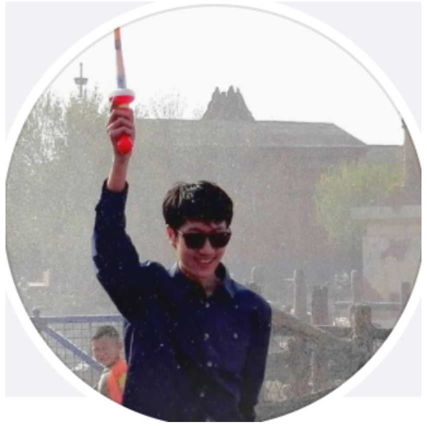
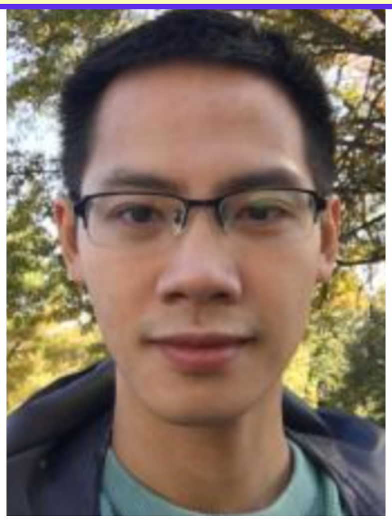
Strange Metals from Mottness

Thanks to:
NSF,DOE

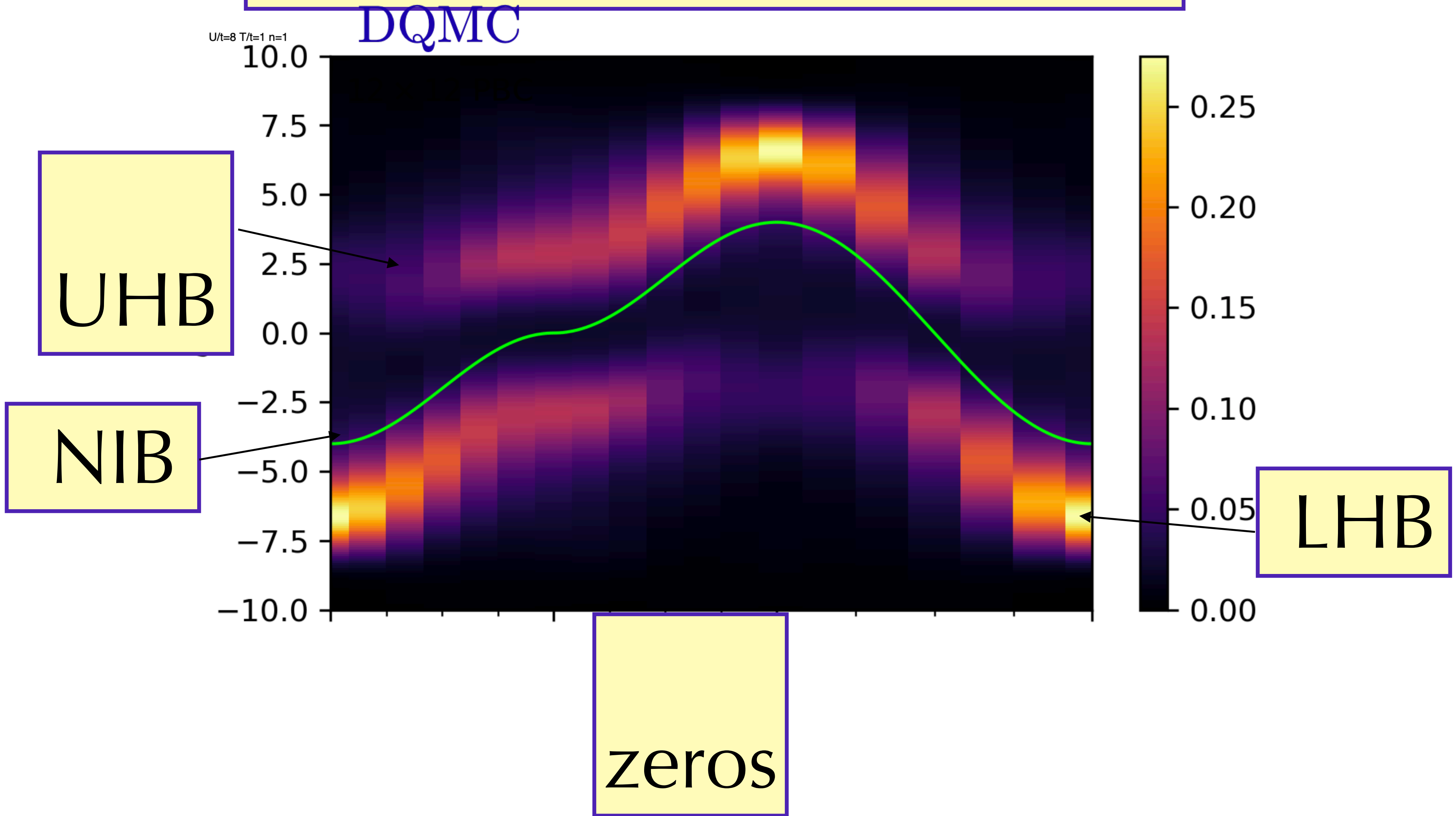
Jinchao Zhao



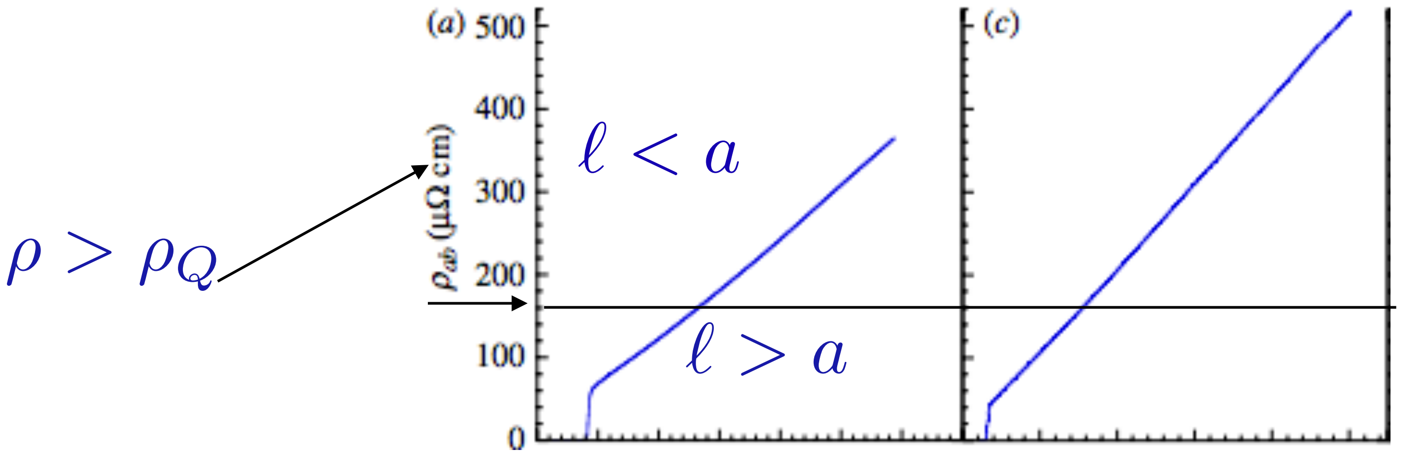
Peizhi Mai



effective momentum distribution?



