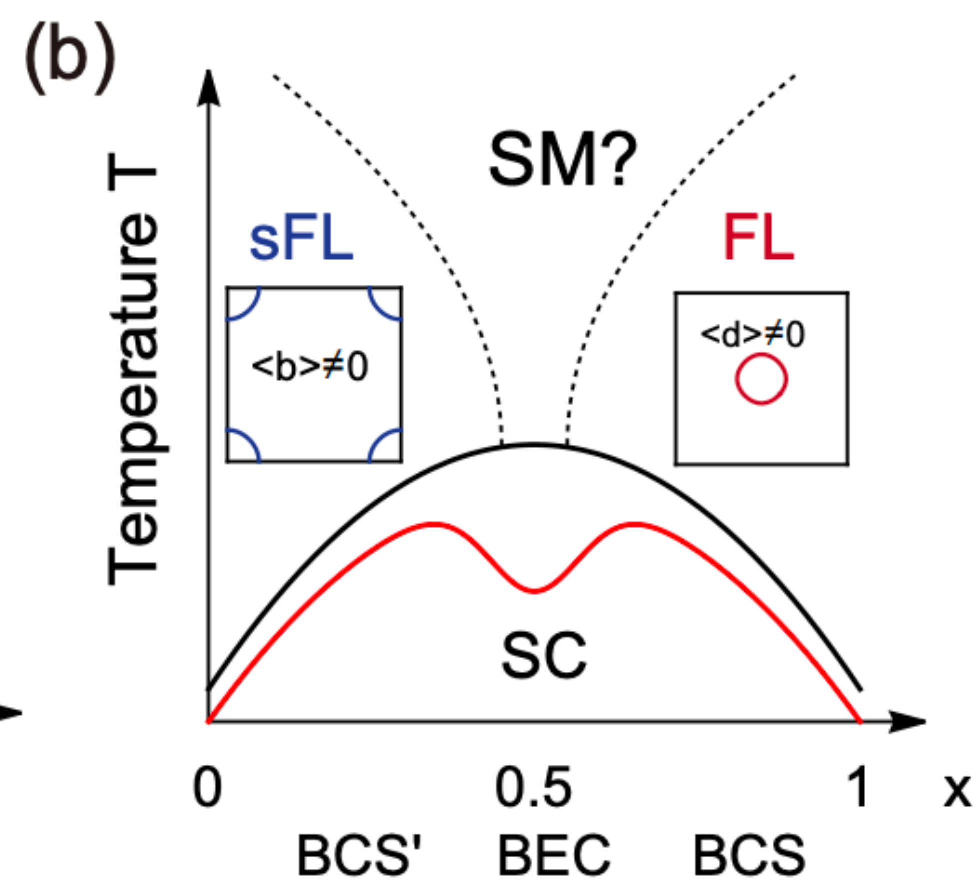


Single layer t-J model



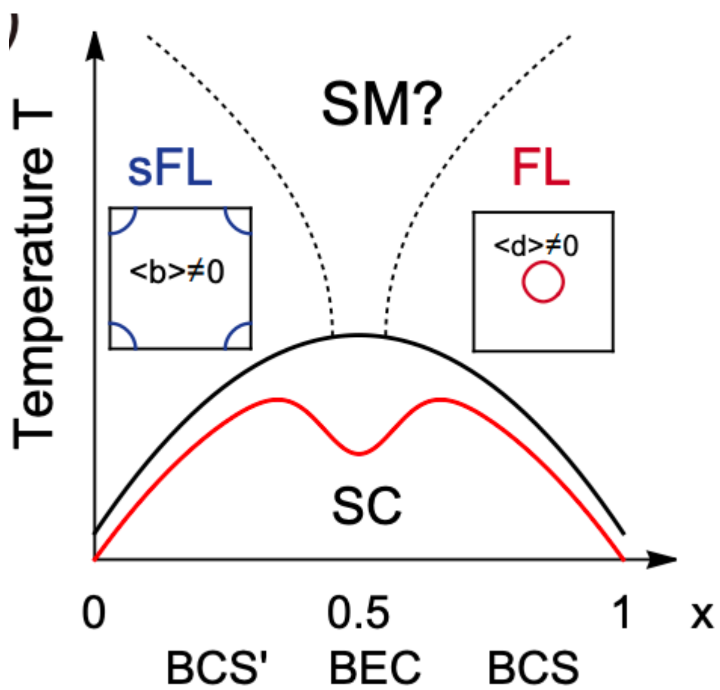
$$n = 1 - x$$

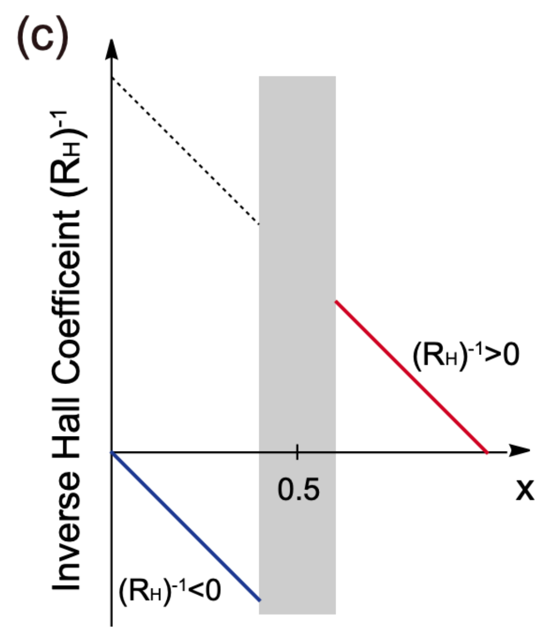
Bilayer ESD t-J model

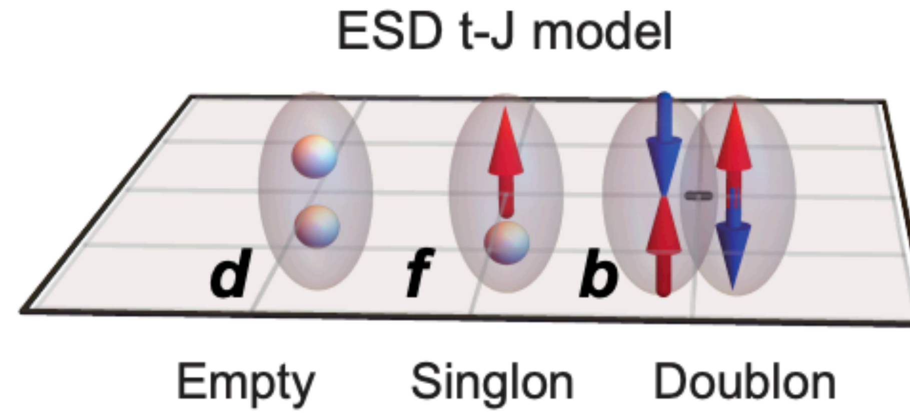


$$n_T = 2 - 2x$$

sFL: Fermi liquid with small Fermi surface







Symmetry: $(U(1)_t \times U(1)_b \times SU(2))/Z_2$ also a layer exchange symmetry

Four copies of Fermi surfaces $\nu = \frac{1-x}{2}$

Oshikawa-Luttinger theorem: Symmetric and Featureless (no fractionalization)

