

Superconductivity and Mottness: Exact Results

Nature Physics, vol.16, 1175-1180 (2020);
Nature Physics, in press, arxiv/2102.03256

<https://arxiv.org/abs/2111.14852>

Luke Yeo



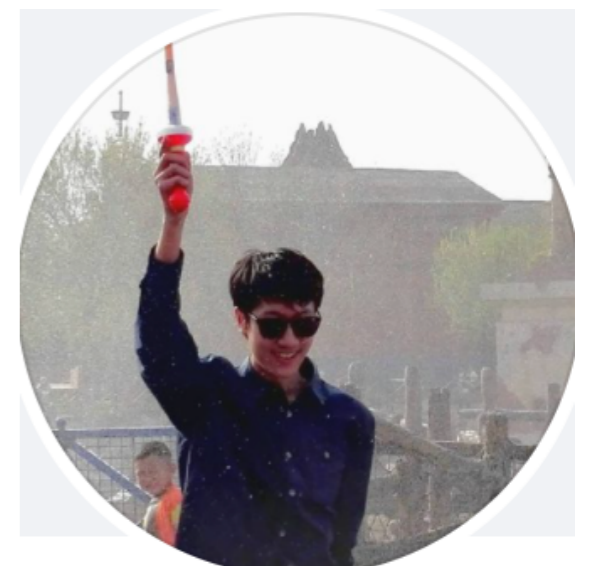
Edwin Huang



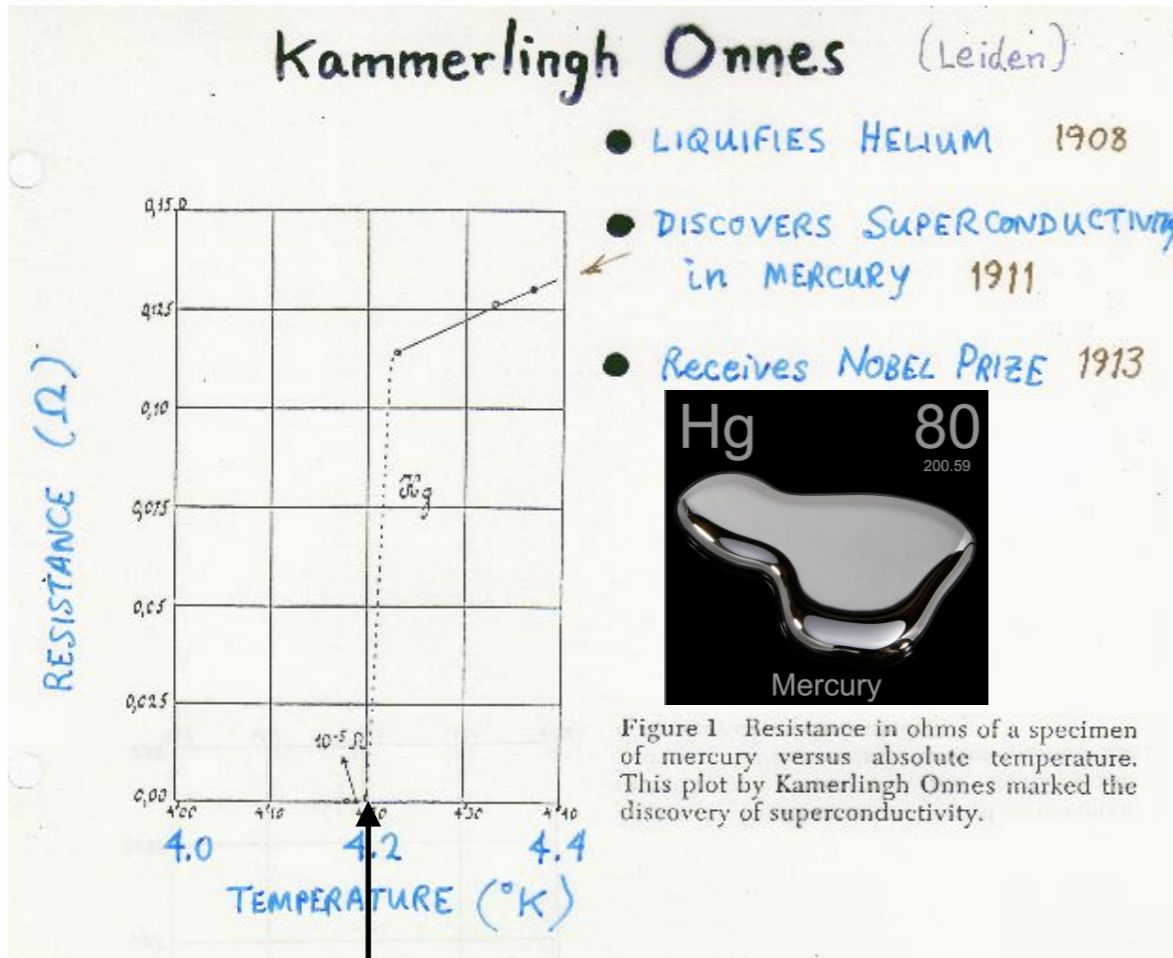
G. La Nave



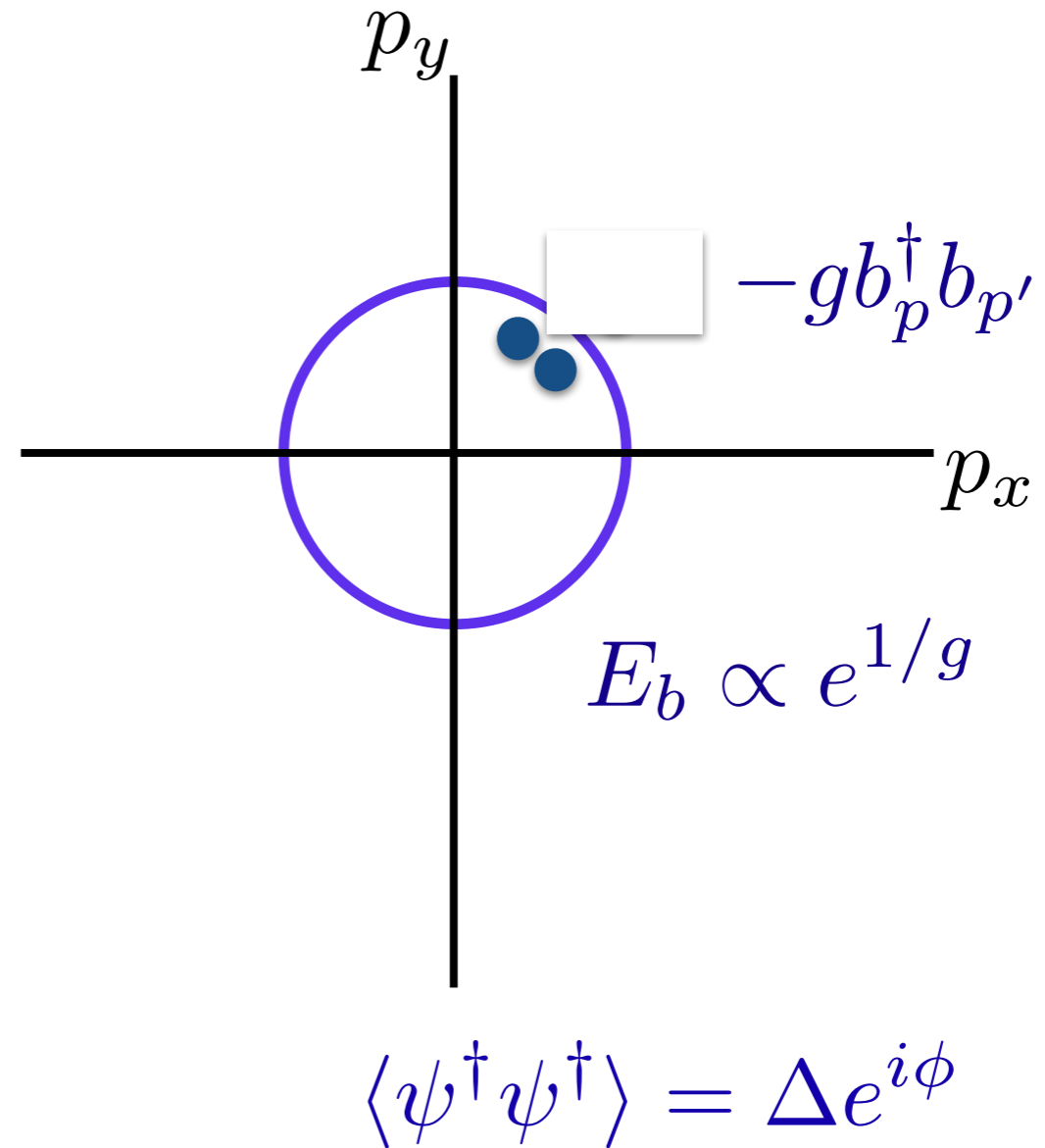
Jinchao Z.

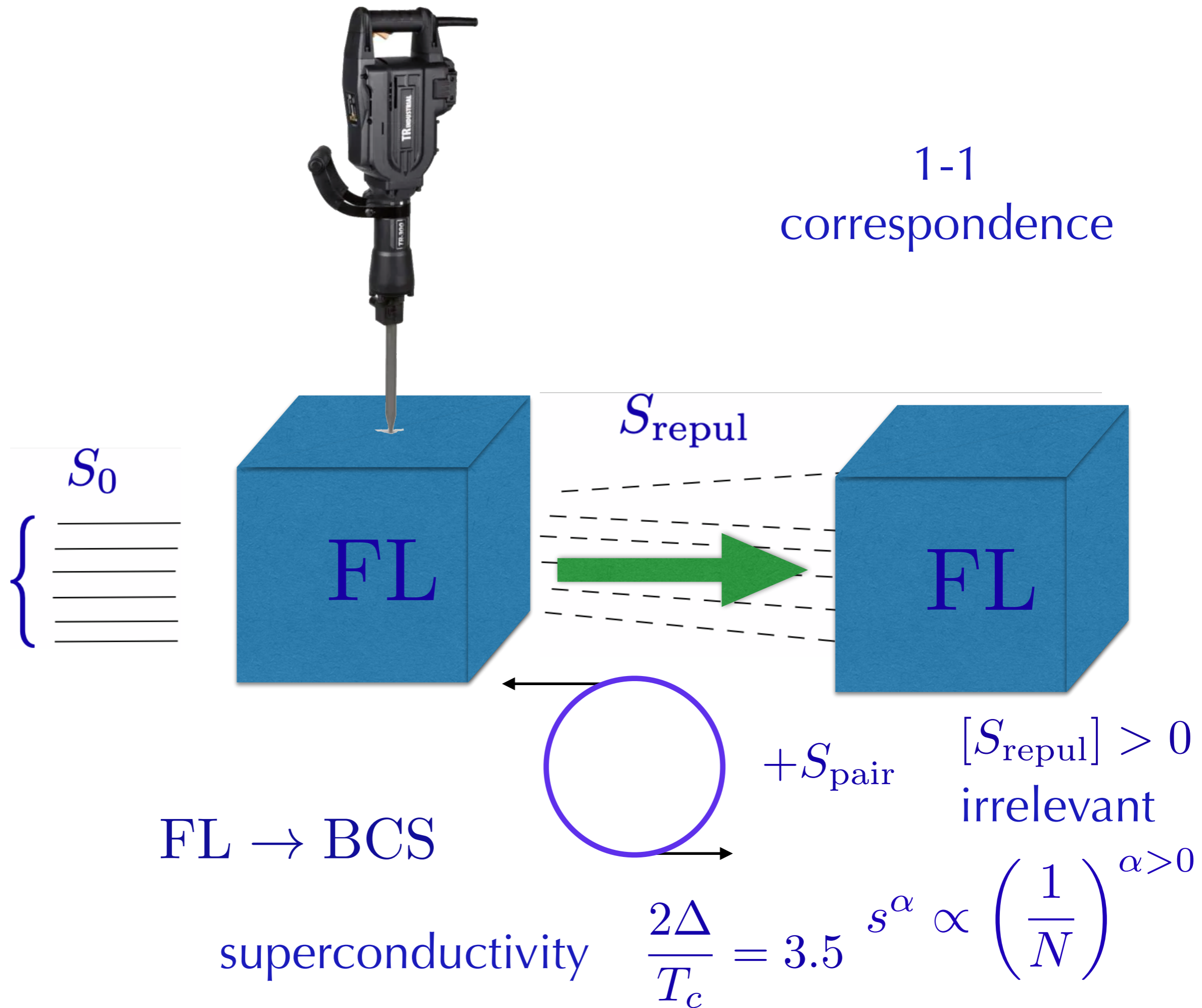


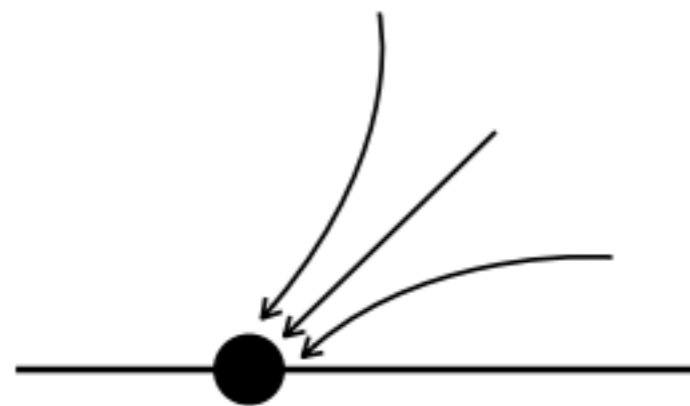
Cooper instability



T_c



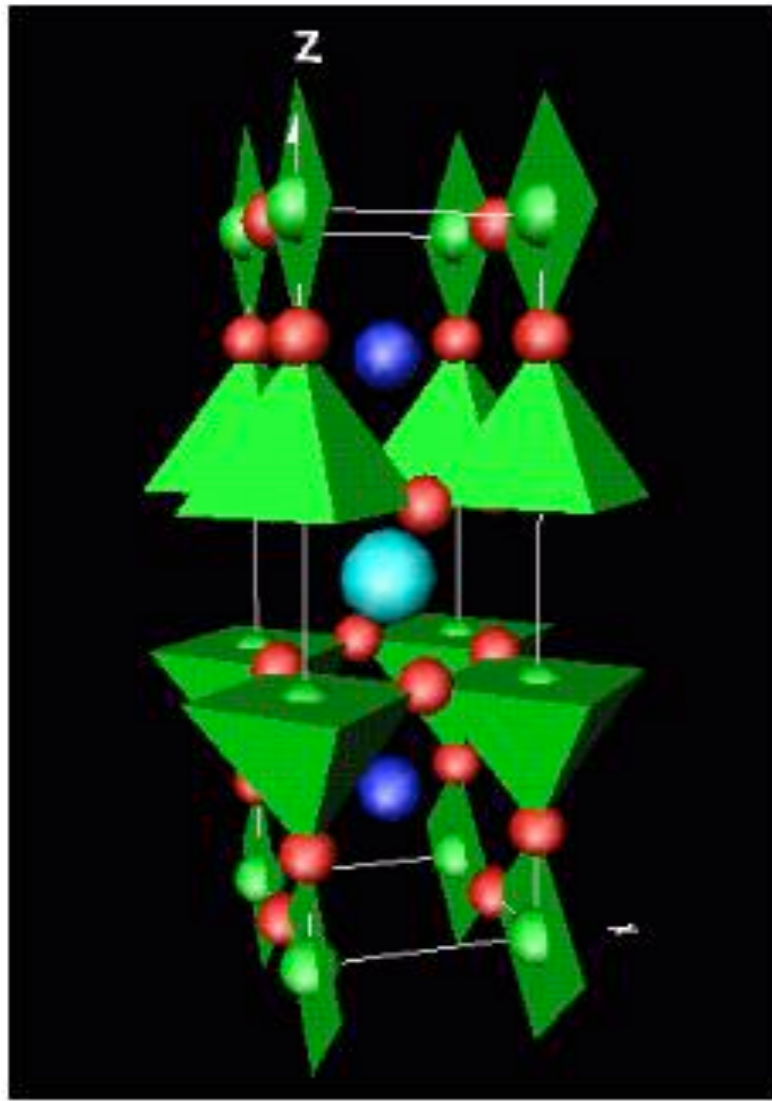




FL
BCS

fixed
point beyond
FL?

quartic
interacting
theory?

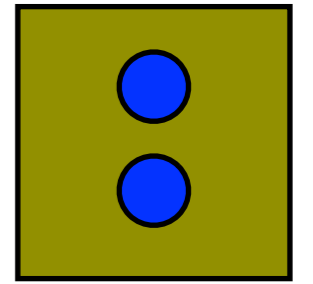


YBa₂Cu₃O₇
Cuprate Superconductors

NiO insulates

d^8 ?