T-linear



$\rho > \rho_Q$

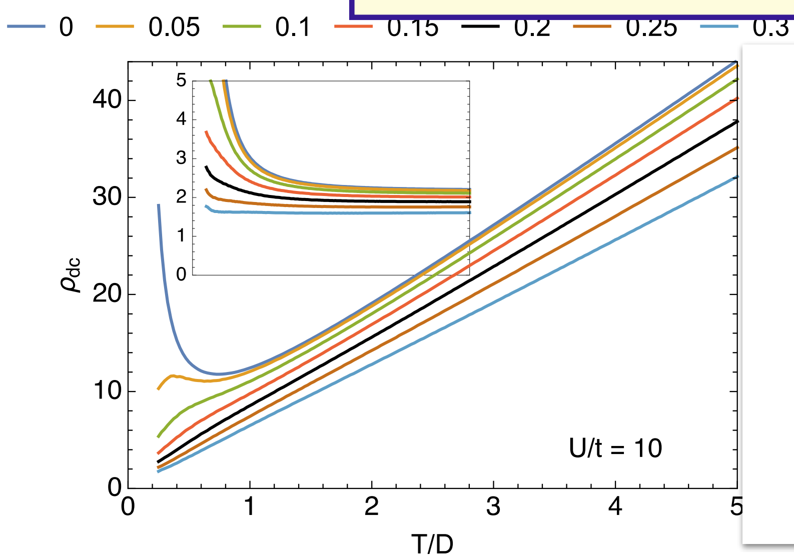
Violates MIR limit

electrons not charge carriers

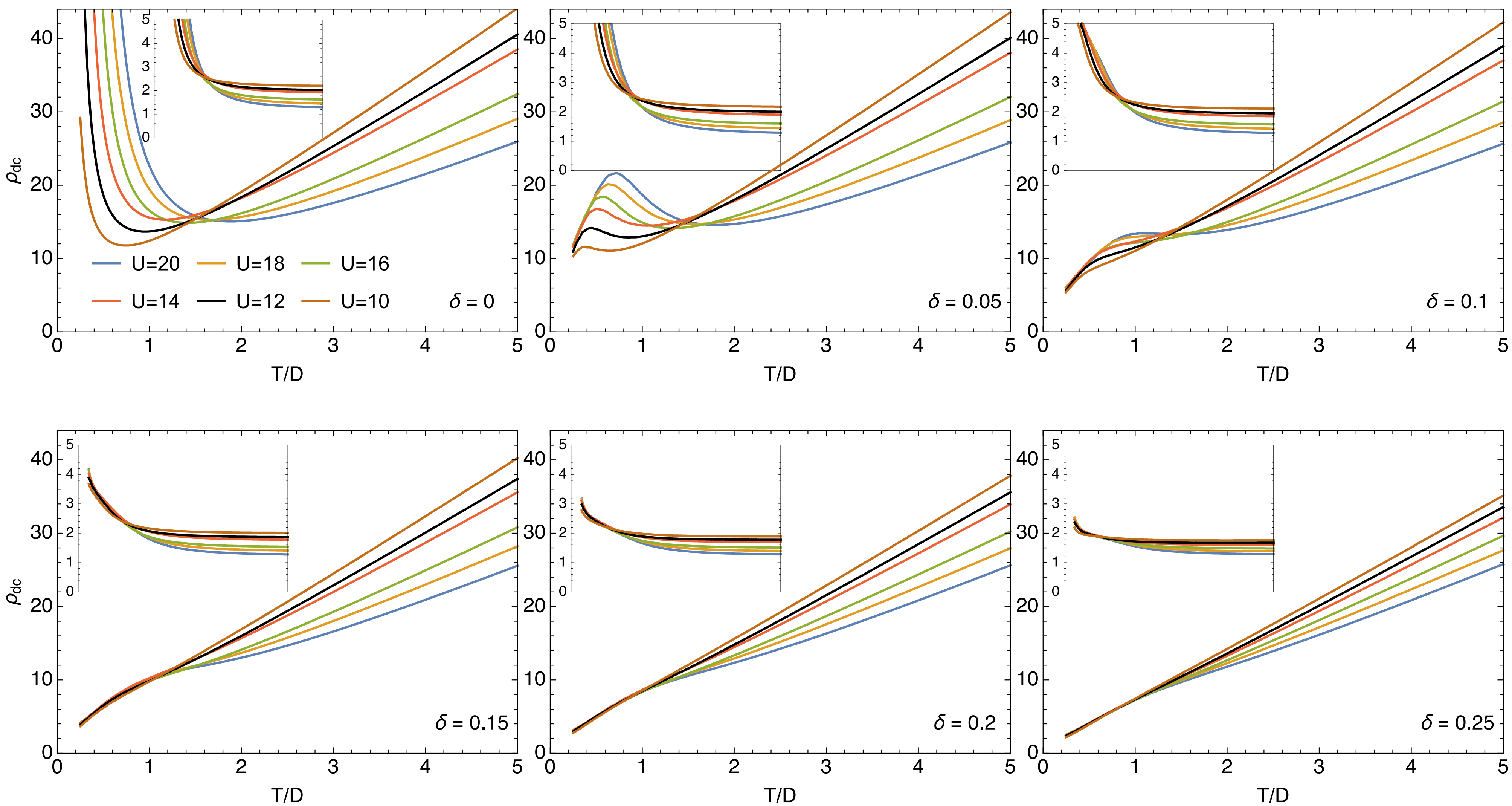
?

Finite-T Lanczos on Hubbard Model

Inset: $\rho_{dc}/(T/D)$



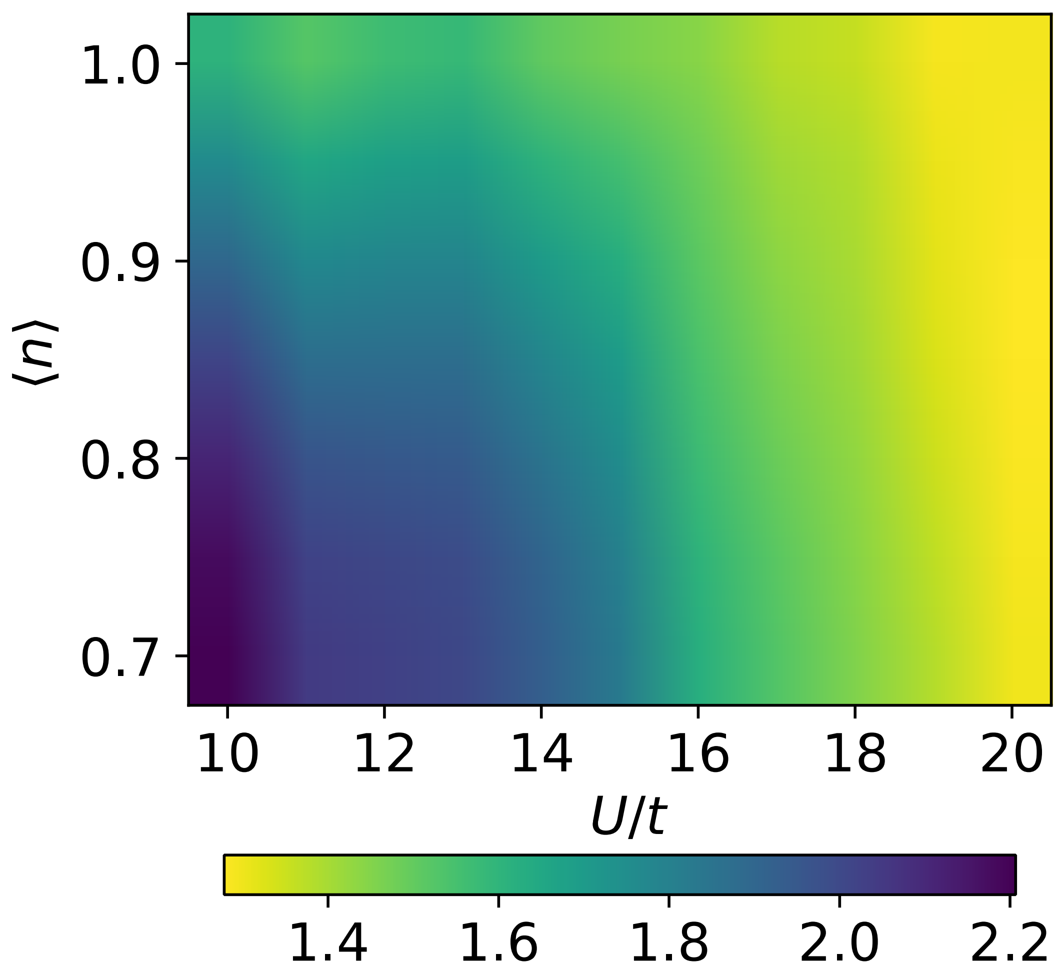
T/D



U=20
U=18
U=16
U=14
U=12
U=10
δ = 0
δ = 0.05
δ = 0.1
δ = 0.15
δ = 0.2
δ = 0.25
ρdc
T/D