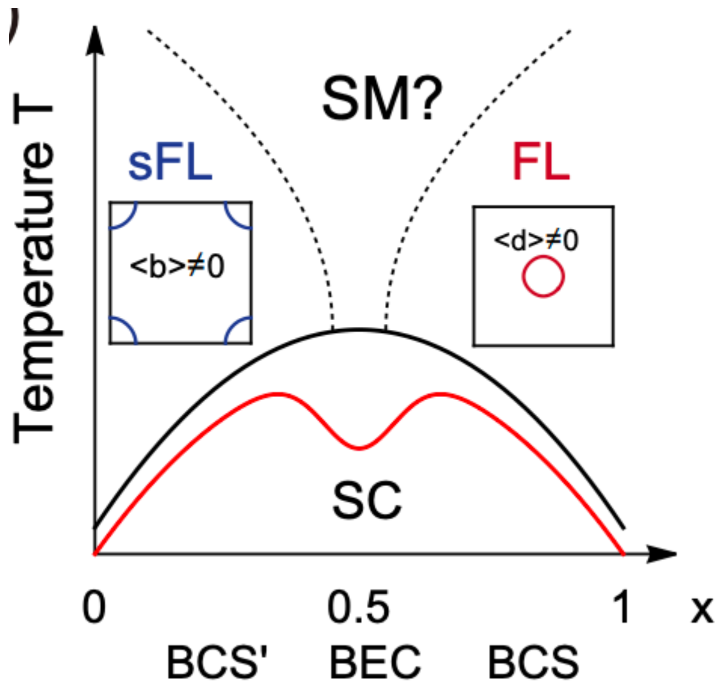
FL **sFL**

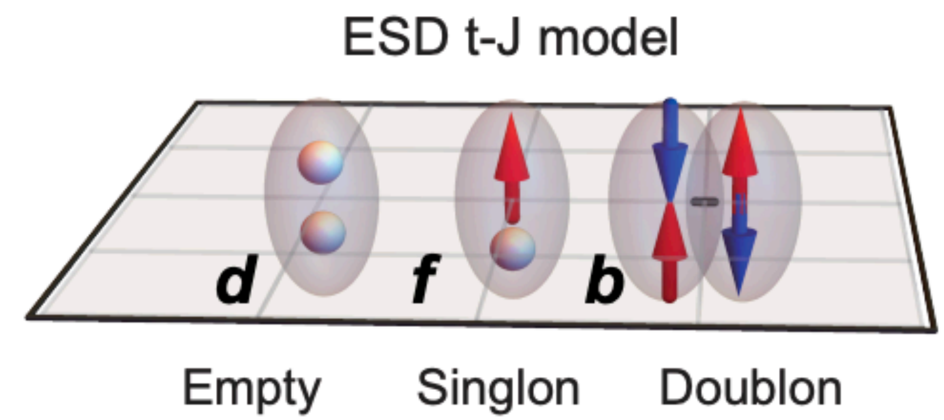
$$A_{FS} - \nu = 0 \;\; or \;\; 1/2$$

Two distinct Fermi liquids for this symmetry! **(Closely related to SMG)**

sFL is clearly beyond any weak coupling theory **(RVB physics without RVB)**

Superconductivity from Feshbach resonance





Start from sFL phase, substituting $b = \langle b \rangle$

$$g = \frac{1}{\sqrt{2}} \langle b \rangle t$$

$$H = \sum_{\langle i,j \rangle} -g(d_i^\dagger + d_j^\dagger)(f_{i,b,\downarrow} f_{j,t,\uparrow} - f_{i,b,\uparrow} f_{j,t,\downarrow}) + h.c.$$

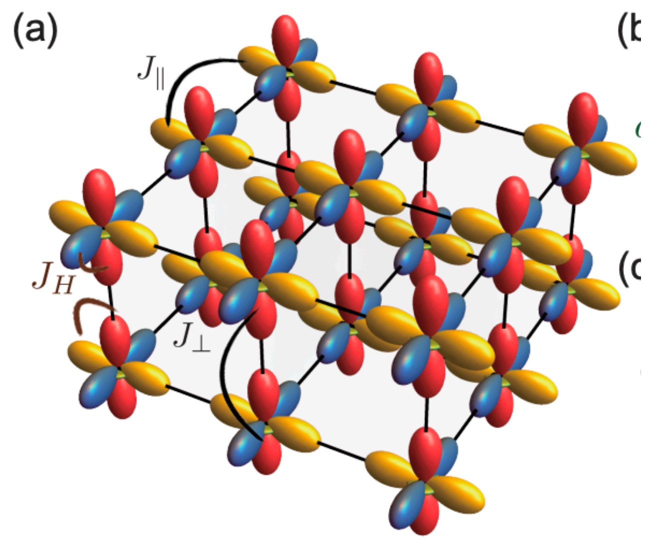
Integrating virtual Cooper pair d, $V_{eff} \sim -\frac{t^2}{\delta_d}$