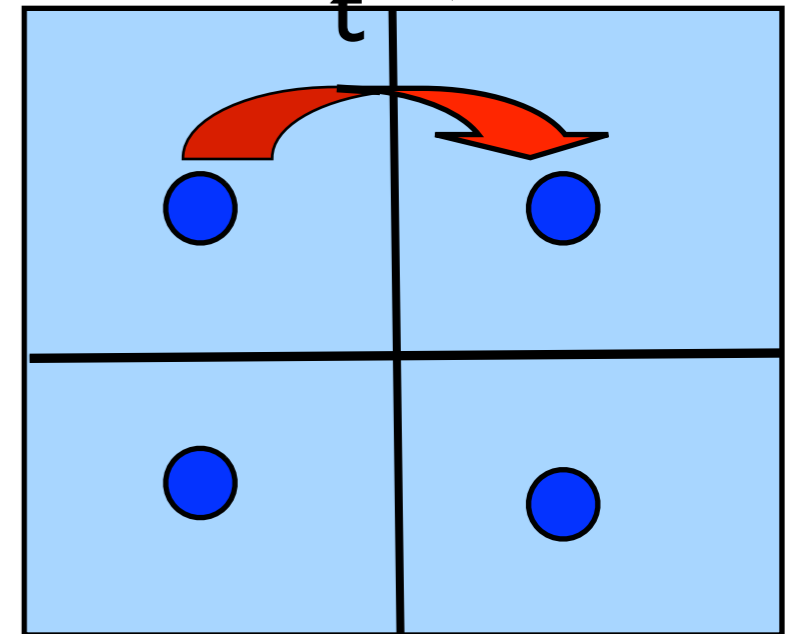
perhaps this costs energy



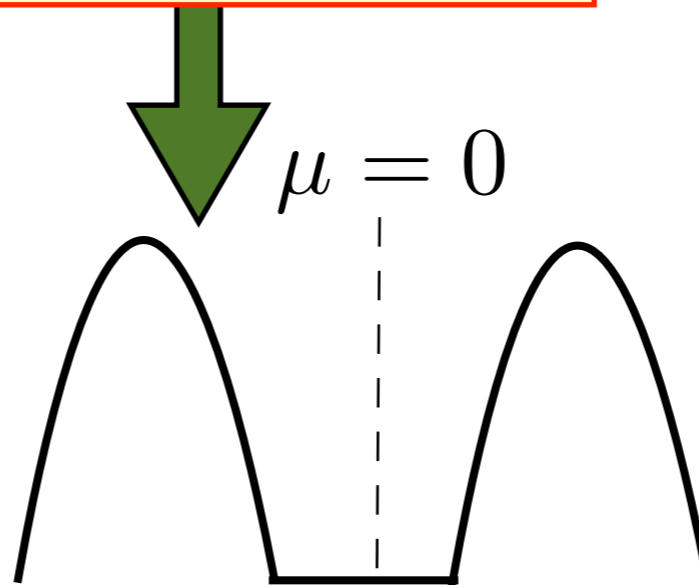
$$U \gg t$$



local real-space physics



no change in size of Brillouin zone



solve the Hubbard Model!!

Cooper instability??

Progress thus far?

DMFT

QMC

disputes

order

Sept. 1997

A Critique of Two Metals

R. B. Laughlin
Department of Physics
Stanford University
Stanford, California 94305

idea is either missing or improperly understood. Another indicator that something is deeply wrong is the inability of anyone to describe the elementary excitation spectrum of the Mott insulator precisely even as pure phenomenology. Nowhere can one find a quantitative band structure of the elementary particle whose spectrum becomes gapped. Nowhere can one find precise information about the particle whose gapless spectrum causes the paramagnetism. Nowhere can one find information about the interactions among these particles or of their potential bound state spectroscopies. Nowhere can one find precise definitions of Mott insulator terminology. The upper and lower Hubbard bands, for example, are vague analogues of the valence and conduction bands of a semiconductor, except that they coexist and mix with soft magnetic excitations no one knows how to describe very well.

Nov. 1997

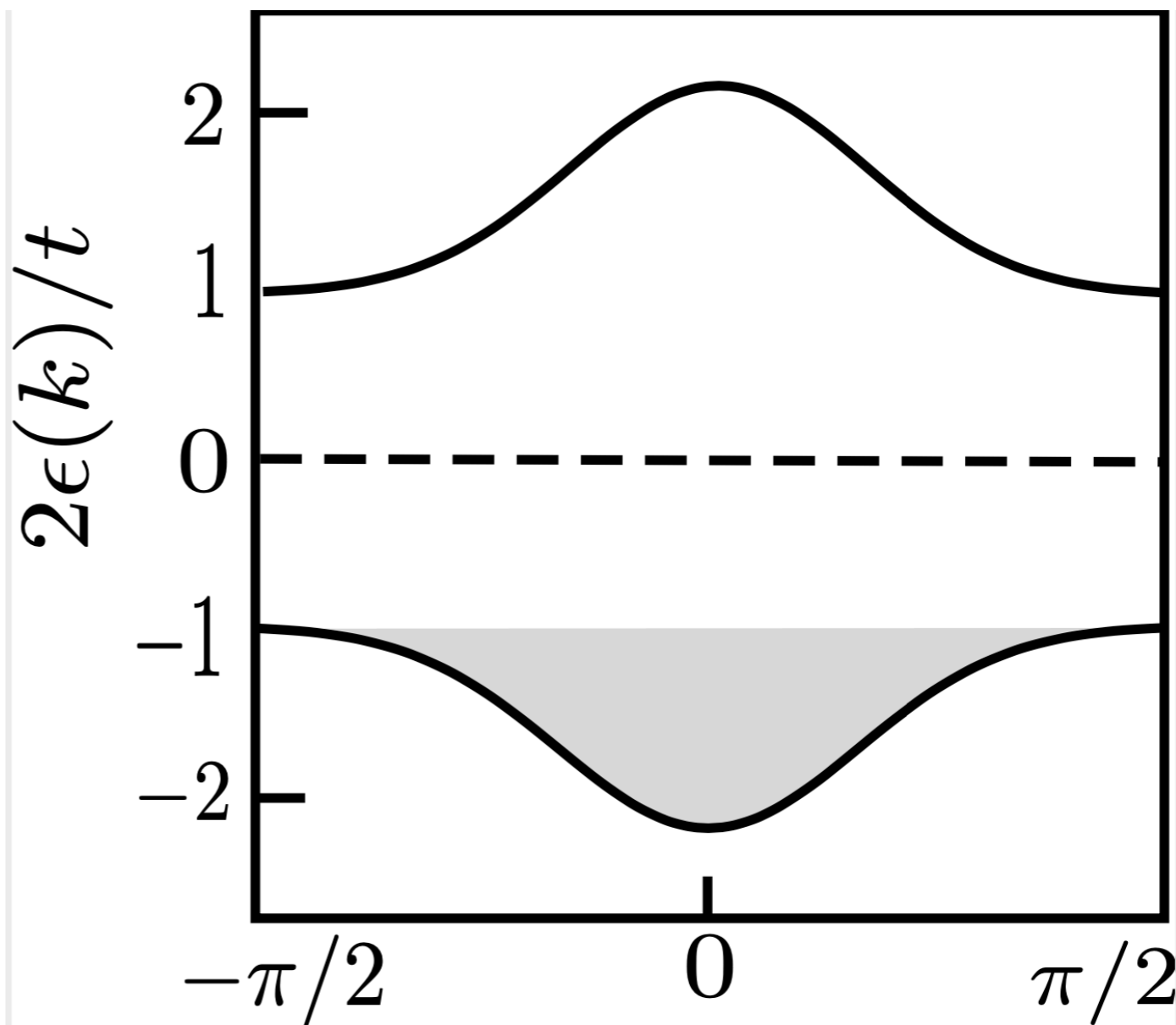
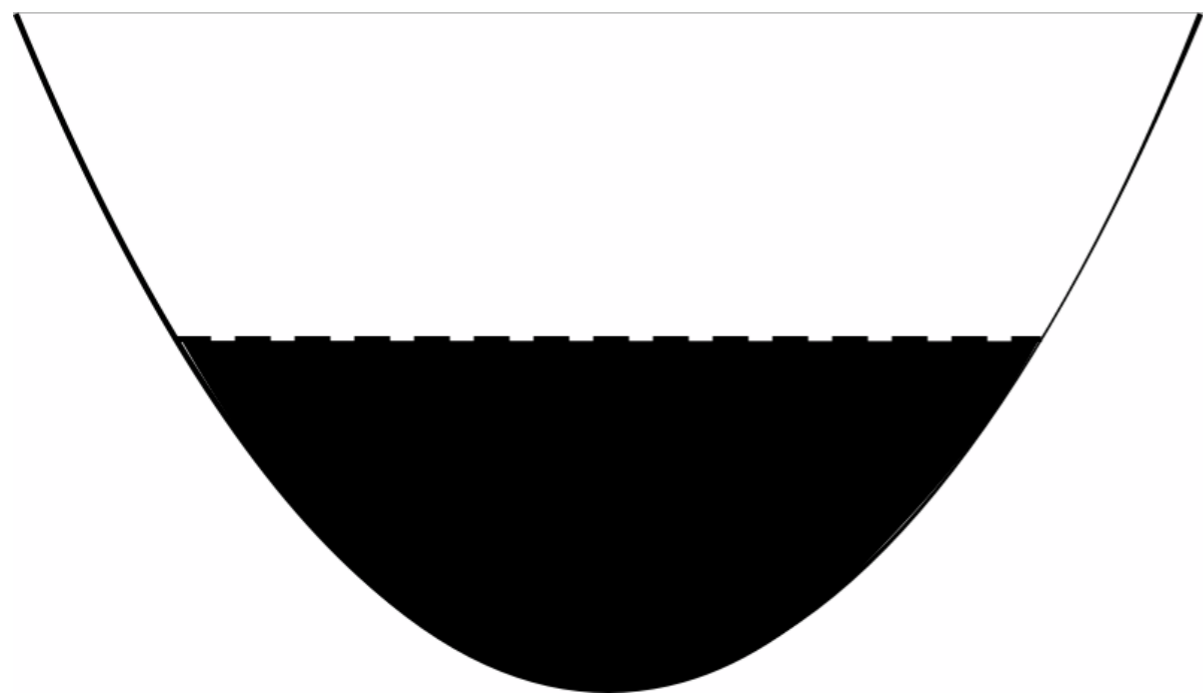
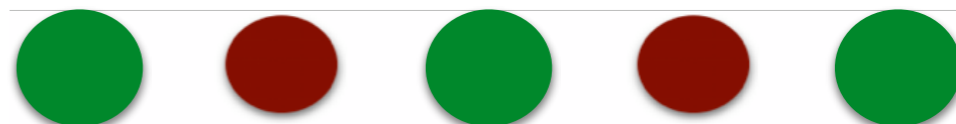
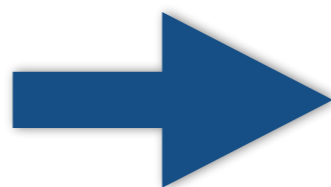
A Critique of “A Critique of Two Metals”

Philip W. Anderson and G. Baskaran

Joseph Henry Laboratories of Physics

Princeton University, Princeton, NJ 08544

The fundamental argument is presented in the second paragraph: “Ten years of work by some of the best minds in theoretical physics have failed to produce any formal demonstration”...of the Mott insulating state. The statement would be ludicrous if it were not so influential. The proviso “at zero temperature” is added, because of course most Mott concern. It is the tragedy of Mott that although he almost certainly won his Nobel prize for the Mott insulator, Slater, who couldn’t think clearly about finite temperature, won the publicity battle.



No Mott Problem

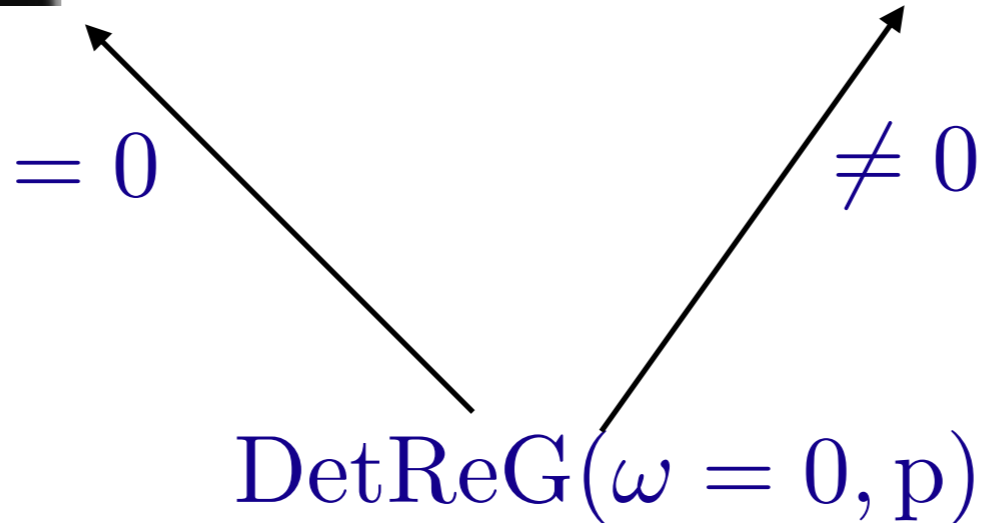


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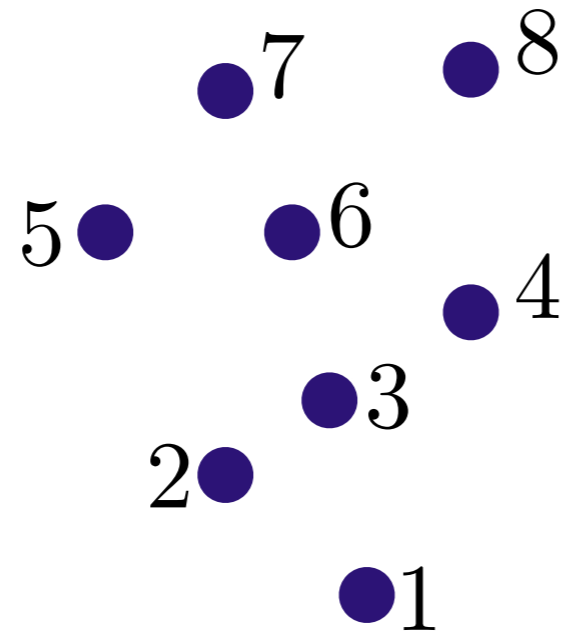


= Mottness

zeros



counting particles



is there a more efficient way?

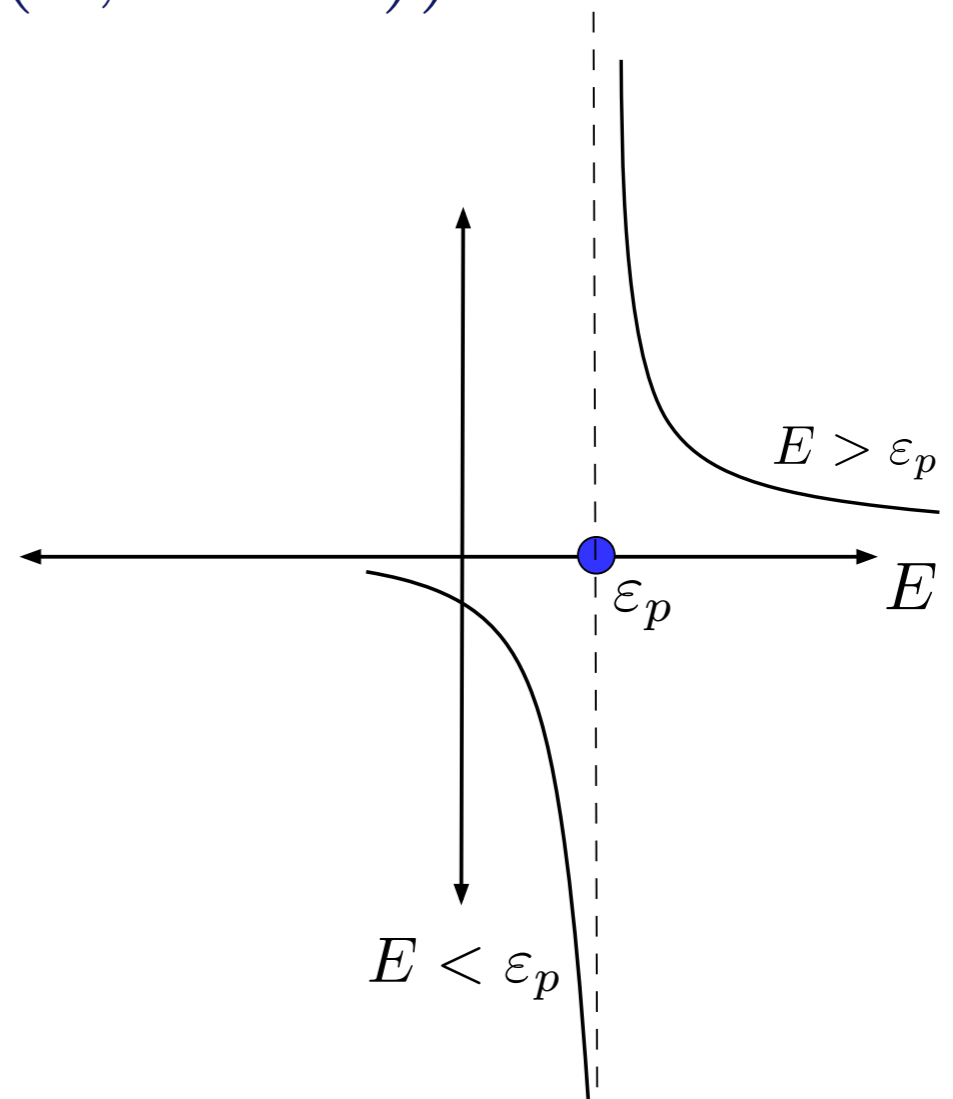
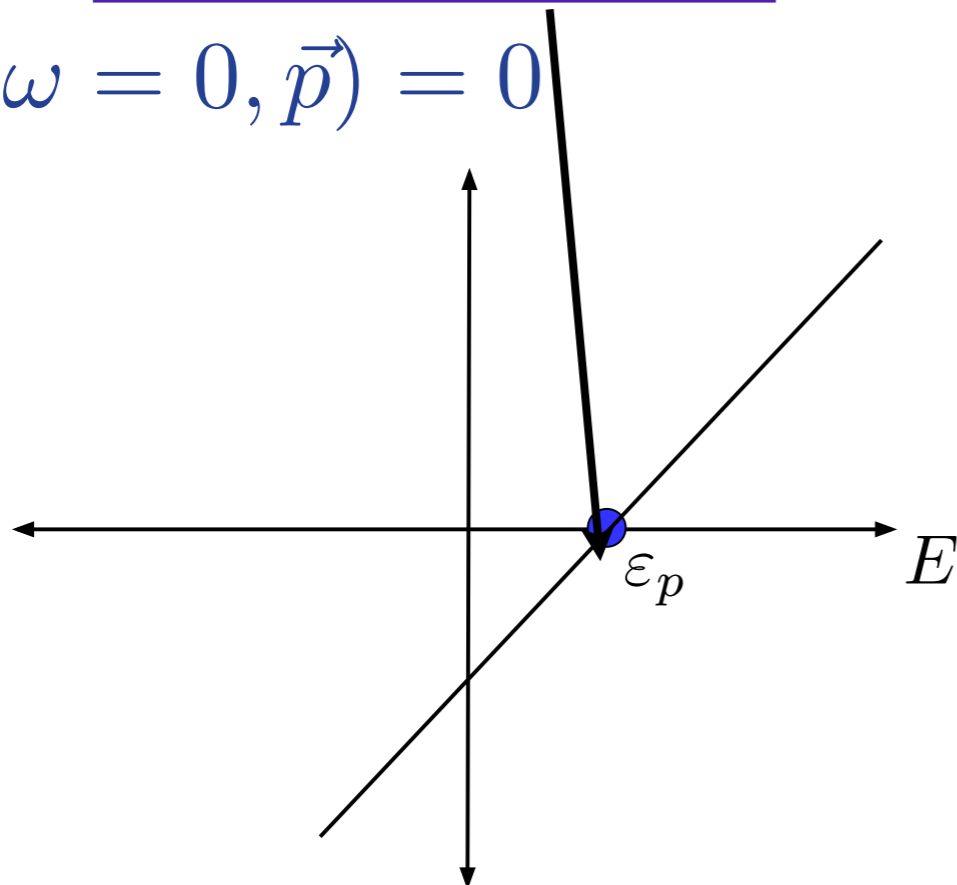
Luttinger counting theorem