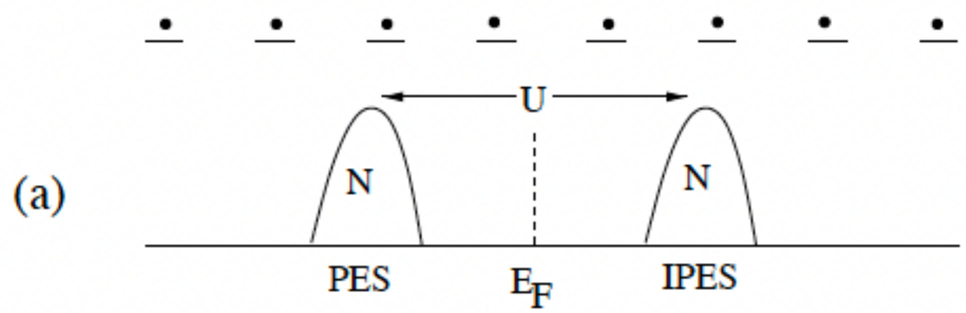
$\rho_{dc}/(T/D)$

At highest T



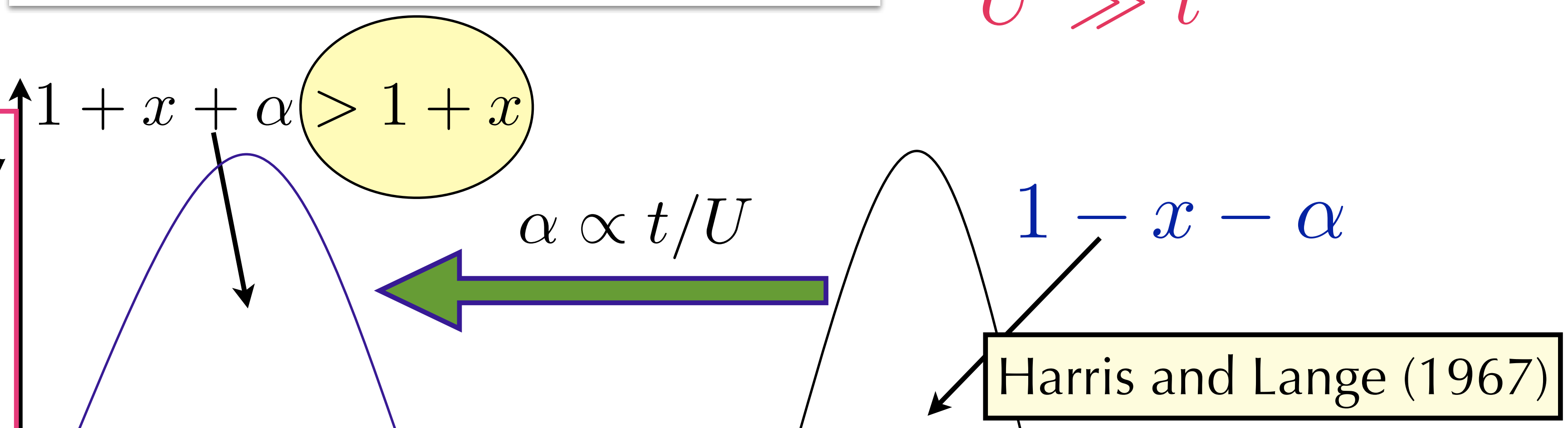
$$\frac{\rho_{\mathrm{dc}}}{T} = \alpha(t/U)$$

spectral function (dynamics)



$U \gg t$

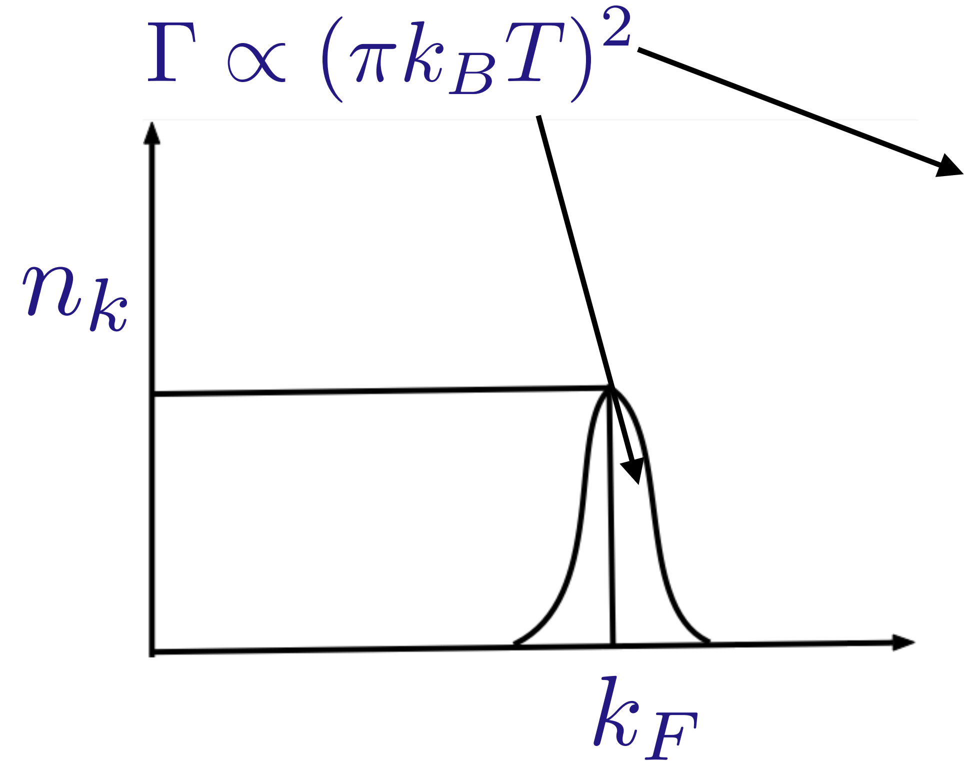
density of states



not exhausted by counting electrons alone effective momentum distribution?

as in Fermi liquids

Scattering Rate: Fermi liquid



2 degrees of freedom

forward scattering: Fermi liquid

$$\Gamma = \frac{2\pi}{\hbar}\sum_{2,3,4}|V(1,2;3,4)|^2\left[n_2(1-n_3)(1-n_4)+(1-n_2)n_3n_4\right]$$

$$\times \quad (2\pi)^d\delta^{(d)}(p_1+p_2-p_3-p_4)\delta(\epsilon_1+\epsilon_2-\epsilon_3-\epsilon_4)$$