(Inter-layer s'-wave)

$T_c \sim e^{-A\delta_d}$

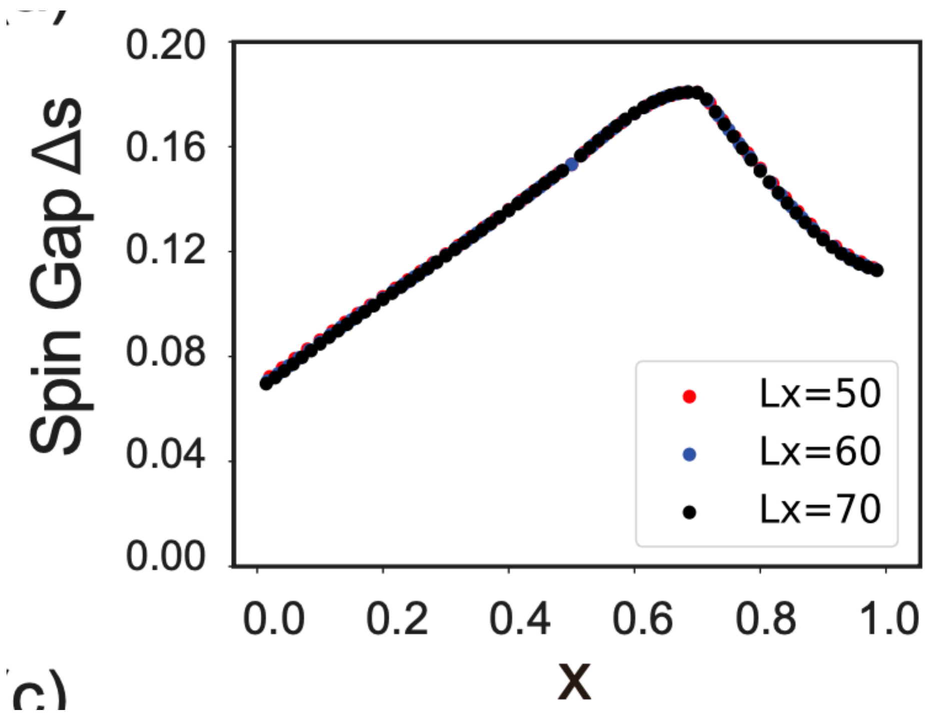
Going larger x, δ_d must decrease to 0; so pairing become stronger