$$G(E) = \frac{1}{E - \varepsilon_p}$$

$$n = 2 \sum_{\mathbf{k}} \Theta(\Re G(\mathbf{k}, \omega = \mathbf{0}))$$

zero-crossing

$$\text{Det}G(\omega = 0, \vec{p}) = 0$$



counting poles (qp)

How do zeros obtain?

$$\text{Re}G(0, p) = \int_{-\infty}^{\infty} \left(\text{band structure} \right) d\omega$$

$\mu = 0$

$\text{Im } G = 0$

Kramers-Kronig

$$= \text{below gap} + \text{above gap} = 0$$

$$\text{DetRe}G(k, \omega = 0) = 0 \text{ (single band)}$$

strongly correlated gapped systems

zeros

no propagation



breakdown
of particle
concept

Mottness

$n = \text{zeros} + \text{poles}?$

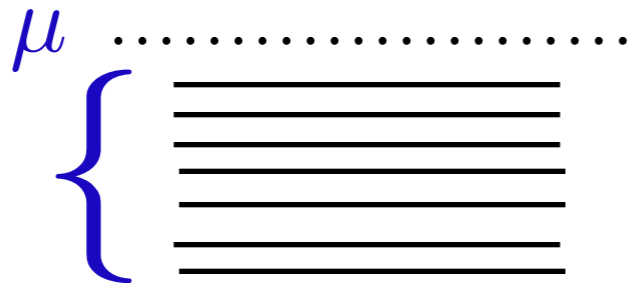
Minimal model
for Mottness?

~~Hubbard
model~~

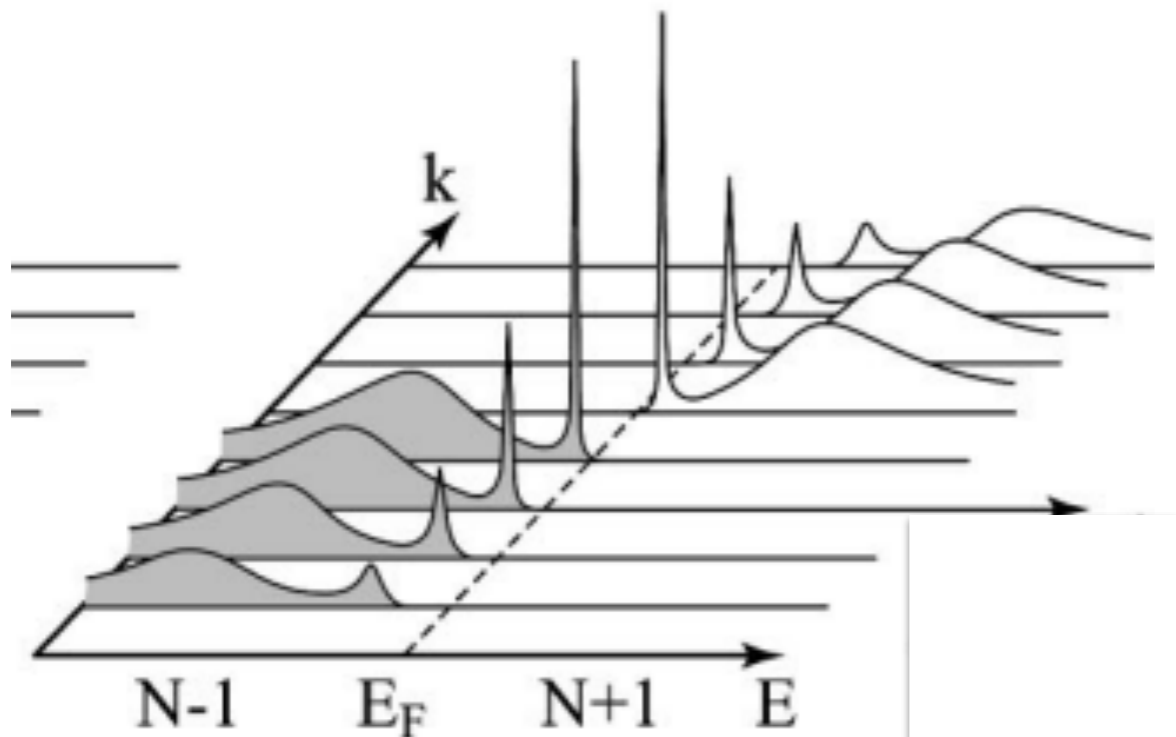
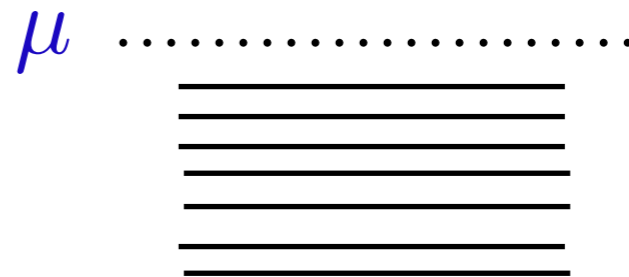
Fermi liquids

NFL

doubly occupied



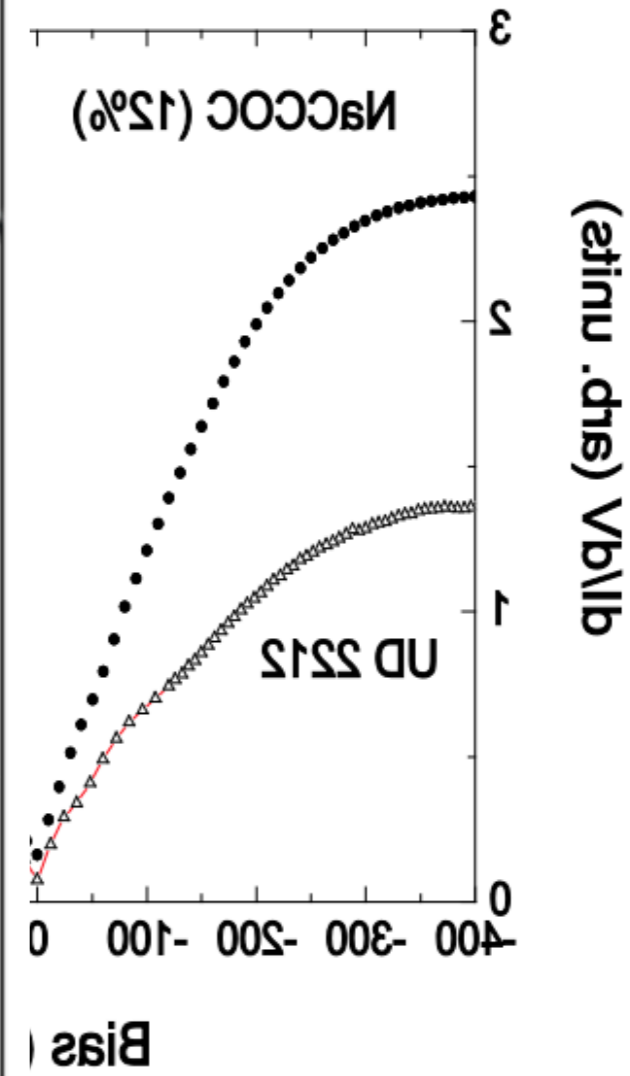
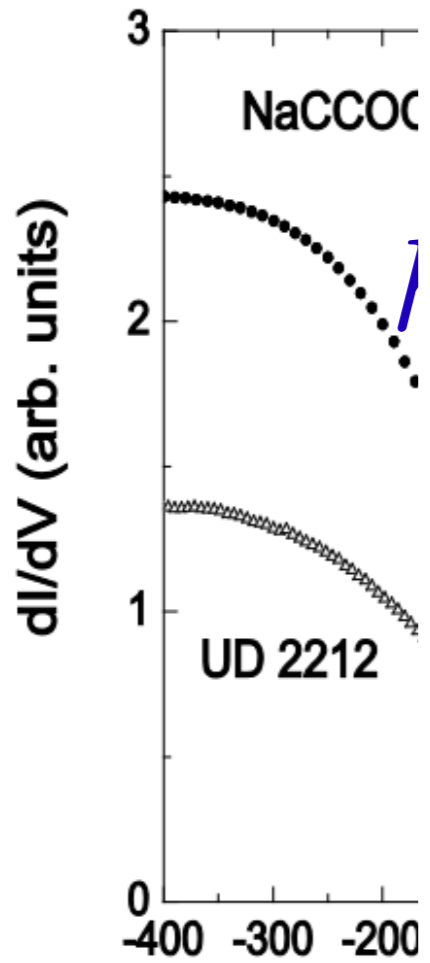
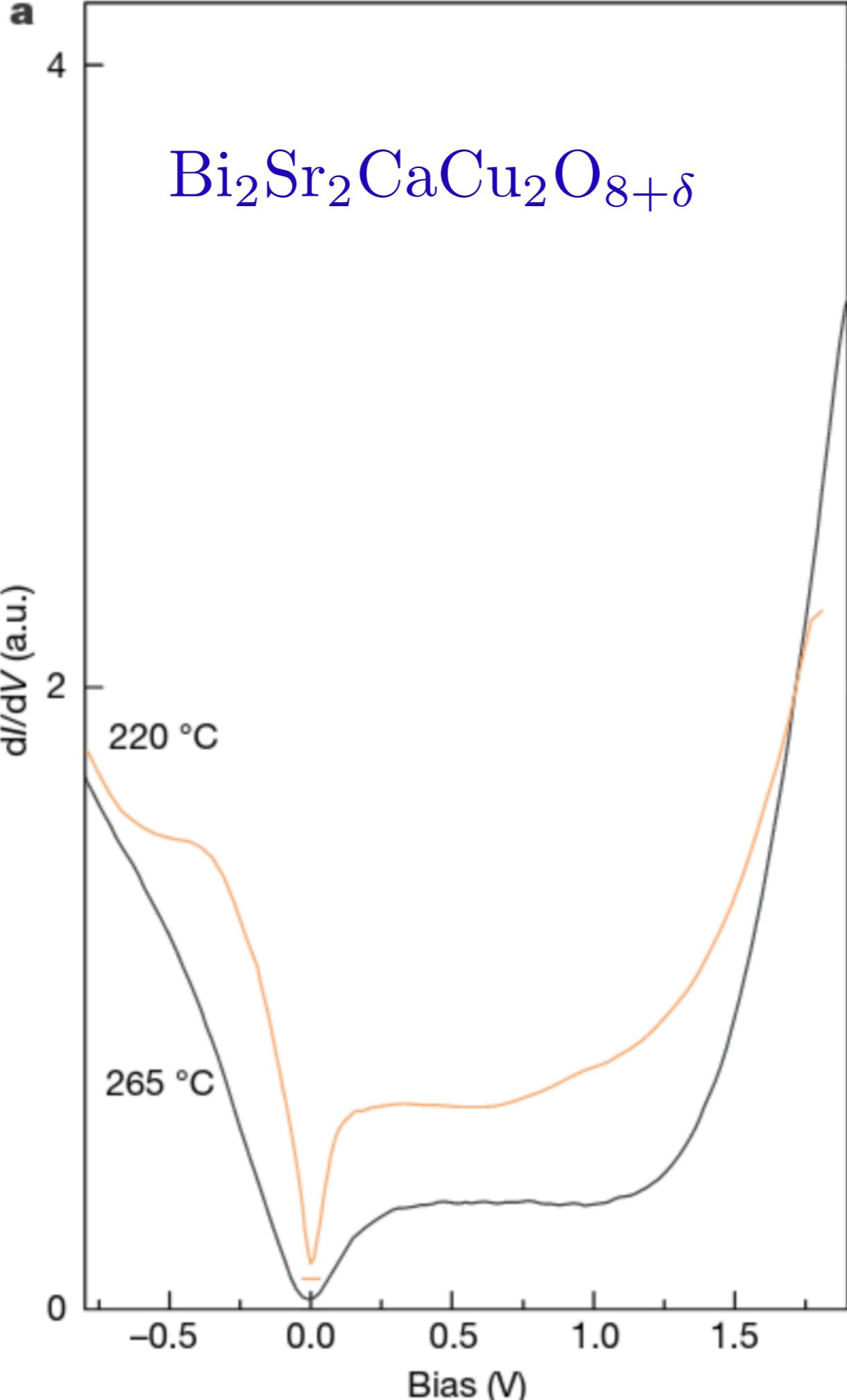
Is single occupancy below chemical potential possible?



Fermi-liquid system

p-h symmetry

with time-reversal symmetry in tact?