$$n_i^{-1} = (1+e^{\beta(\epsilon_i-\mu)})$$

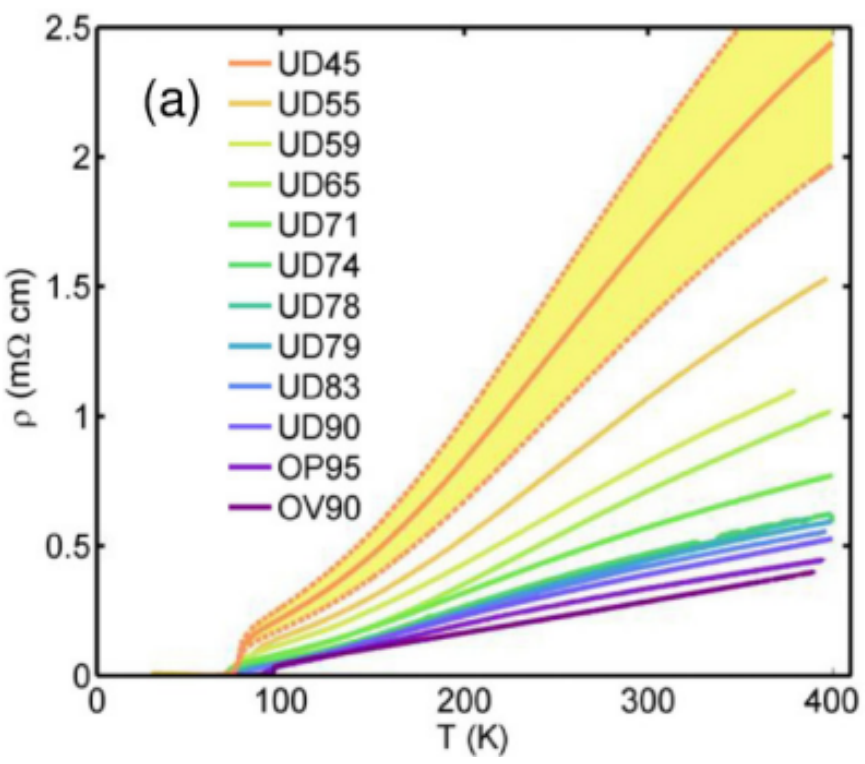
$$d\epsilon_2 d\epsilon_3$$

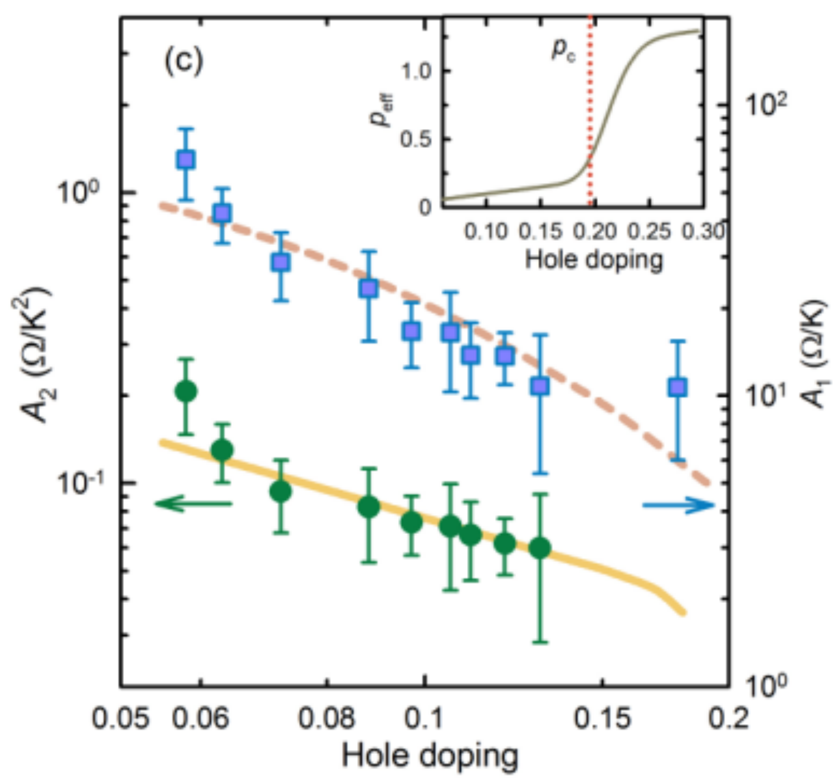
$$\Gamma \propto \left(\epsilon_1^2+(\pi k_B T)^2\right)$$

How to change this result?

Experimentall y

$$\rho \propto c + A_1 T + A_2 T^2$$



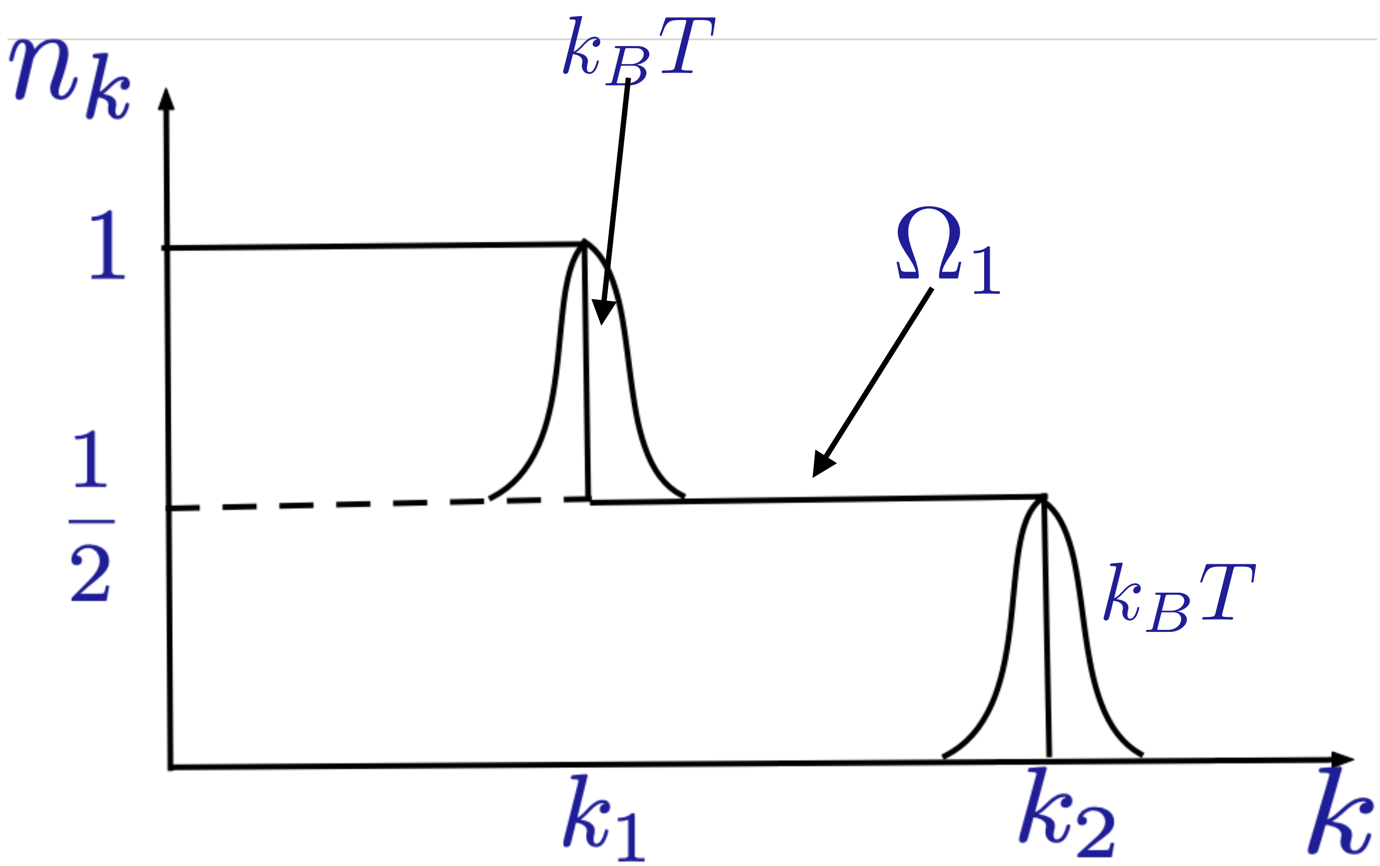


scattering rate

$$\Gamma \propto c + a_1 T + a_2 T^2$$

?

what if: single band



phase space

$(k_BT + \Omega_1)^2$

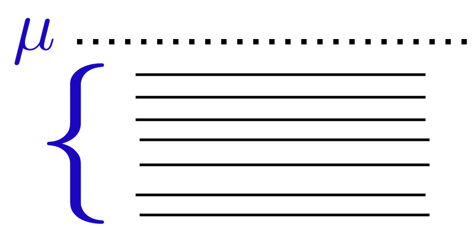
$$\Gamma \propto c + a_1 T + a_2 T^2$$

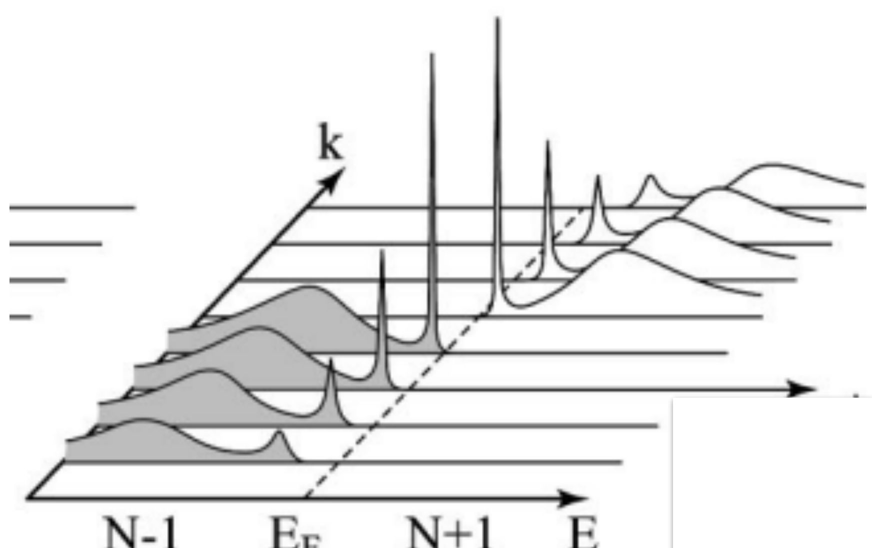
are exact statements possible?