DMRG evidence in 1D

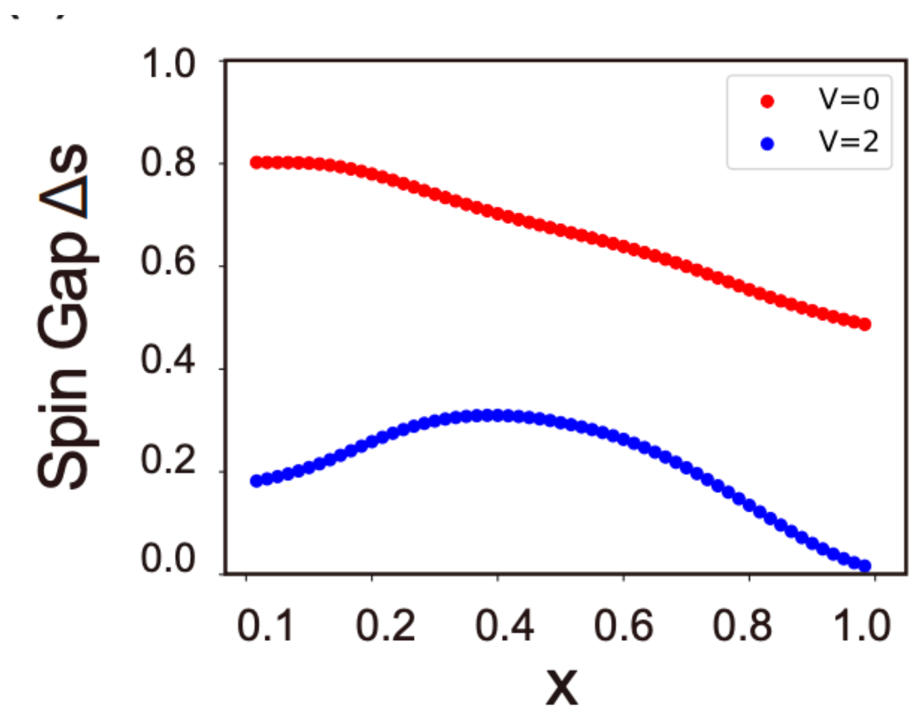


Bilayer type II t-J model with $L_z = 2,\ L_y = 1,\ L_x \to \infty$

Type II t-J model: including both orbitals, take $J_H \to +\infty$



$t = 1,\ J_\perp = 1, V = 0$

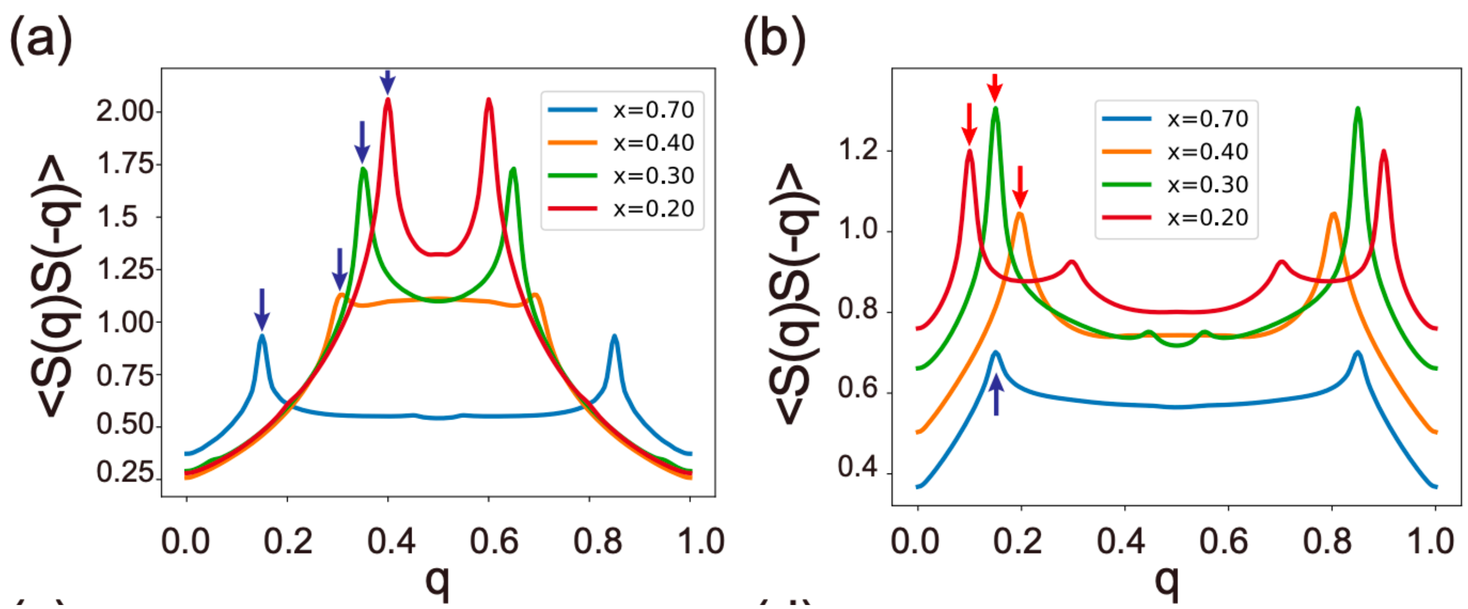


$t = 1,\ J_\perp = 5$

A Luther-Emery liquid for the entire x; Spin gap can reach 20% t