LAS
PW

theory.
theorist
asymm

iversity

iversal refusal of
ole-particle
he first step of any

single
occupancy

?

particle-hole
asymmetry



Anderson
Haldane
2000

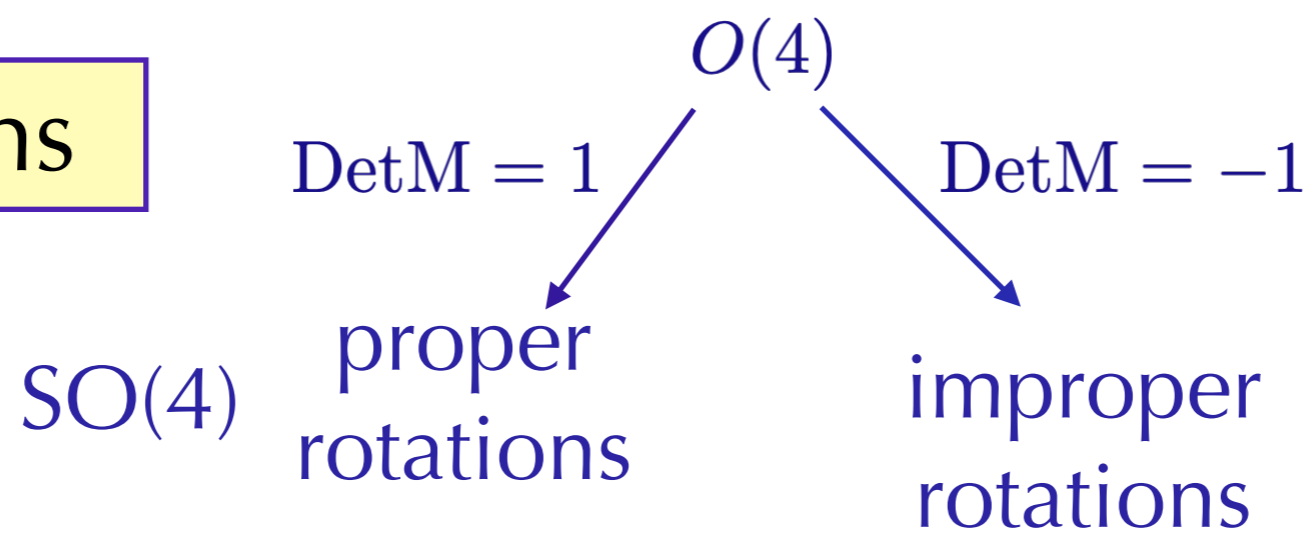
3 citations

Fermi liquids

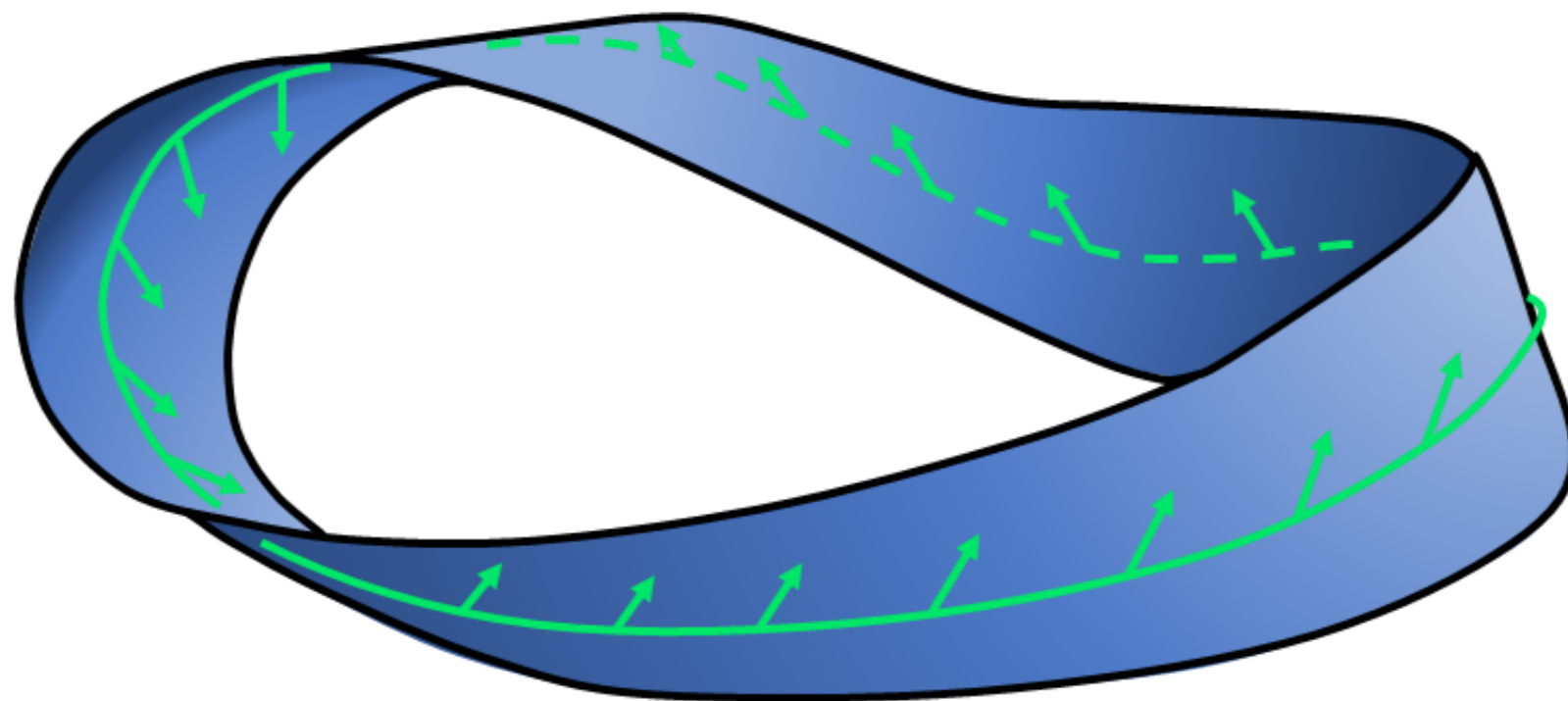
$$H = \sum_{p,\sigma} (\epsilon(p) - \epsilon_F) n_{p\sigma} + \dots \rightarrow 0$$

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

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



$$Z_2 = O(4) \div SO(4)$$



$$\epsilon(p) = \epsilon_F$$

Fermi
Surface

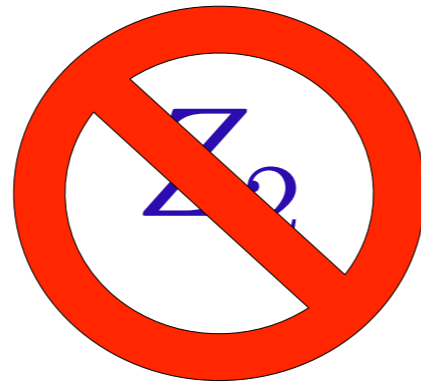
$$H = 0$$



p/h transformation

$$\left. \begin{array}{l} n_{p\uparrow} \rightarrow 1 - n_{p\uparrow} \\ n_{p\downarrow} \rightarrow n_{p\downarrow} \end{array} \right\} \mathbb{Z}_2 \text{ at Fermi surface only}$$

How to destroy Fermi liquids?



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

~~p-symmetry~~

odd
under Z_2

scaling dimension

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

relevant
interaction

New fixed point!

Hatsugai-Kohmoto
model

General HK Model

$$\sum_k (\xi_k (n_{k\uparrow} + n_{k\downarrow}) + U n_{k\uparrow} n_{k\downarrow})$$

$$[H_t, H_U] = 0$$

Solvable Mott transition

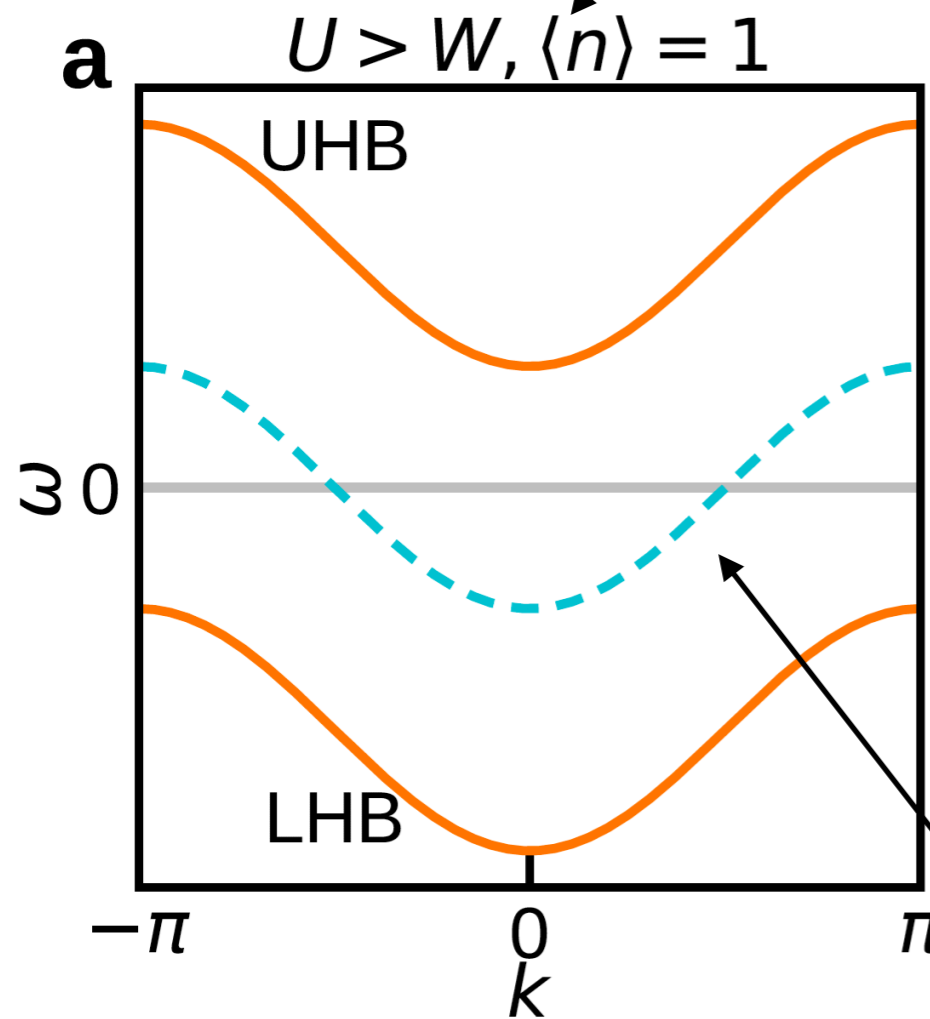
$$G_{k\sigma}(i\omega_n \rightarrow z) = \frac{1 - \langle n_{k\bar{\sigma}} \rangle}{z - \xi_k} + \frac{\langle n_{k\bar{\sigma}} \rangle}{z - (\xi_k + U)} \neq \frac{1}{z - \xi_k}$$