yes

Fermi liquids

doubly occupied





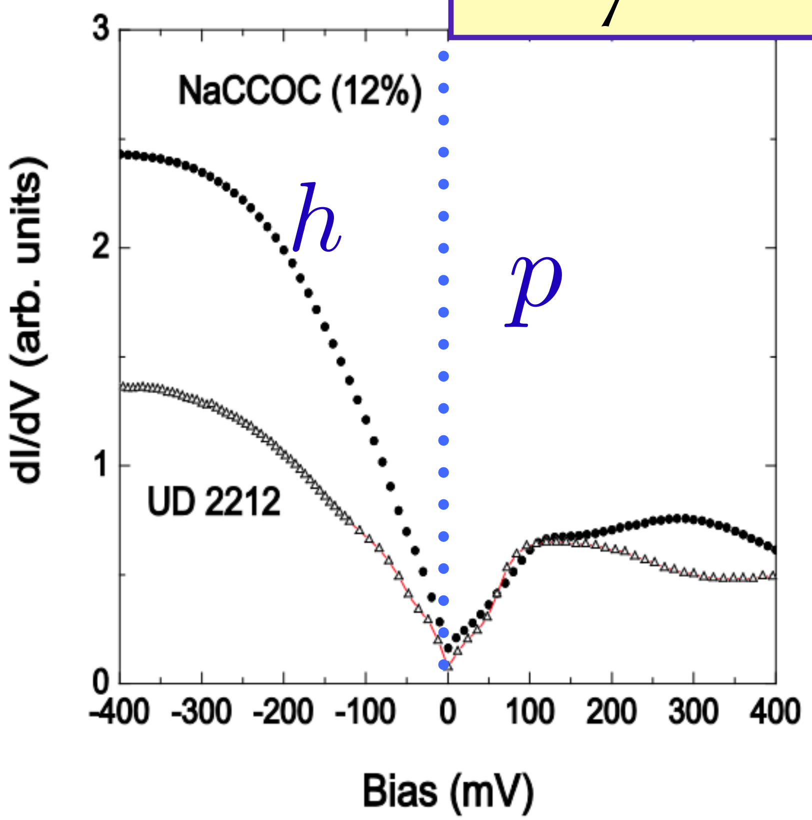
p-h symmetry

NFL

Is single occupancy below chemical potential possible?

with time-reversal symmetry in tact?

p-h asymmetry



LAST WORDS ON THE CUPRATES

P W Anderson, Princeton University

theory. I remain baffled by the almost universal refusal of theorists to confront this evident fact of hole-particle asymmetry head on. Its meaning is that the first step of any single occupancy

?

particle-hole asymmetry

Anderson
Haldane

3 citations

Fermi liquids

$$H = \sum_{p,\sigma} (\epsilon(p) - \epsilon_F)\, n_{p\sigma} + \cdots \rightarrow 0$$

$(n_{p\uparrow}, n_{p\downarrow})$ conserved currents

$(c_{p\uparrow}, c_{p\downarrow}, \text{h.c.})$ 4 objects

$O(4)$

$\text{DetM} = 1$ → SO(4) proper rotations

$\text{DetM} = -1$ → improper rotations

$$\text{Det}M = \pm 1 \implies Z_2 = O(4) \div SO(4)$$

Improper Rotations

Majorana basis

$$\begin{pmatrix} c_{p\uparrow} \\ c^\dagger_{p\uparrow} \\ c_{p\downarrow} \\ c^\dagger_{p\downarrow} \end{pmatrix} \longrightarrow \begin{pmatrix} c_{p\uparrow} + c^\dagger_{p\uparrow} \\ i(c_{p\uparrow} - c^\dagger_{p\uparrow}) \\ c_{p\downarrow} + c^\dagger_{p\downarrow} \\ i(c_{p\downarrow} - c^\dagger_{p\downarrow}) \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} c_{p\uparrow} + c^\dagger_{p\uparrow} \\ i(c_{p\uparrow} - c^\dagger_{p\uparrow}) \\ c_{p\downarrow} + c^\dagger_{p\downarrow} \\ i(c_{p\downarrow} - c^\dagger_{p\downarrow}) \end{pmatrix} \Rightarrow c_{p\downarrow} \rightarrow c^\dagger_{p\downarrow}$$

p-h transformation

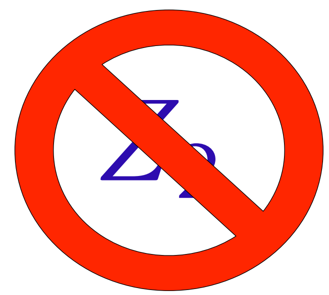
$\epsilon(p) = \epsilon_F$ Fermi

$$H = 0$$

$$\left.\begin{aligned} n_{p\uparrow} &\rightarrow 1 - n_{p\uparrow} \\ n_{p\downarrow} &\rightarrow n_{p\downarrow} \end{aligned}\right\} Z_2$$

at Fermi surface only

How to destroy Fermi liquids?



$$H = \sum_{p,\sigma} (\epsilon(p) - \epsilon_F)\, n_{p\sigma} + U n_{p\uparrow} n_{p\downarrow}$$

odd under Z_2

New fixed point!

Hatsugai-Kohmoto model

scaling dimension

$[n_{p\uparrow} n_{p\downarrow}] = -2$

relevant interaction

Hubbard not necessary!

General HK Model

$$\sum_k (\xi_k (n_{k\uparrow} + n_{k\downarrow}) + U n_{k\uparrow} n_{k\downarrow}) \quad [\hat{U}_{\rm int}(k), \hat{T}] = 0$$

Solvable Mott transition:U>W

$$G_{k\sigma}(i\omega_n \to z) = \frac{1 - \langle n_{k\bar{\sigma}} \rangle}{z - \xi_k} + \frac{\langle n_{k\bar{\sigma}} \rangle}{z - (\xi_k + U)} \neq \frac{1}{z - \omega_k}$$