DMRG evidence of small Fermi surface

Suppressing pairing with V=100

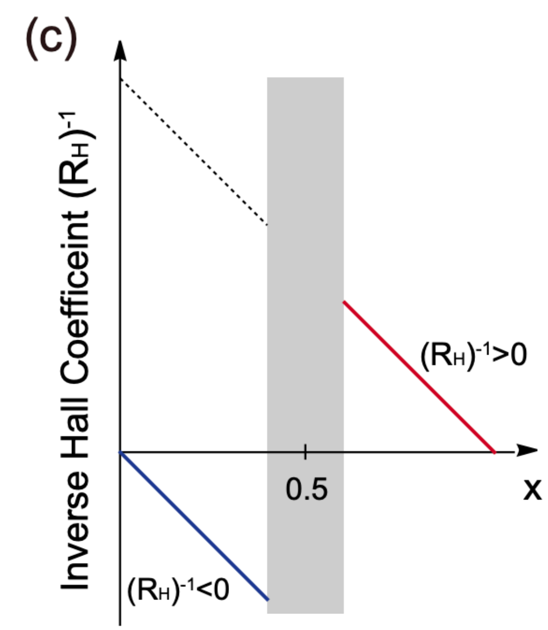


$2k_F$

$J_\perp = 0.5$ $\qquad$ $J_\perp = 4$

Small $J_\perp$: $2k_F = \dfrac{1-x}{2}$

Large $J_\perp$: $2k_F = \begin{cases} \dfrac{1-x}{2}, & \text{if } x > 0.5 \\ \dfrac{x}{2}, & \text{if } x < 0.5 \end{cases}$