lower Hubbard band

upper Hubbard band

Mott transition: composite excitations

$$\Delta E = U - 4dt = U - W$$

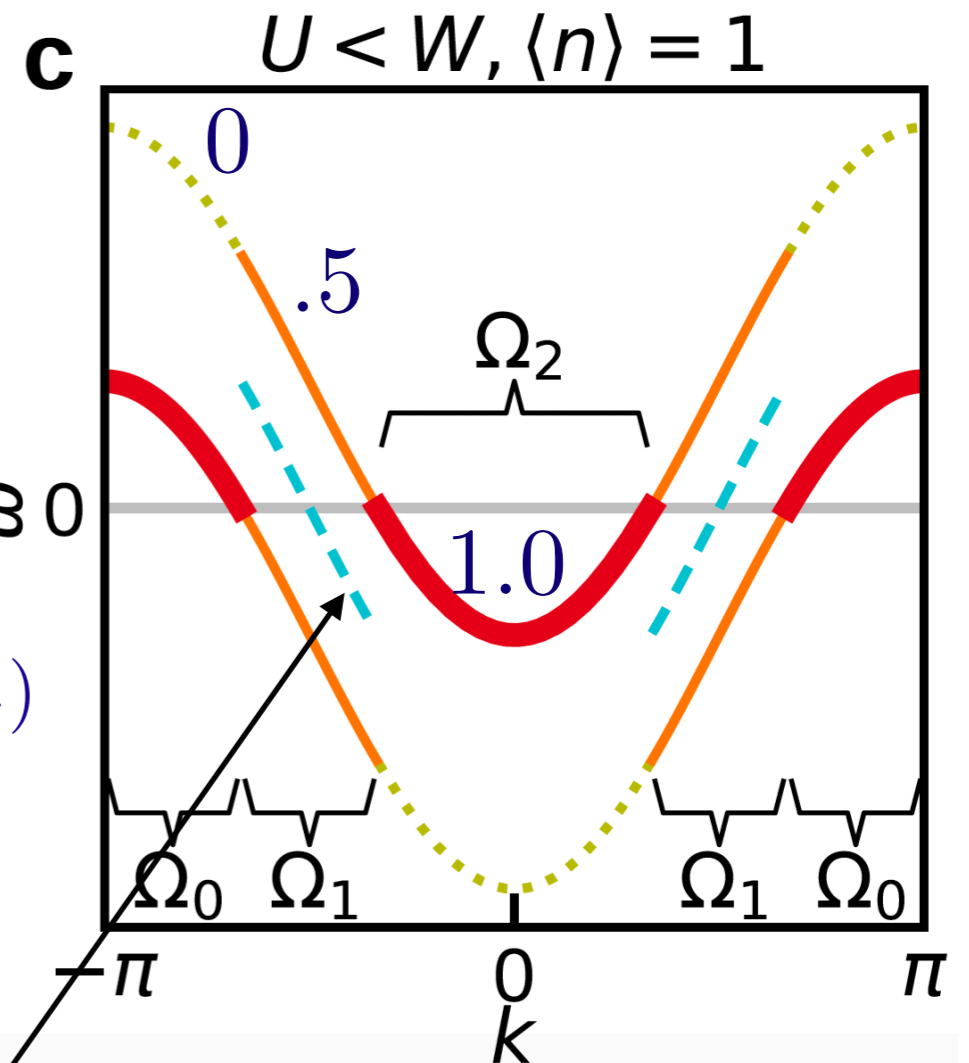


insulator

$$\eta_{k\sigma}^\dagger = c_{k\sigma}^\dagger n_{k\bar{\sigma}}$$

$$\zeta_{k\sigma}^\dagger = c_{k\sigma}^\dagger (1 - n_{k\bar{\sigma}})$$

Luttinger Surface



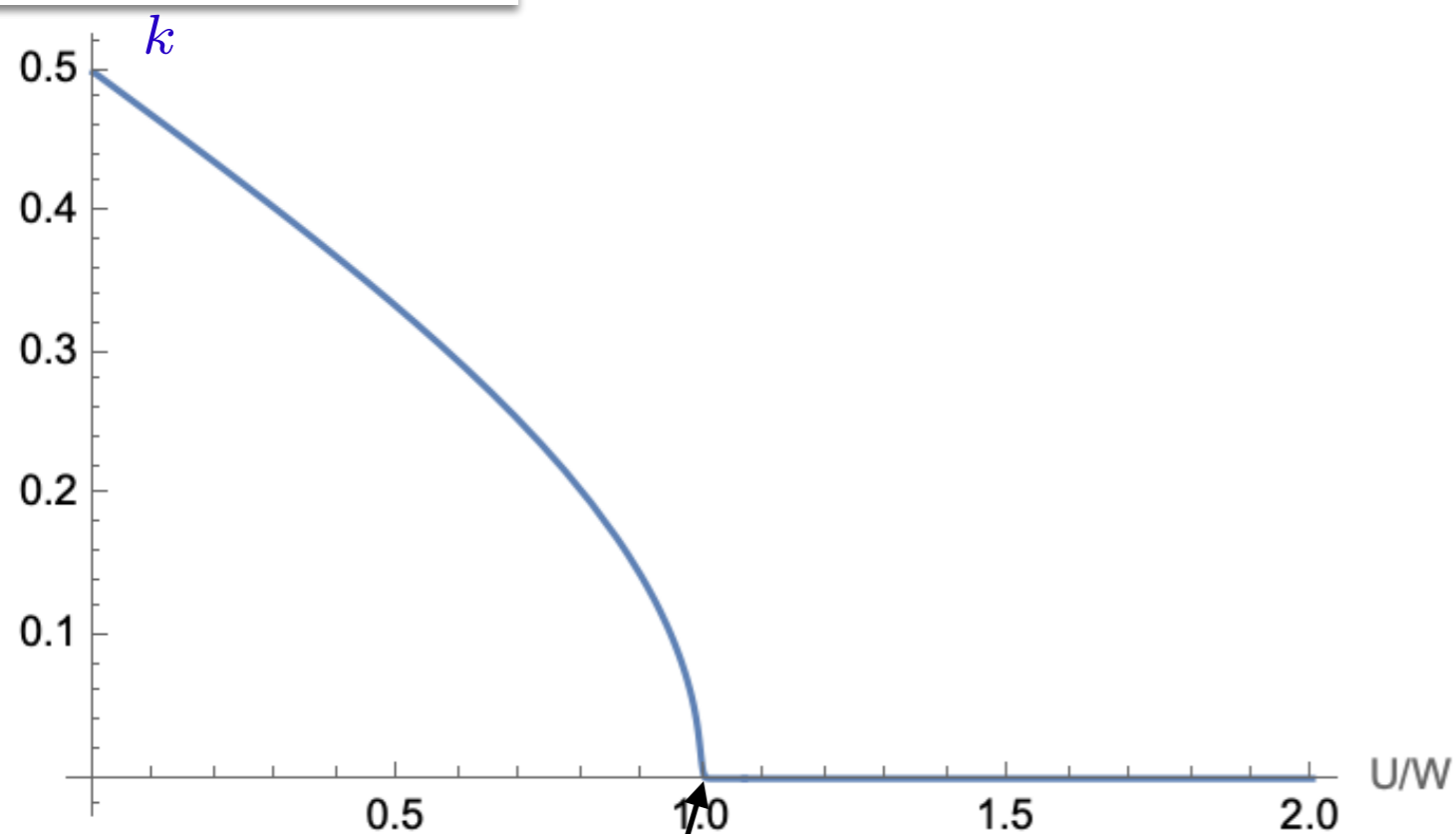
metal

HK

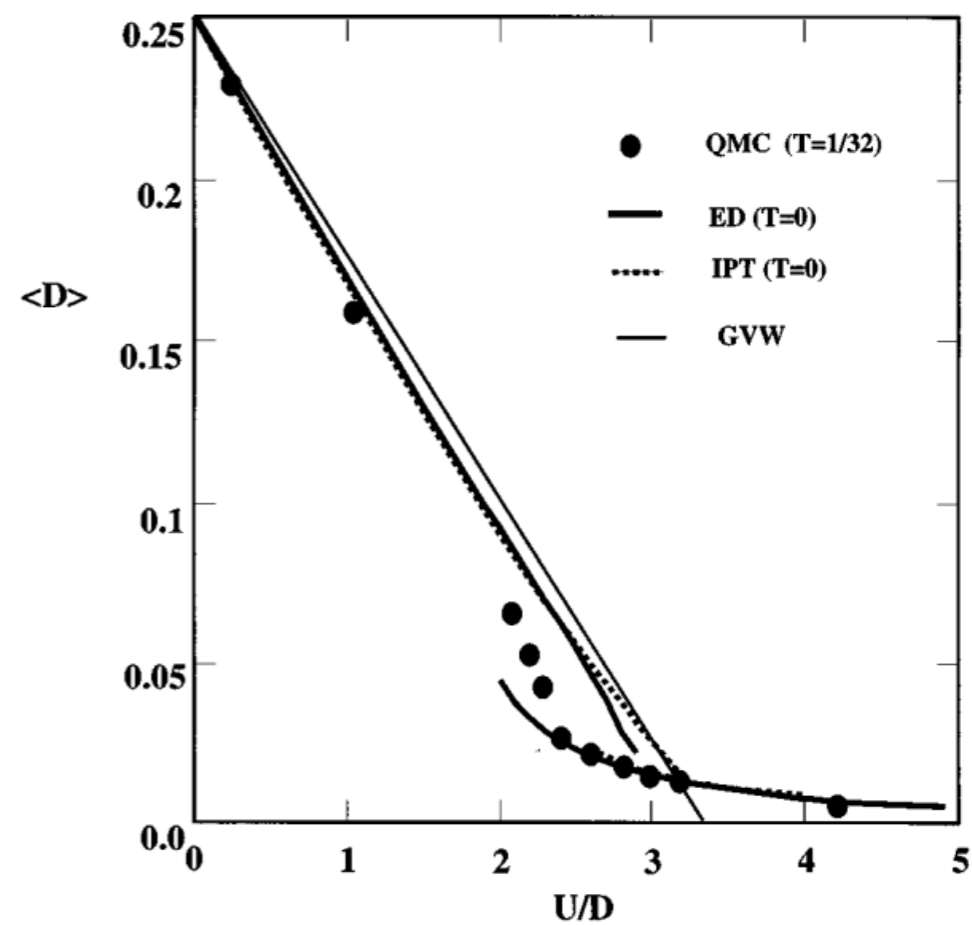
Mott transition

Hubbard

$$D = \sum_k \langle n_{k\uparrow} n_{k\downarrow} \rangle$$



$$D = \langle n_{i\uparrow} n_{i\downarrow} \rangle$$

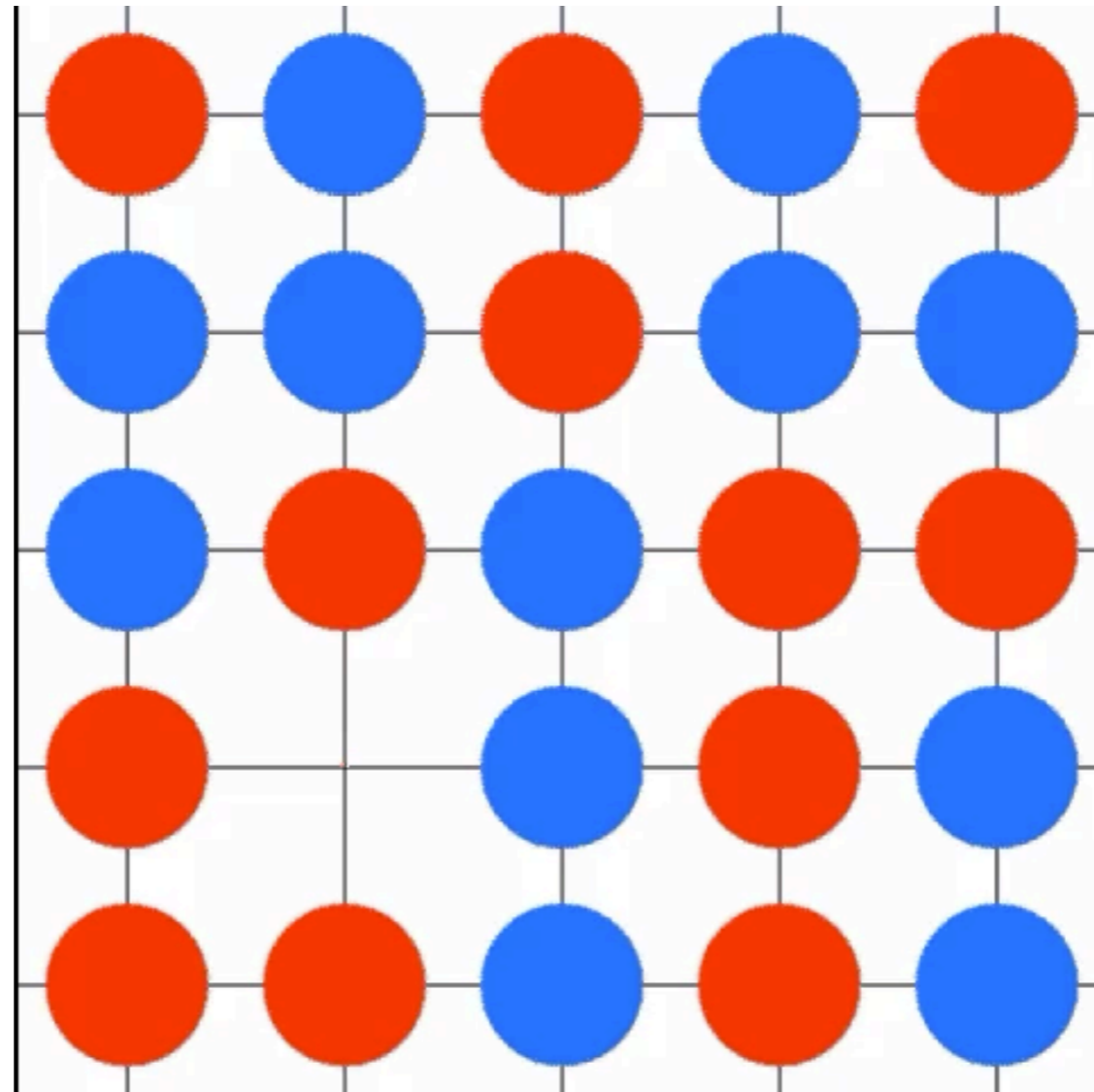


Mott transition

real space

what does the HK model leave out??

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



dynamical spectral weight transfer

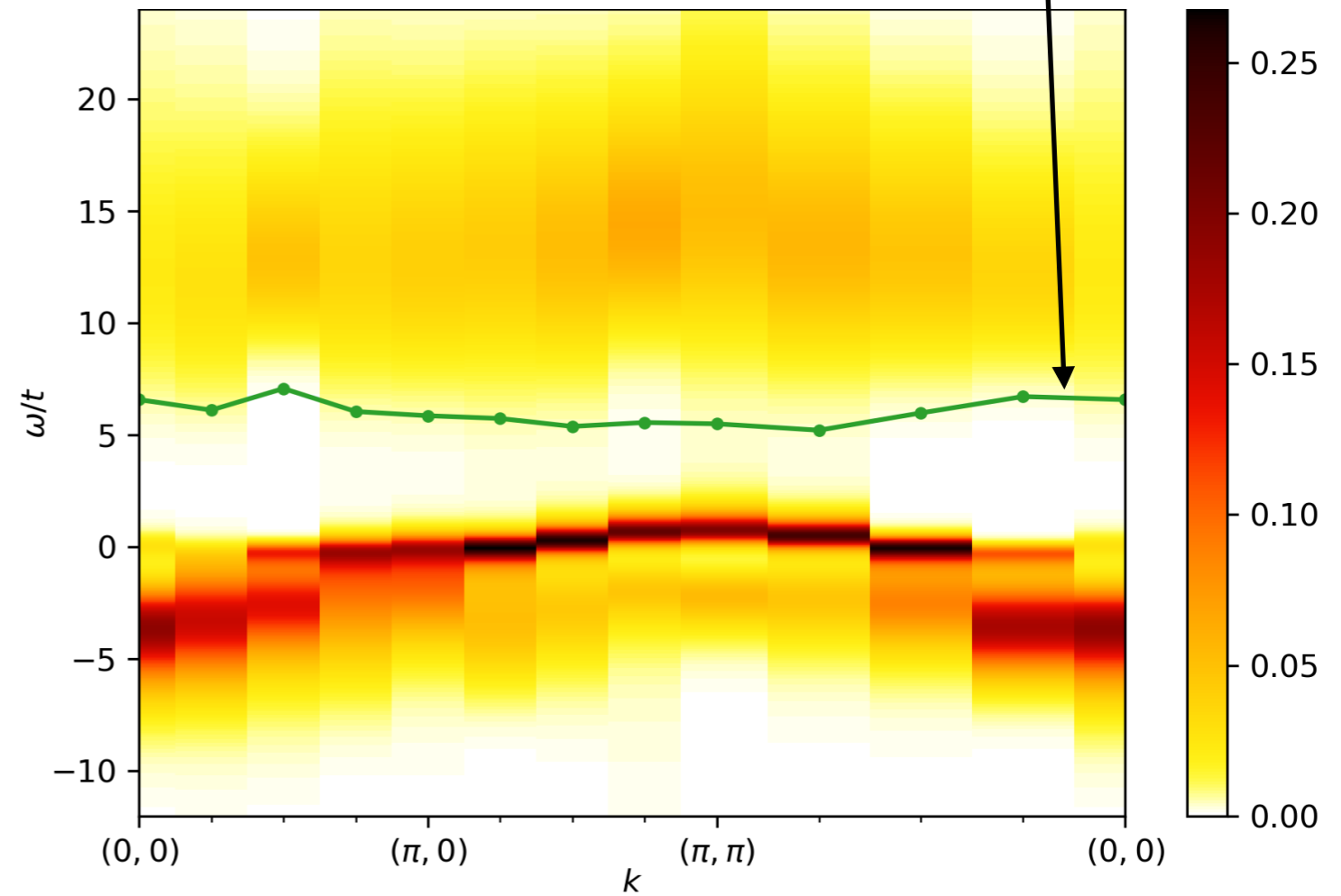
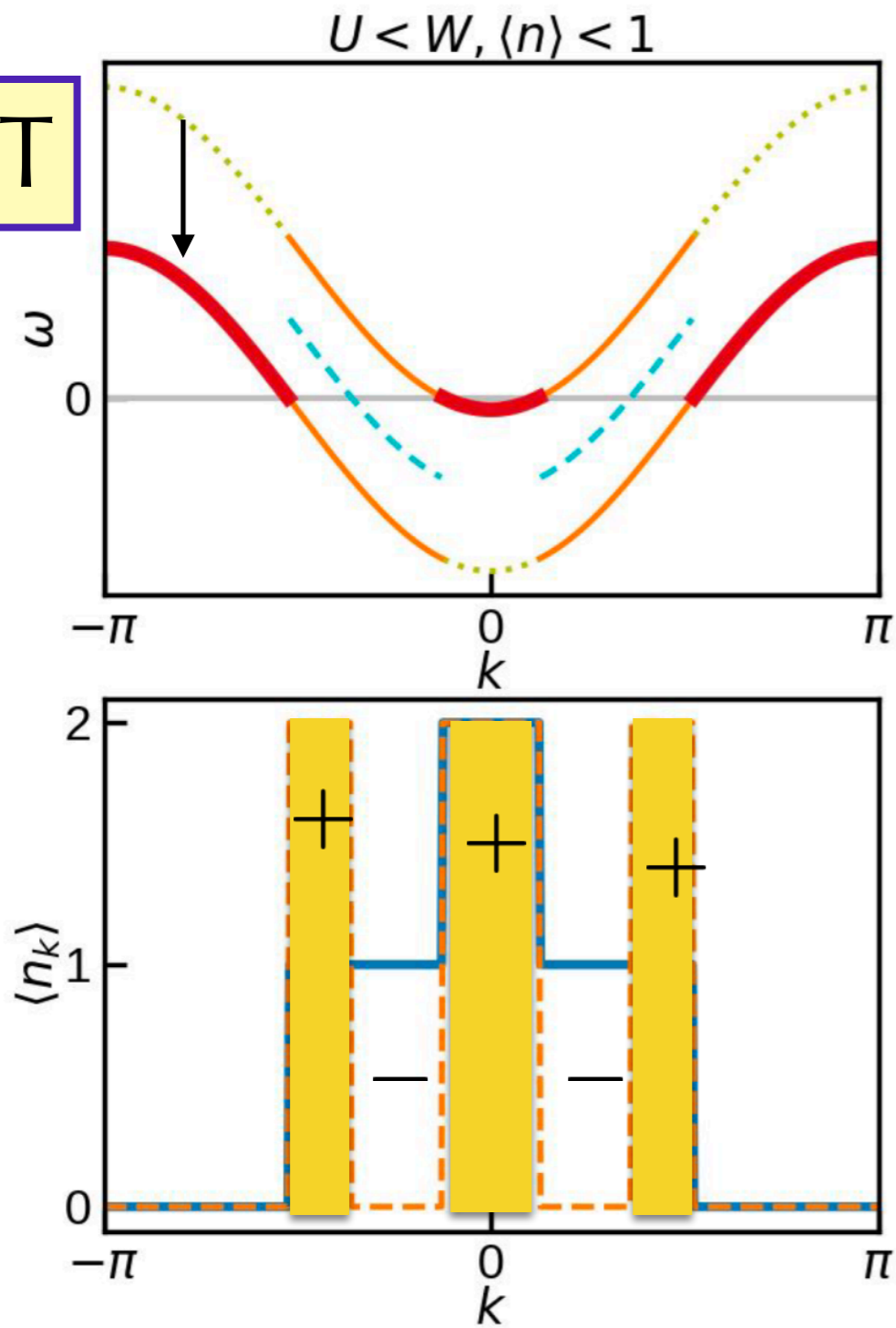
counting charges