lower Hubbard band

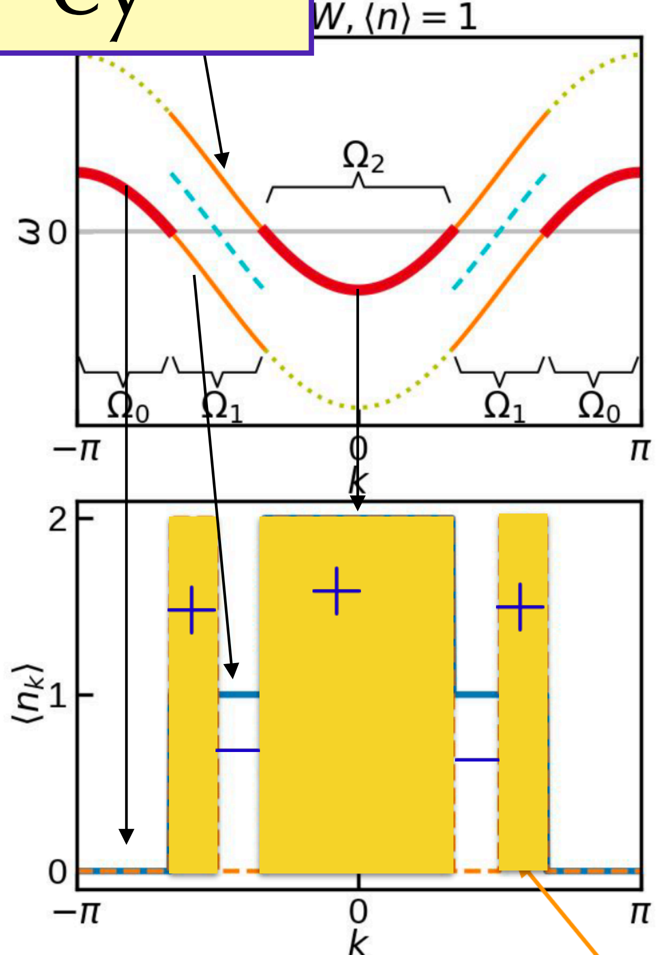
upper Hubbard band

zeros

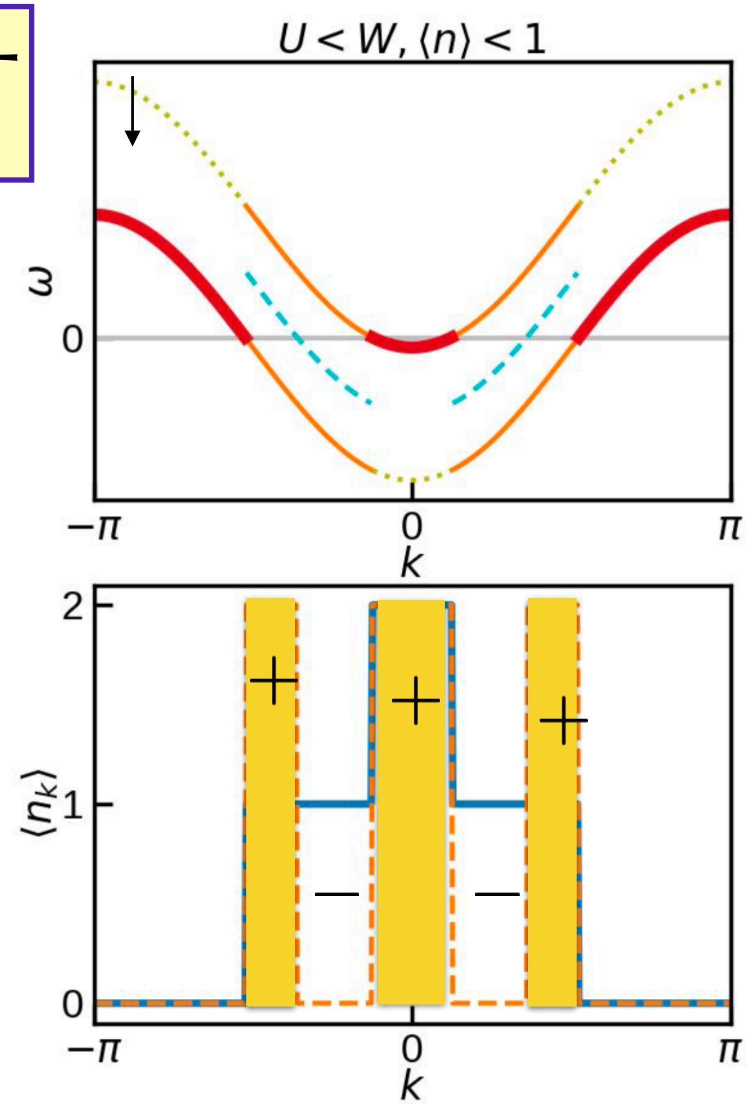
single occupancy

counting charges

SWT



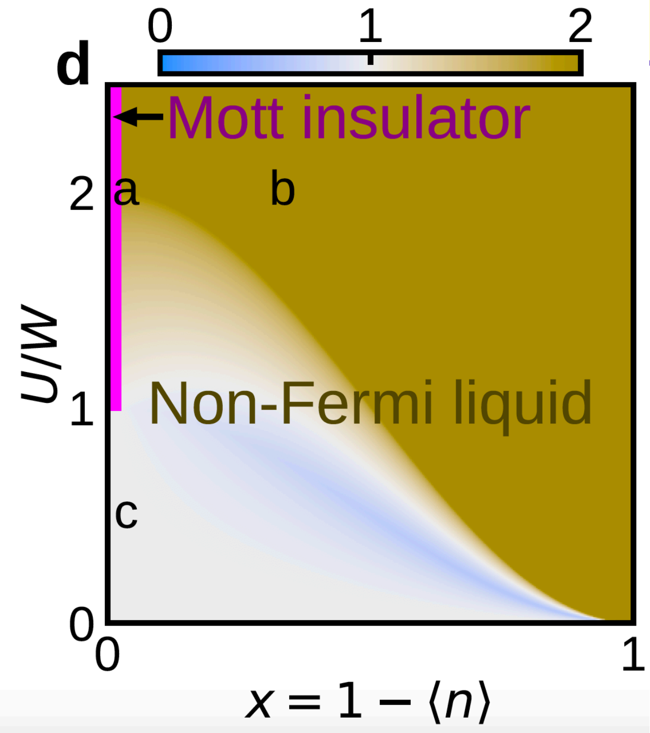
$n_{\rm Lutt} = \langle n \rangle$

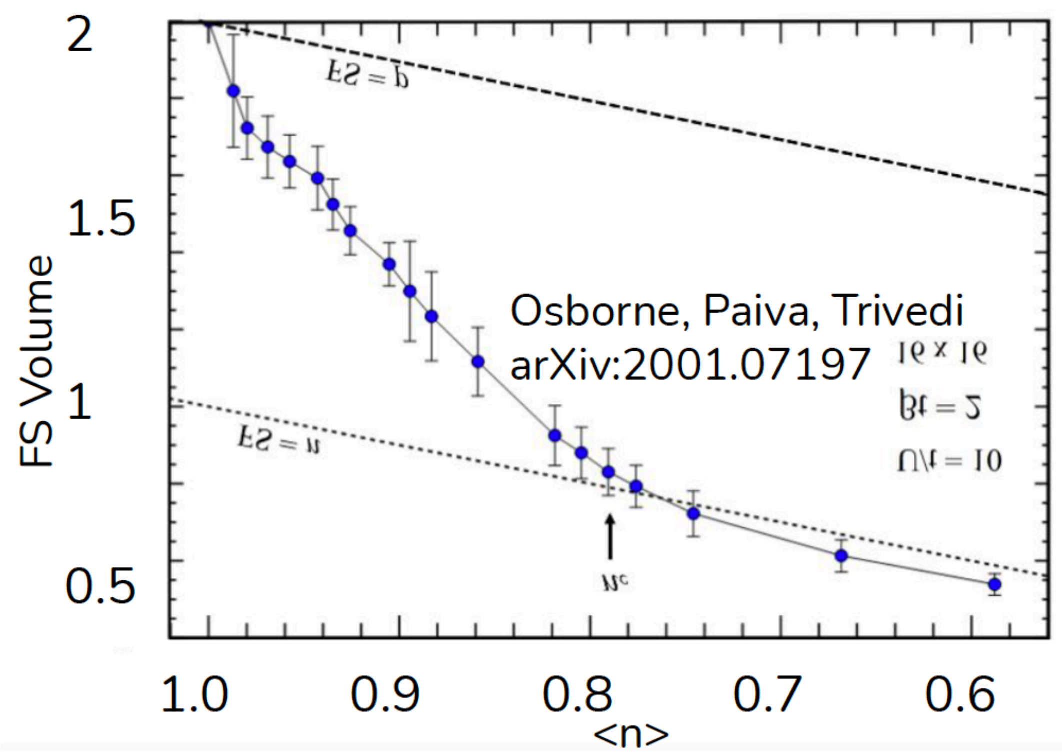


$n_{\rm Lutt} \neq \langle n \rangle$

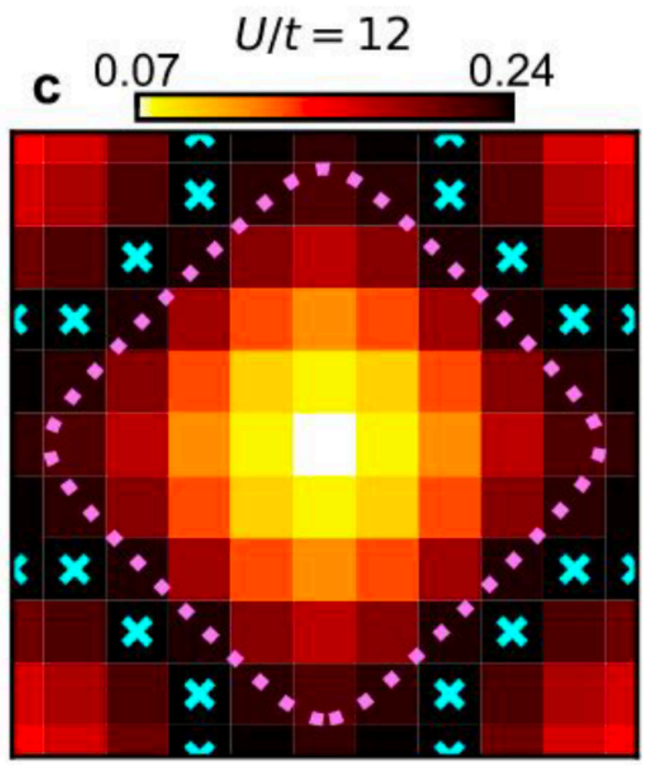
zeros ≠particles

Other violations of Luttinger count





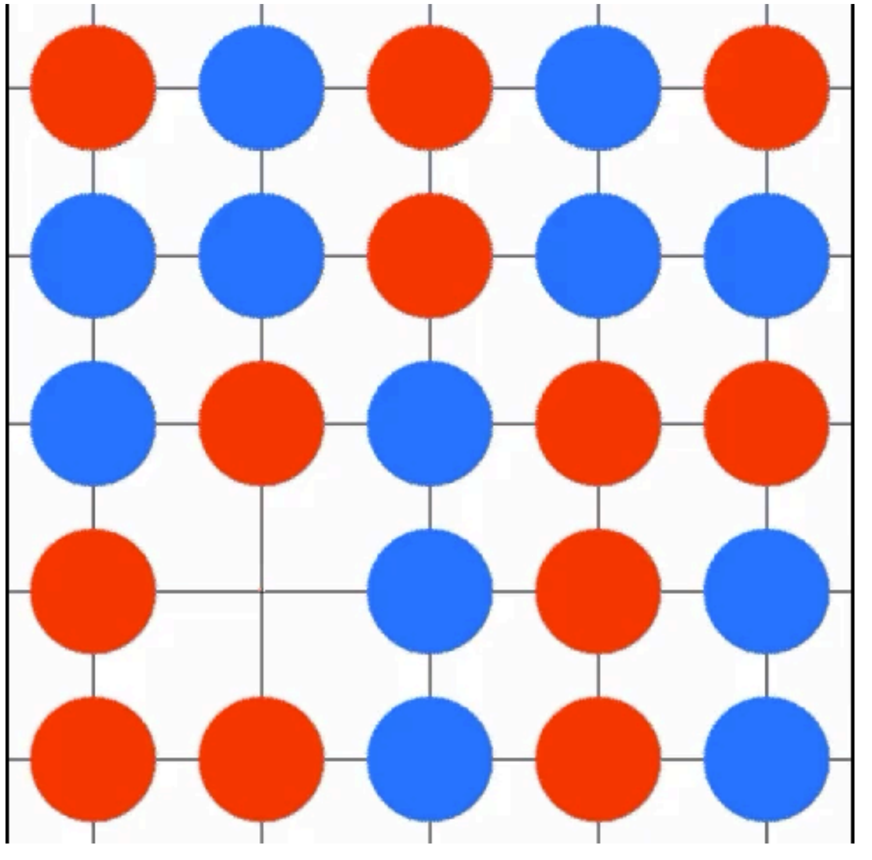
Hubbard model, QMC



Wang, Ding, Moritz, EWH, Devereaux
npj Quantum Materials 5, 51 (2020)

what does the HK model leave out??

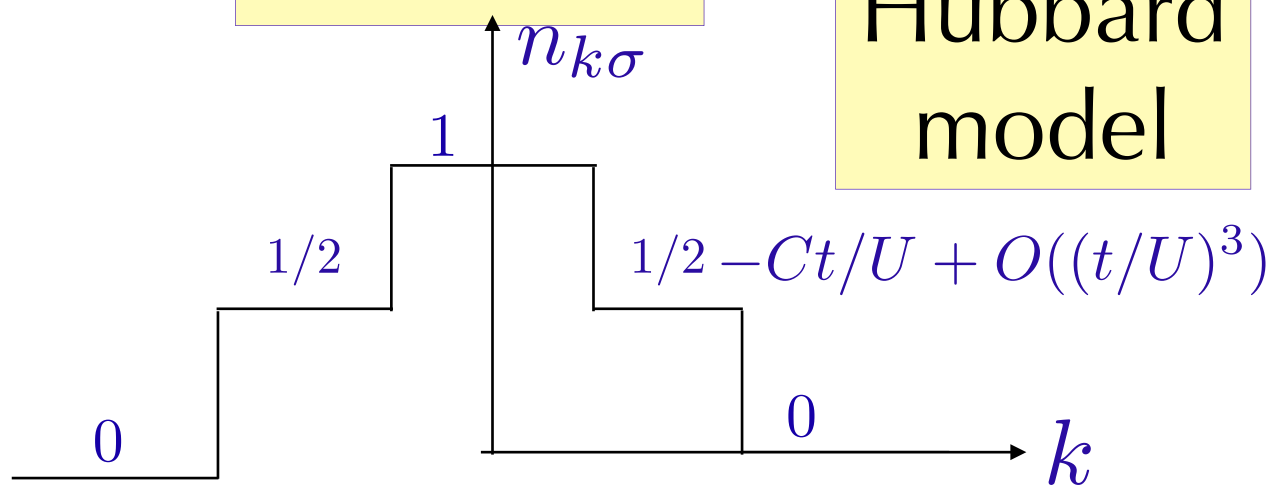
$$[H_t, H_U] \neq 0$$



dynamical spectral weight transfer

occupancy in HK model

Hubbard model