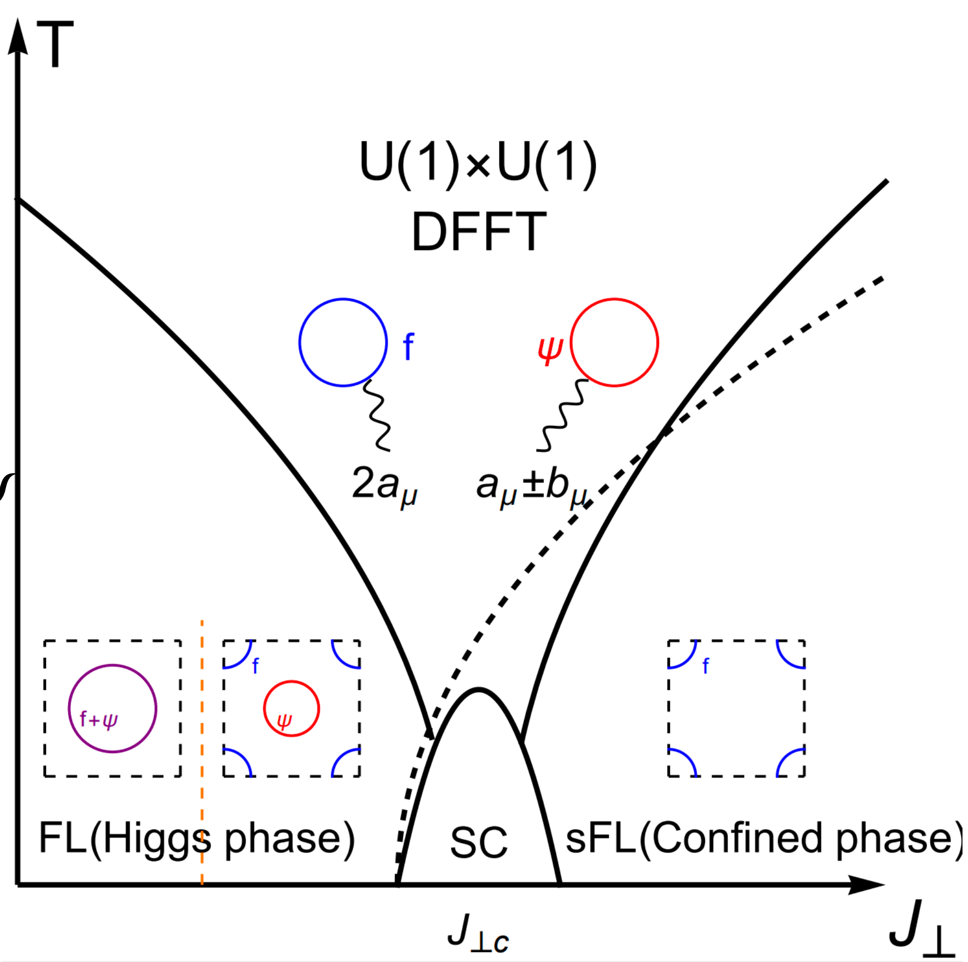


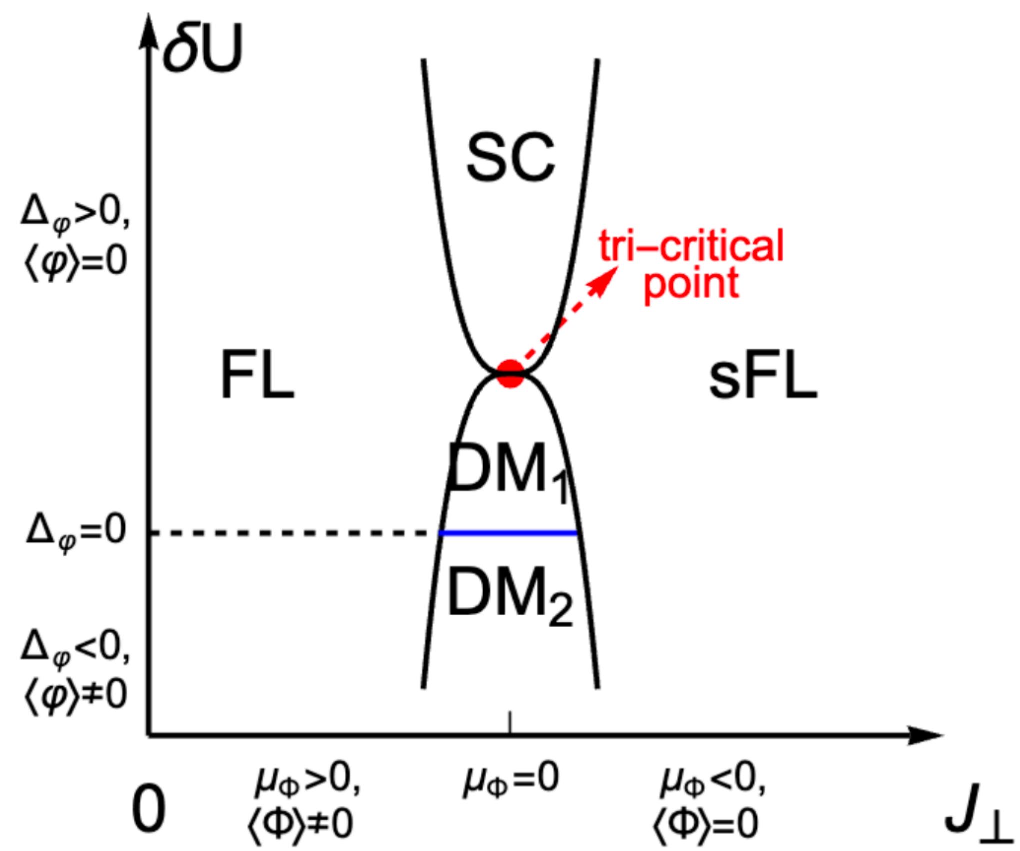
Deconfined Fermi liquid to Fermi liquid Transition

Fractionalization $$c_{i;a\sigma} = \sum_{\sigma'} f^{\dagger}_{i;\bar{a}\sigma'} \psi_{i;\bar{a}\sigma'} \psi_{i;a\sigma}.$$

$U(1) \times U(1)$ Gauge theory

$$H_M = -\Phi f^{\dagger} \psi$$





DM: deconfined metal phase

Deconfined tri-criticality down to zero T?