Hubbard model

surface
of zeros

$$n = 0.9$$

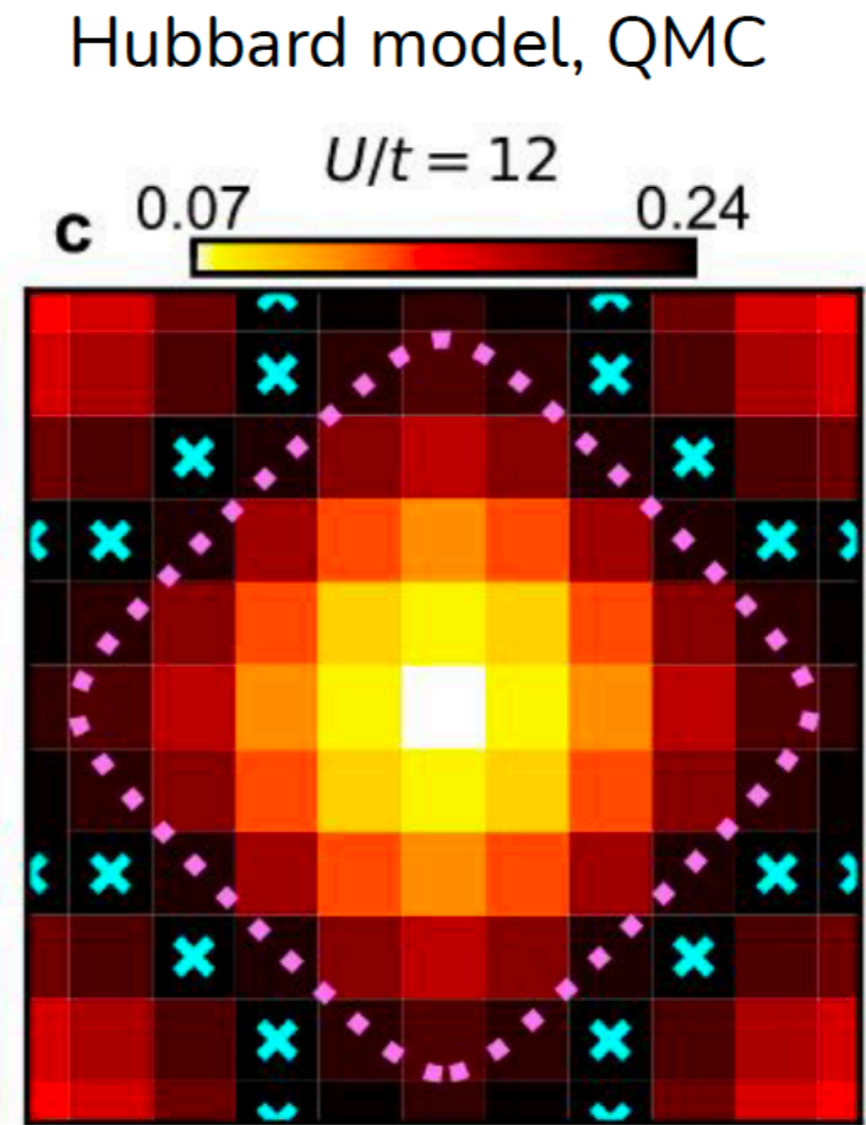
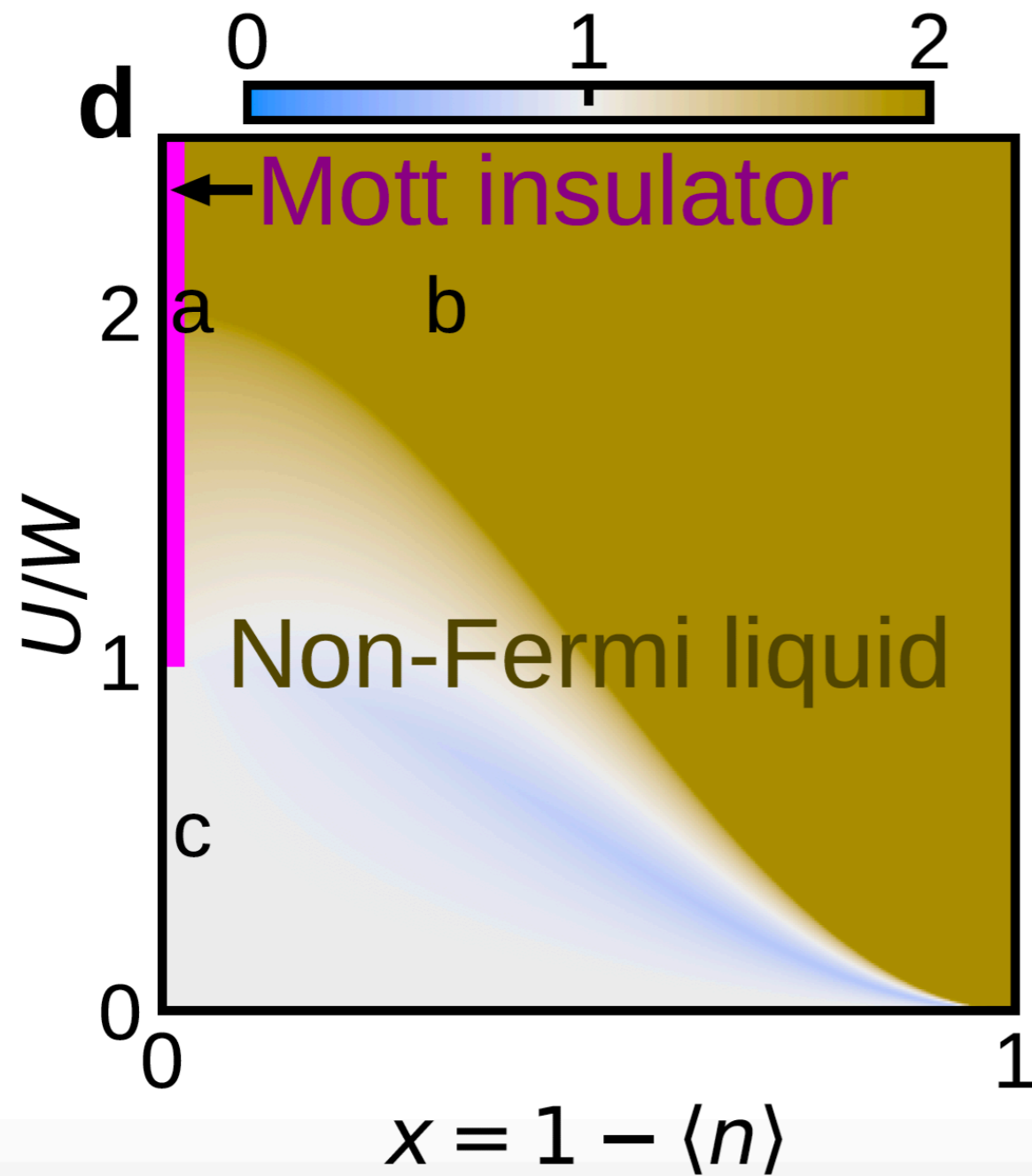
SWT



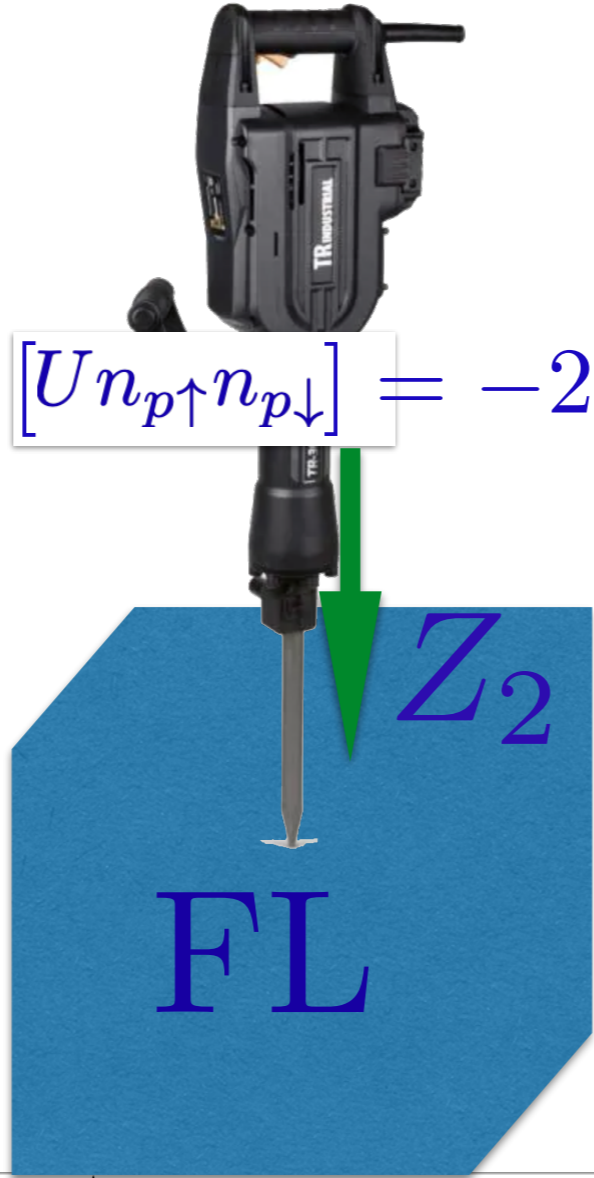
$$n_{\text{Lutt}} \neq \langle n \rangle$$

zeros \neq particles

Luttinger count Comparison



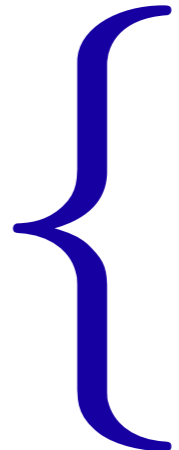
Wang, Ding, Moritz, EWH, Devereaux
npj Quantum Materials 5, 51 (2020)



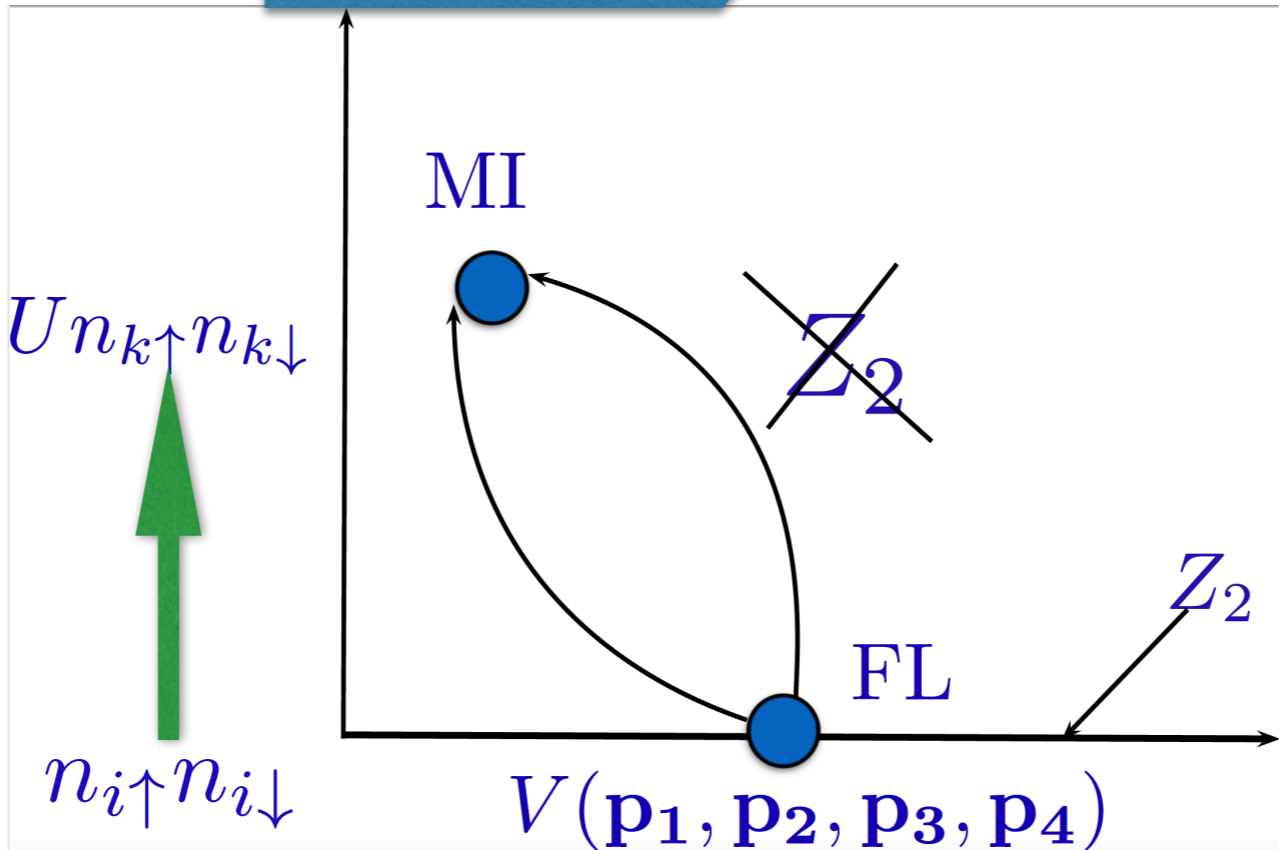
$$[U n_{p\uparrow} n_{p\downarrow}] = -2$$

FL

Z_2

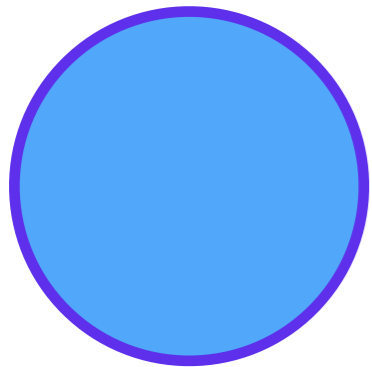


$$\frac{1}{N} \left(\frac{1}{s} \right)^2 \propto \frac{1}{s}$$

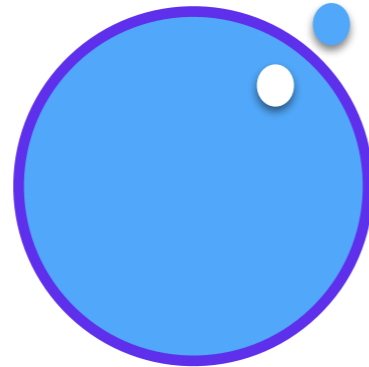


Hubbard
not
necessary
(universality
class)

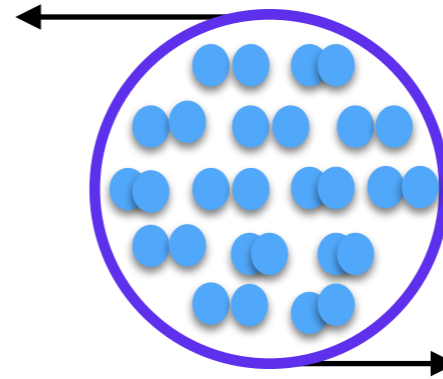
Fermi gas



Fermi liquid



BCS
superconductor



Mottness

2

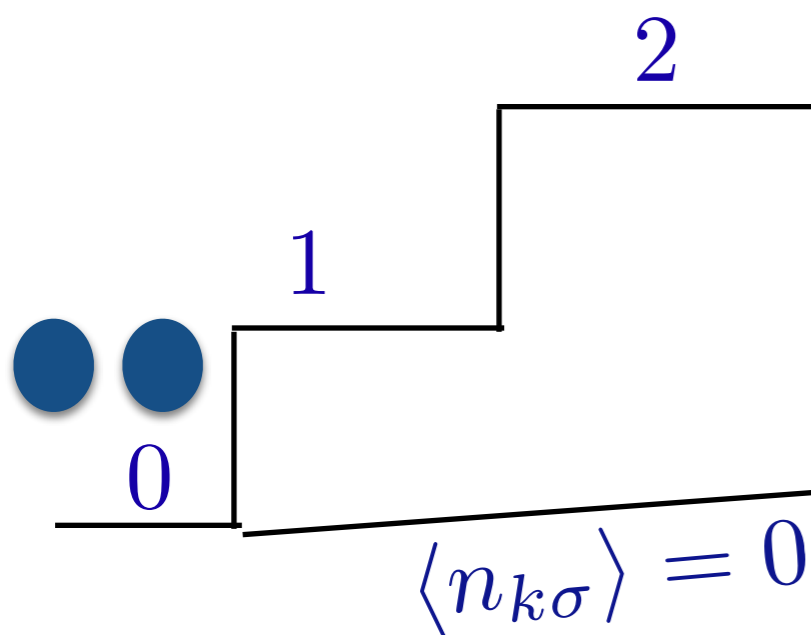
1

0



Superconductivity?