$$n_{k\sigma} = \frac{e^{-\beta\xi_k} + e^{-\beta(2\xi_k+U)}}{1 + 2e^{-\beta\xi_k} + e^{-\beta(2\xi_k+U)}}$$

not electrons

forward scattering: phase space integral

$$\Gamma = I(\epsilon, T) = \int d\epsilon_2 d\epsilon_3 d\epsilon_4 \delta(\epsilon + \epsilon_2 - \epsilon_3 - \epsilon_4) \left[n_2(1-n_3)(1-n_4) + (1-n_2)n_3 n_4 \right]$$

poles: $\epsilon_{\pm}^{(n)} = (-\lambda_{\pm} + (2n+1)\pi i)T$

$$\lambda_{\pm} = \ln \frac{1 \pm \sqrt{1 - e^{-U/T}}}{e^{-U/T}} \quad \to 0(U=0)$$

$$= \frac{1}{2}\left((\pi T)^2 + \epsilon^2 + (\lambda_+^2 + \lambda_-^2 - \lambda_+\lambda_-)T^2 - \epsilon T(\lambda_+ + \lambda_-)\right)$$

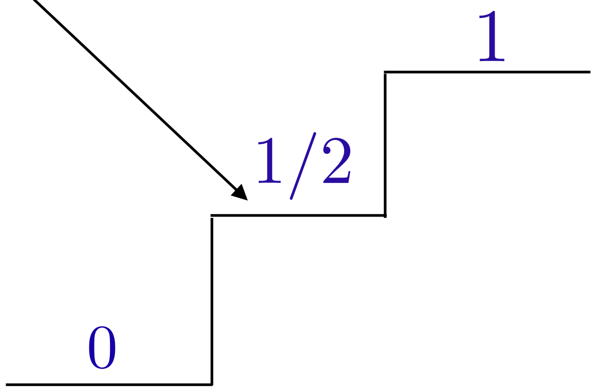
$$\Omega_1 \gg U$$

$$\Gamma \propto \frac{1}{2}\left(U^2 + (3U \ln 2)T + (\pi^2 + 3(\ln 2)^2)T^2\right)$$