Summary

(I) Nickelate La3Ni2O7 is described by a simple bilayer model

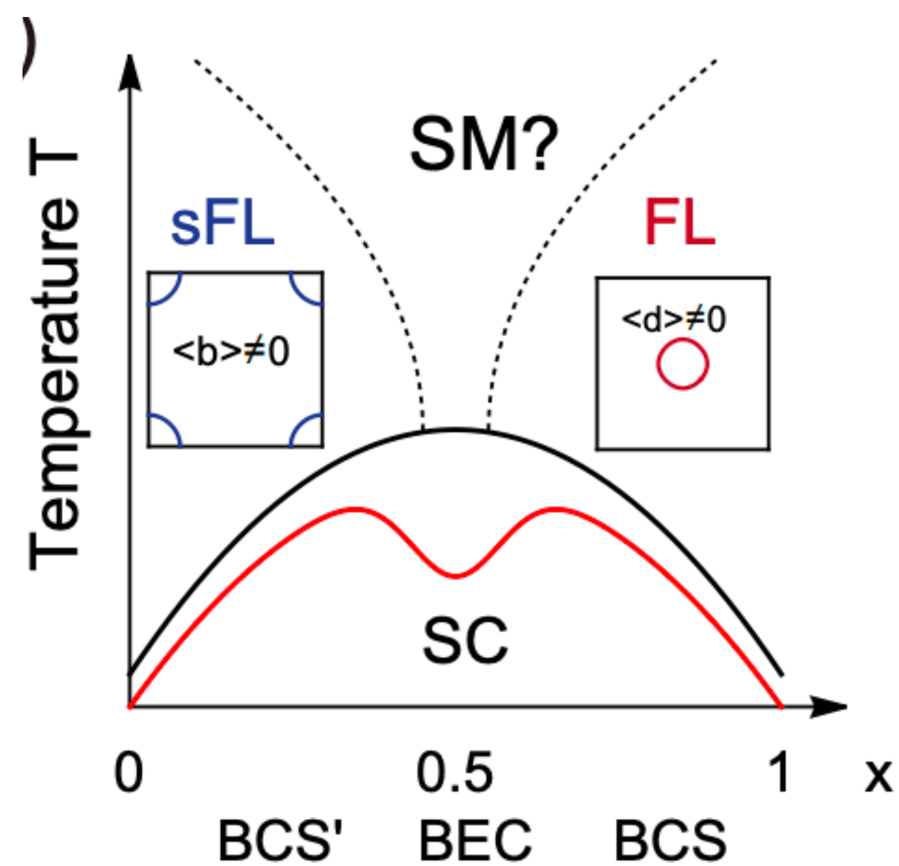
Physics of bilayer is actually much simpler than single layer

(II) Unambiguous theory of small Fermi surface phase

Analog of PG metal in cuprate

(III) Robust superconductor

(IV) Small to large Fermi surface transition?



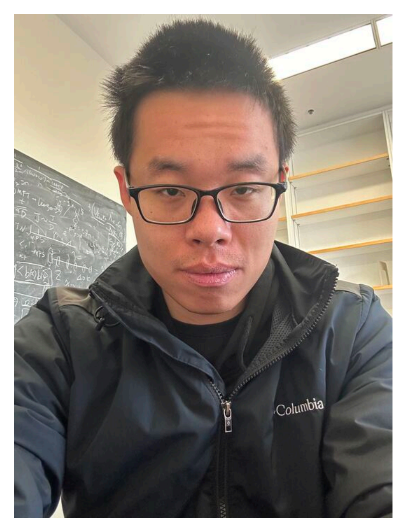
Acknowledgement

Hanbit Oh, and Ya-Hui Zhang. "Type-II t− J model and shared superexchange coupling from Hund's rule in superconducting $La_3Ni_2O_7$." *Physical Review B* 108.17 (2023)

Hui Yang*, Hanbit Oh*, and Ya-Hui Zhang. "Strong pairing from small Fermi surface beyond weak coupling: Application to $La_3Ni_2O_7$." arxiv:2309.15095 (2023)

Xiaofan Wu, Hui Yang, and Ya-Hui Zhang. “Deconfined Fermi liquid to Fermi liquid transition." to appear soon

Hanbit Oh



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