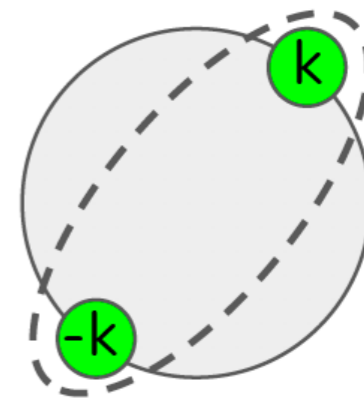
Cooper Instability



$$\langle n_{k\sigma} \rangle = 0$$

$$H = H_{\text{HK}} - gH_p$$

$$|\psi\rangle = \sum_{k \in \Omega_0} \alpha_k b_k^\dagger |\text{GS}\rangle$$

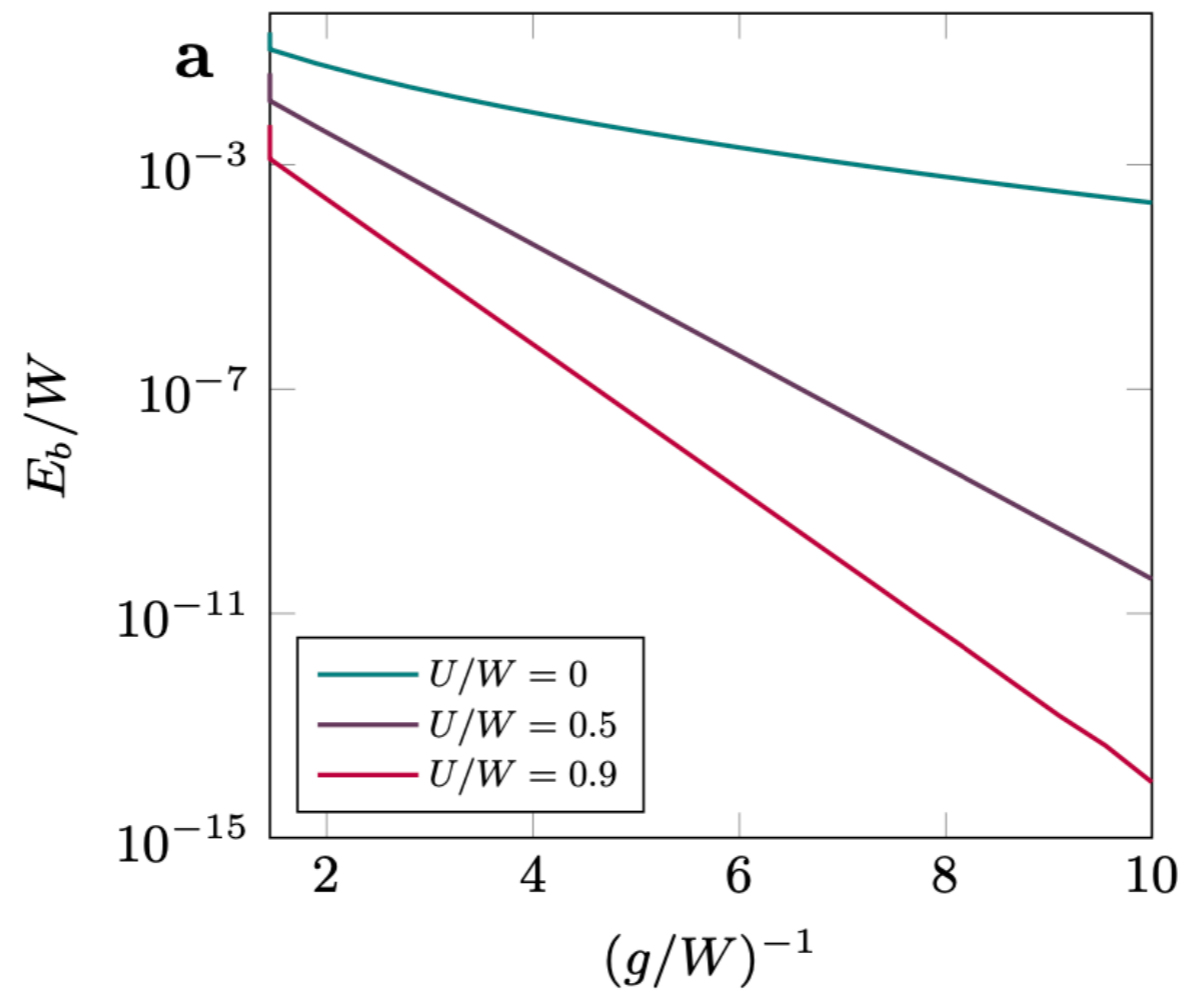


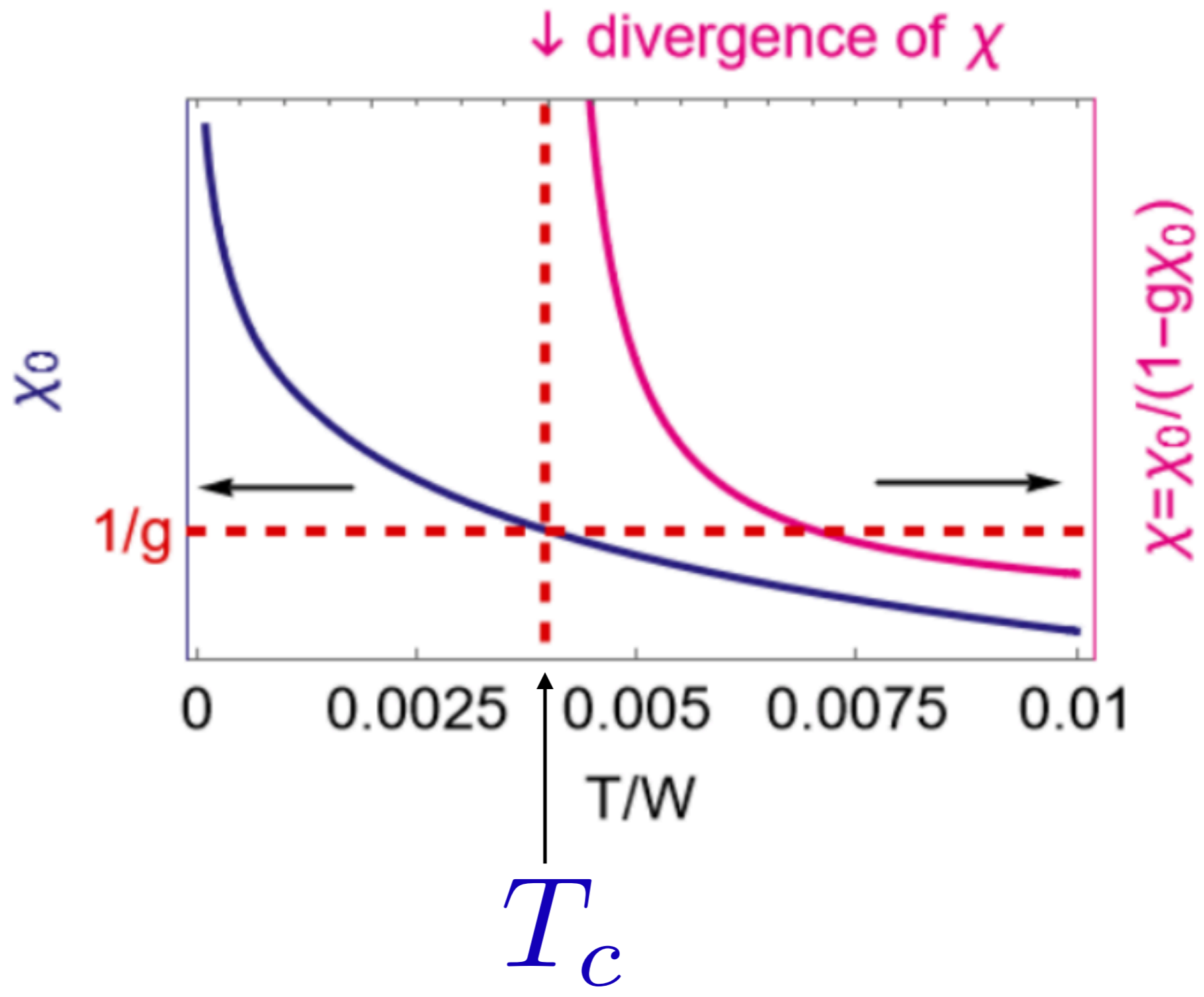
$$= \sum_{k, k'} b_k^\dagger b_{k'}$$

$$E_b = \langle \text{GS} | H | \text{GS} \rangle - \langle \psi | H | \psi \rangle \leq 0$$

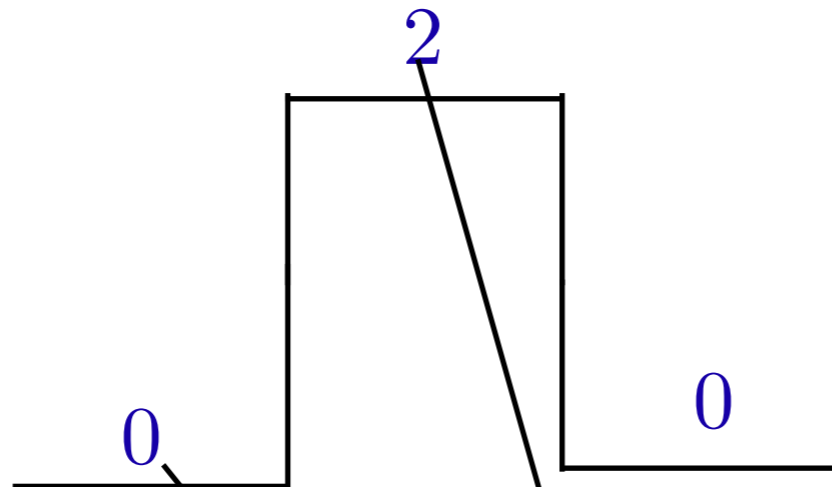
Cooper Instability

$$E_b = -E \sim W(1 - (U/W)^2)e^{-\pi W \sqrt{1 - (U/W)^2} / g}$$



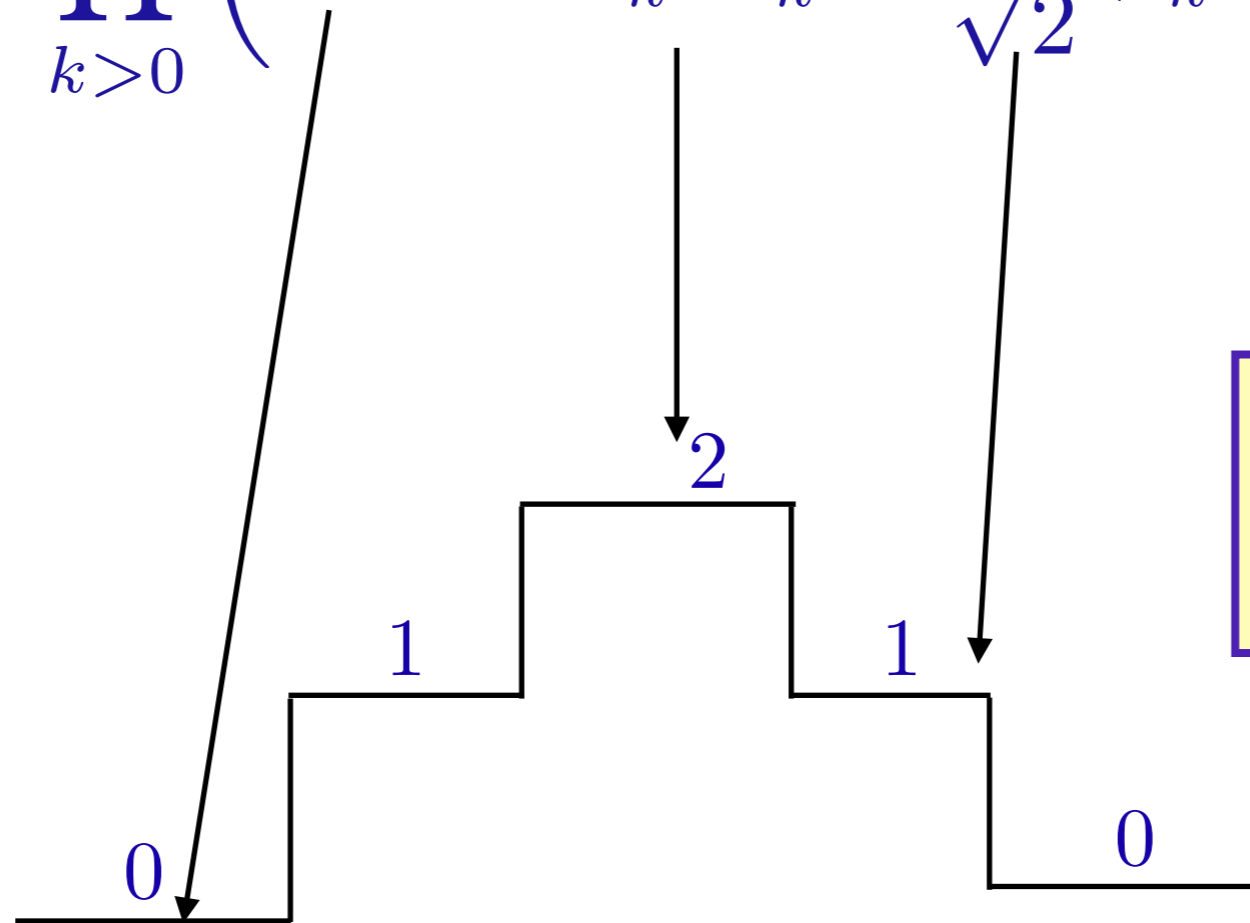


BCS variational wave function



$$|\psi_{\text{BCS}}\rangle = \prod_k (u_k + v_k b_k^\dagger |0\rangle)$$

$$|\psi\rangle = \prod_{k>0} \left(x_k + y_k b_k^\dagger b_{-k}^\dagger + \frac{z_k}{\sqrt{2}} (b_k^\dagger + b_{-k}^\dagger) \right) |0\rangle$$



HK
generalization

three variational parameters

gap equation

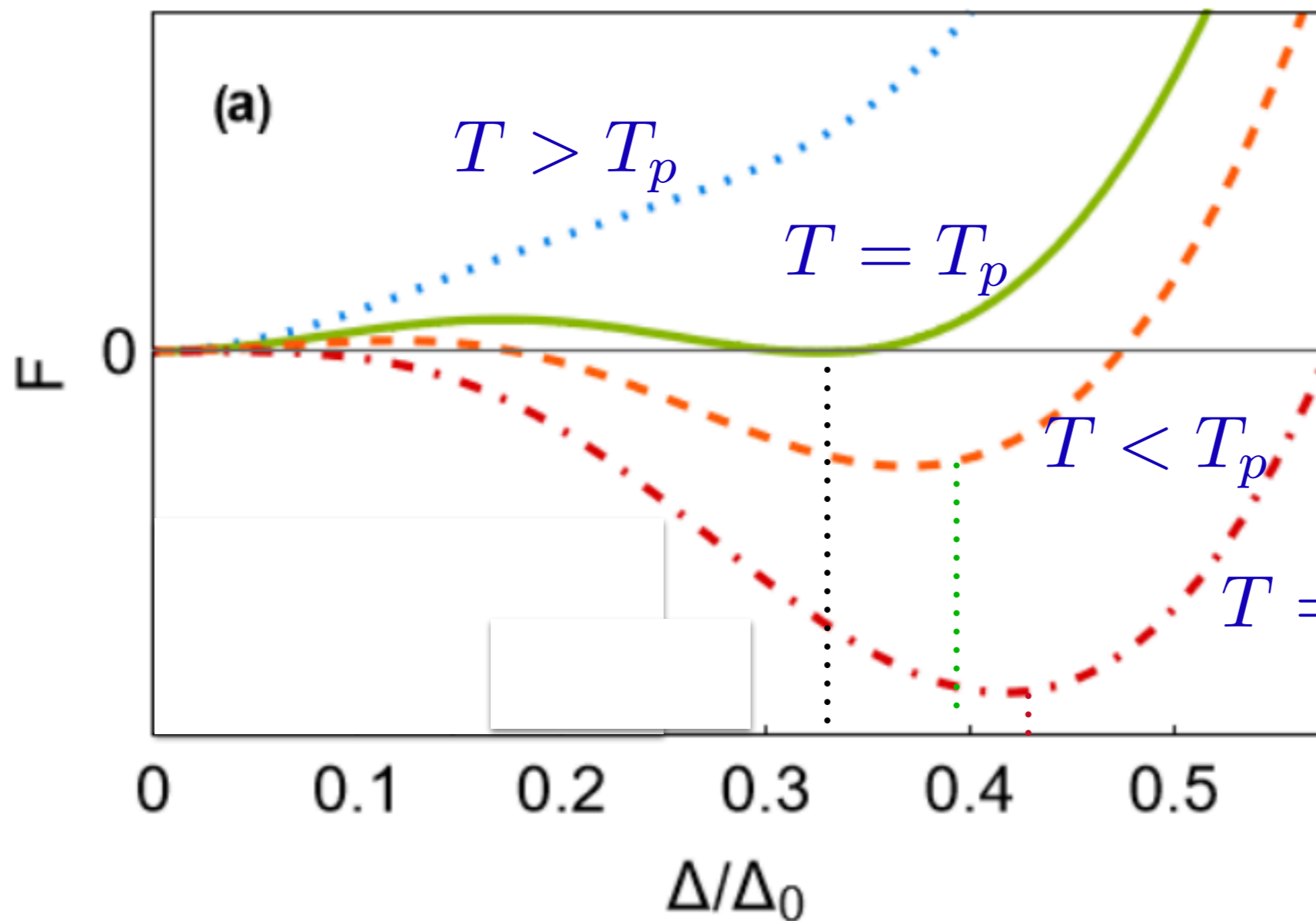
gap/ T_c ratio

$$\Delta = (W - U)^{1/2} U^{1/2} e^{-\frac{W}{2g}}$$

$$T_c = (W - U)^{4/5} U^{1/5} \frac{e^\gamma}{\pi} e^{-\frac{4}{5} \frac{W}{g}}.$$

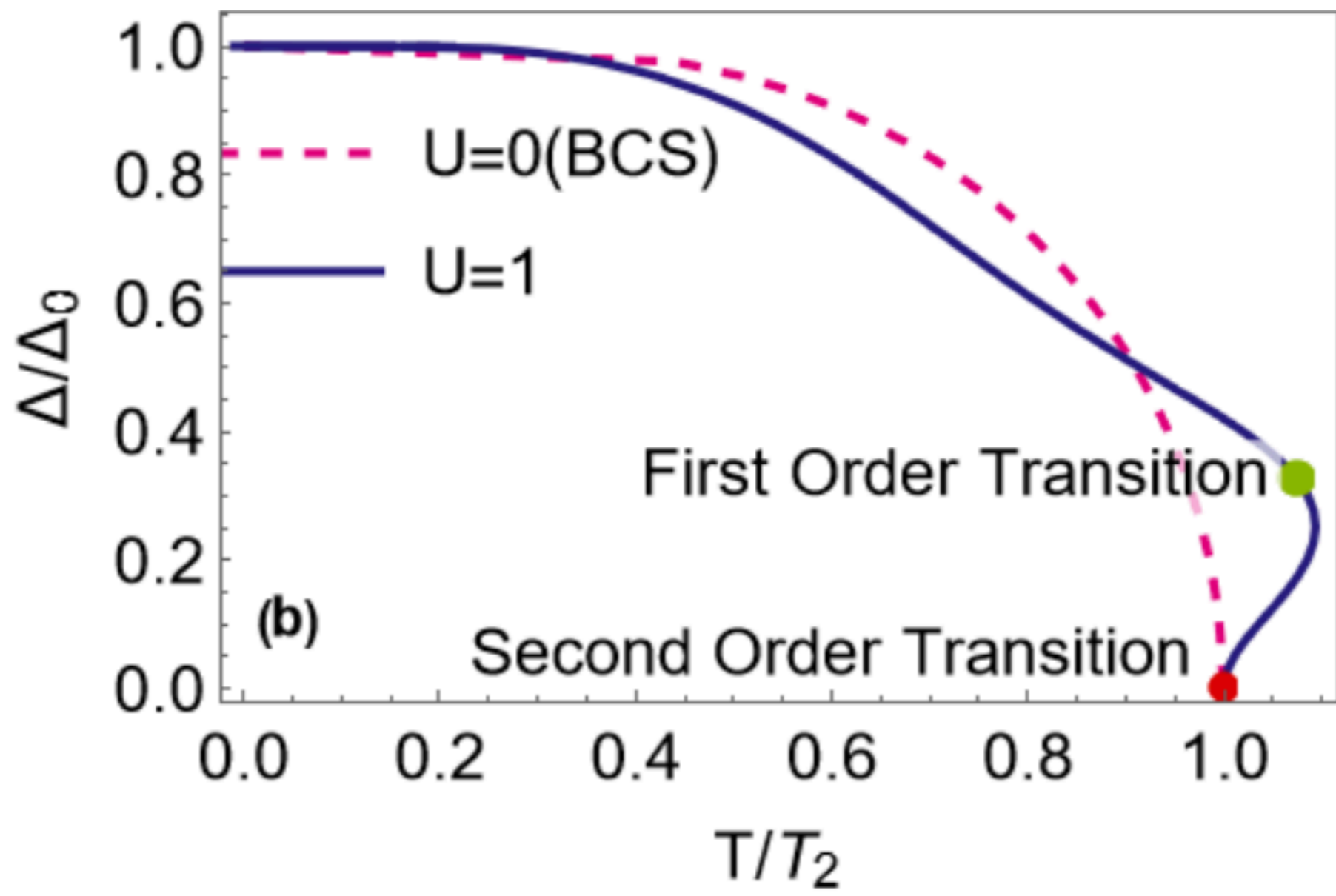
$$\lim_{g \rightarrow 0} \frac{\Delta}{T_c} \rightarrow \infty$$