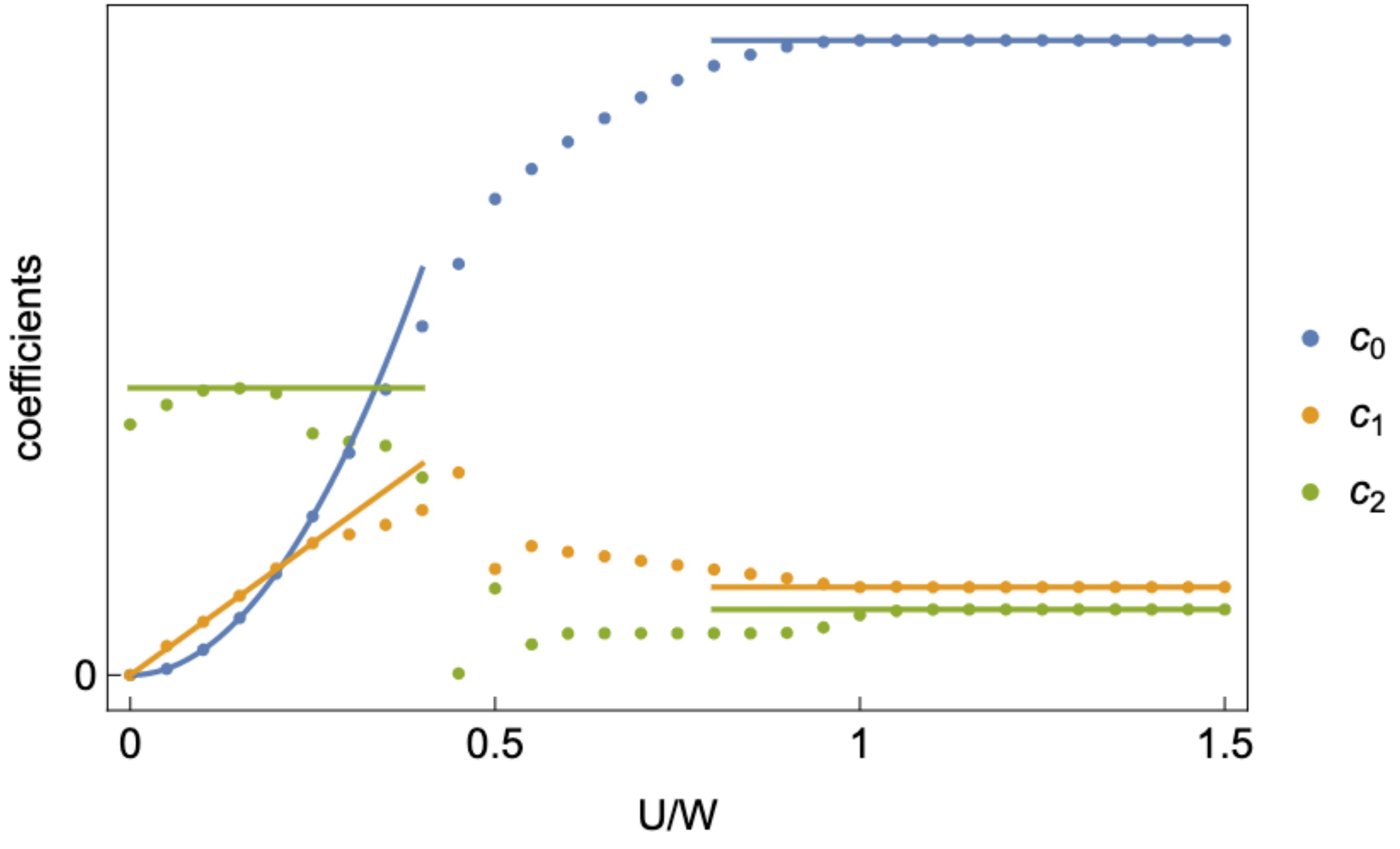
$$U \gg W, \Omega_1 \gg T$$

$$I(0,T) = \frac{3}{8}\Omega_1^2 + \frac{\ln 2}{2}\Omega_1 T + \frac{\pi^2 + 2\ln^2 2}{4}T^2$$

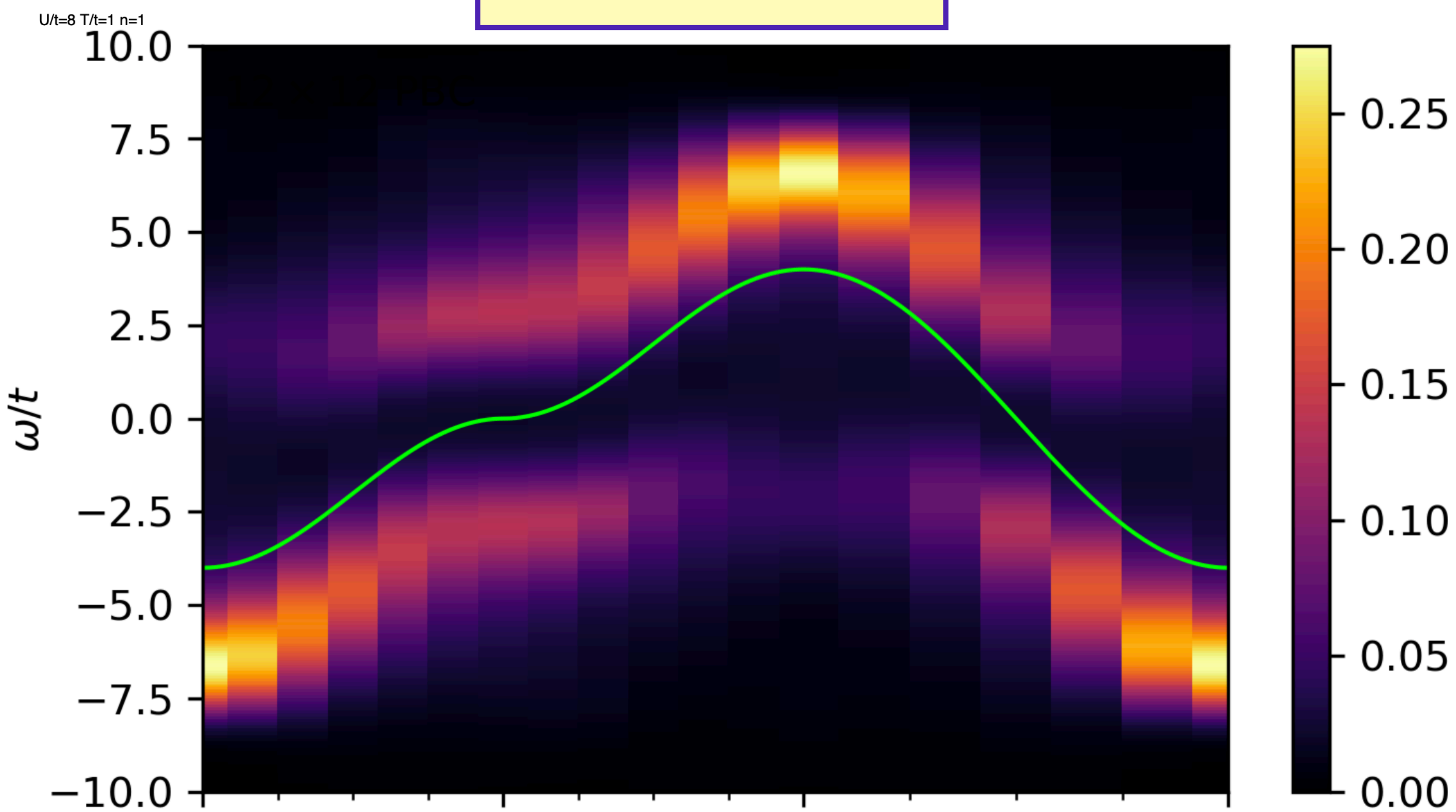
dominates



$$I(T,0) \approx c_0 + c_1 T + c_2 T^2 + O(T^3)$$



Mottness



$n_{k\sigma} \neq n_{\rm FD}$

forward scattering

strange metallicity