non-BCS superconductivity

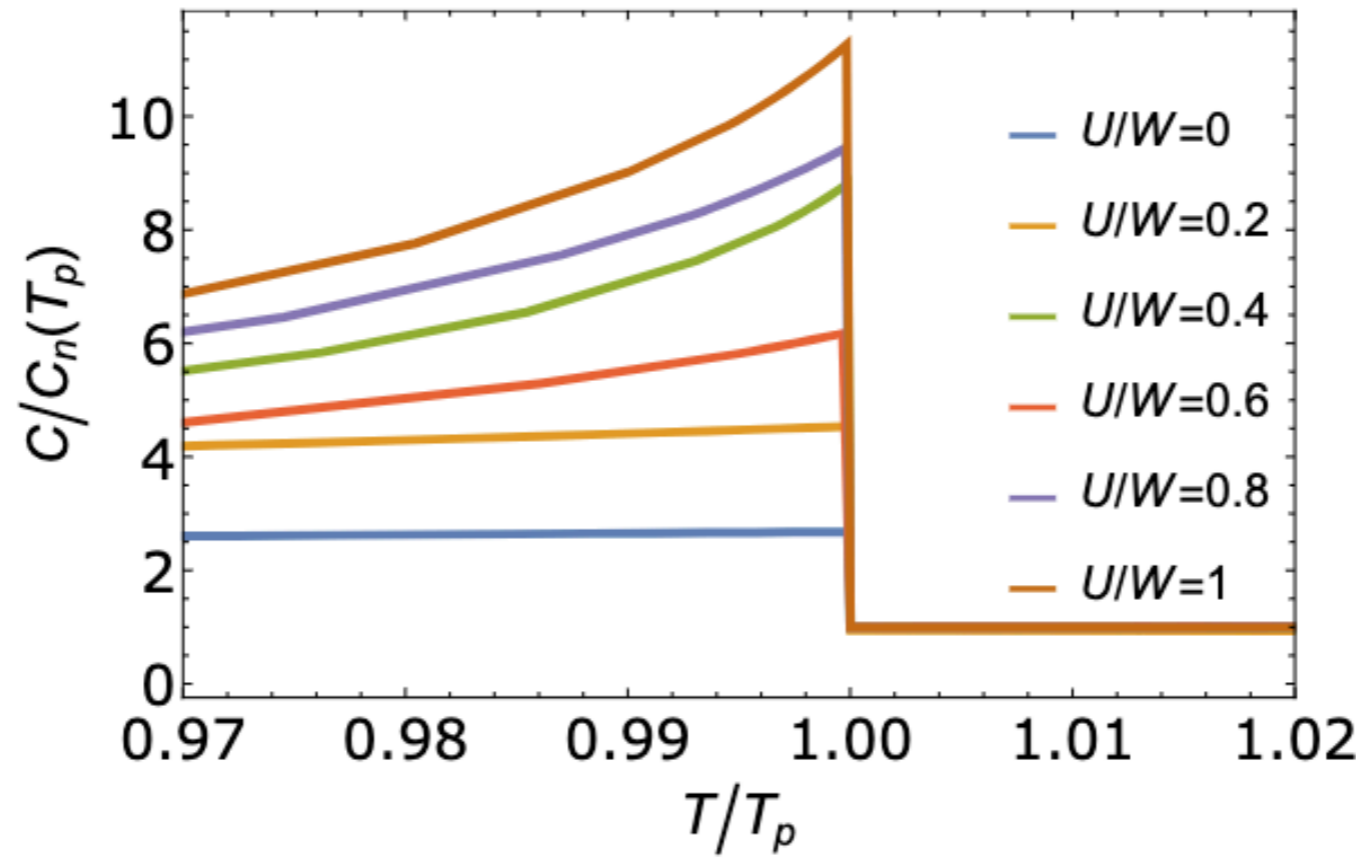


$t_G \approx 10^{-11}$

MF theory
 is accurate!

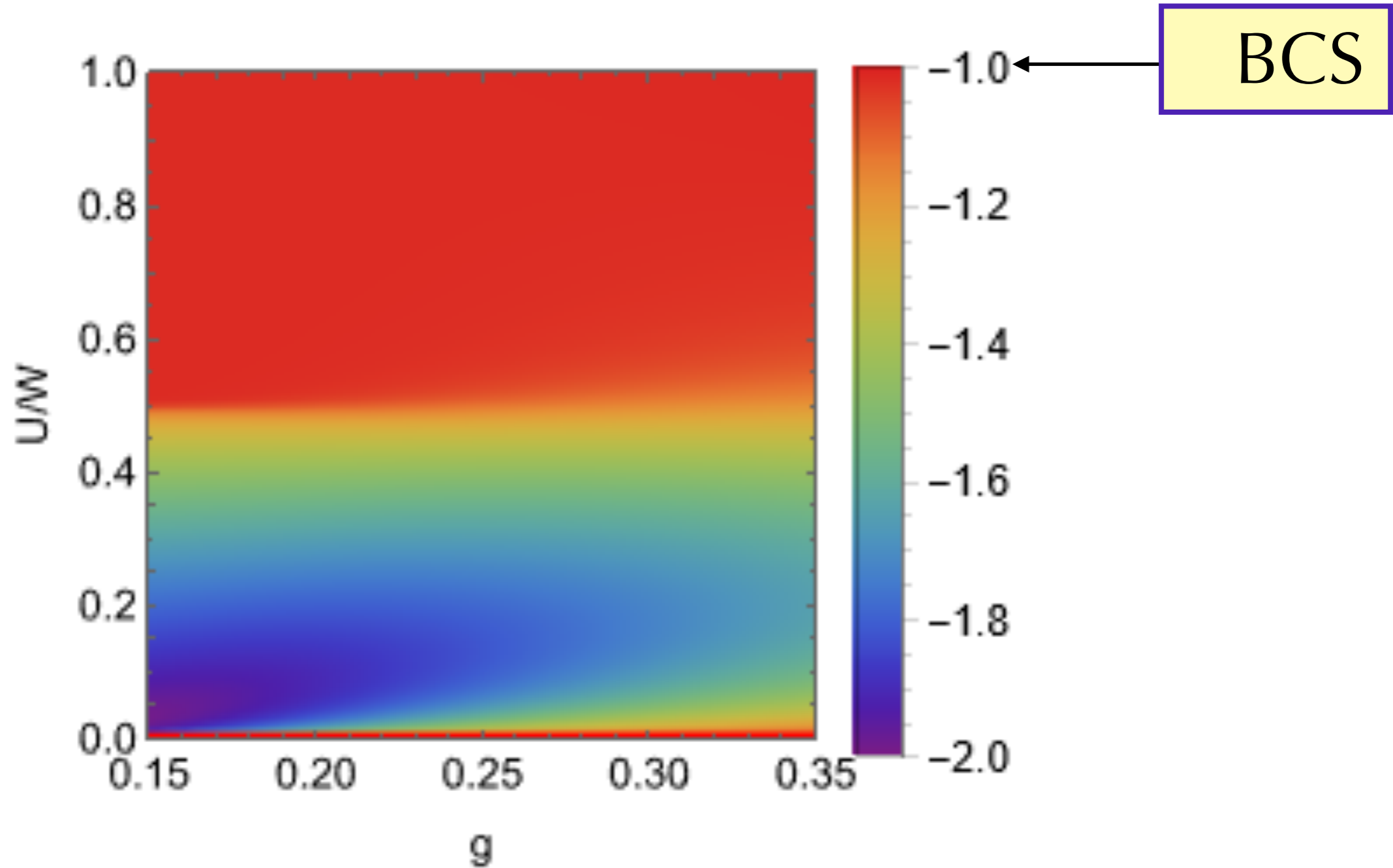


heat capacity jump



Condensation Energy

$$E_{\text{cond}}/N(0)\Delta^2 < 0$$



Bogoliubov excitations

$$\gamma_{k\sigma} |\psi_{\text{BCS}}\rangle = 0$$

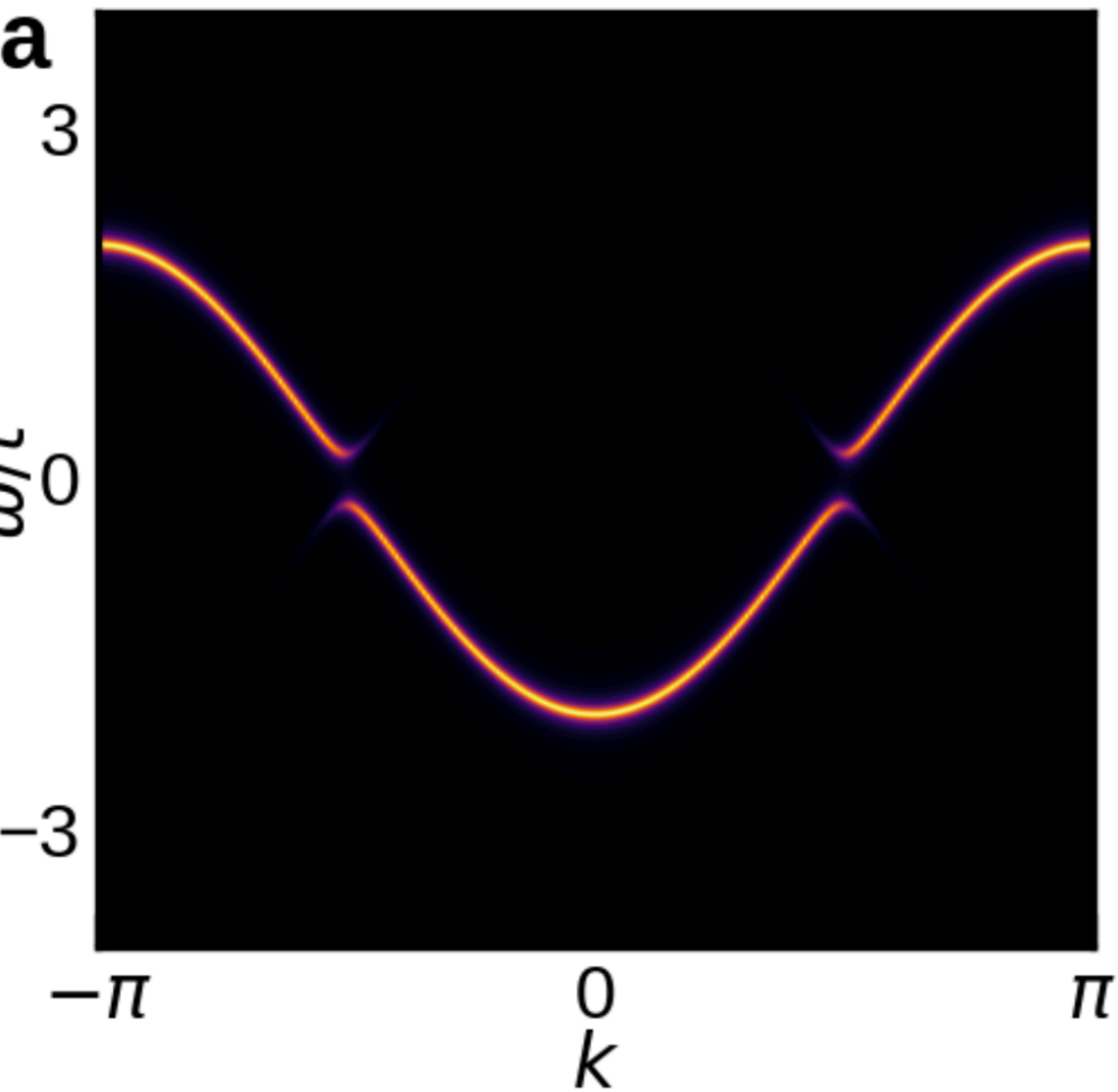
$$\gamma_{k\sigma} = u_k c_{k\sigma} - \sigma v_k c_{-k\bar{\sigma}}^\dagger$$


PYHons excitations

$$\gamma_{k\sigma}^l \propto \sqrt{2} x_k \zeta_{k\sigma}^\dagger - \sigma z_k \zeta_{-k\bar{\sigma}}$$

$$\gamma_{k\sigma}^u \propto z_k \eta_{k\sigma}^\dagger - \sigma \sqrt{2} y_k \eta_{-k\bar{\sigma}}$$

BCS



PYHon band

can we explain the color change?

REPORT

Superconductivity-Induced Transfer of In-Plane Spectral Weight in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

H. J. A. Molegraaf¹, C. Presura¹, D. van der Marel^{1,*}, P. H. Kes², M. Li²

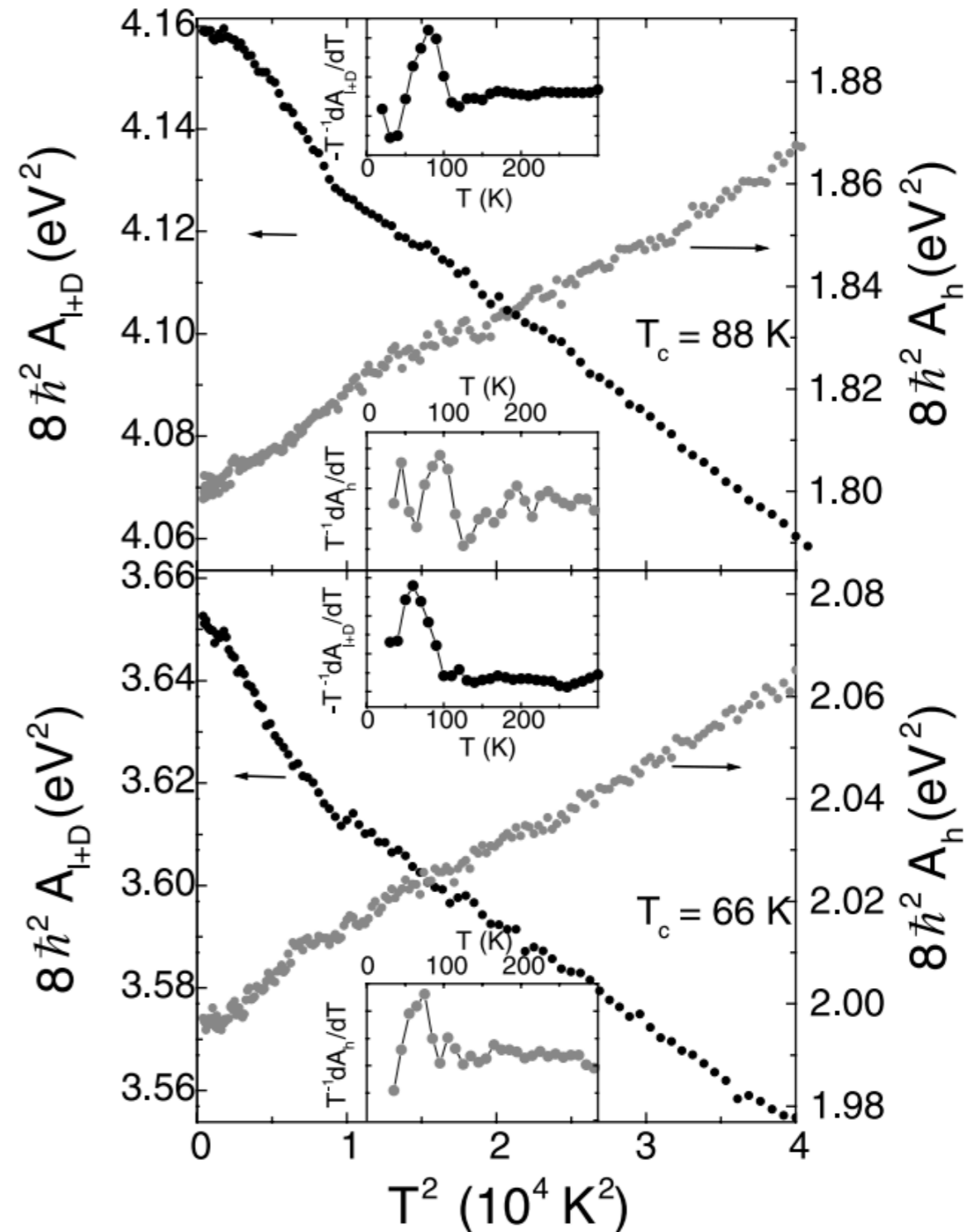
+ See all authors and affiliations

Science 22 Mar 2002:
Vol. 295, Issue 5563, pp. 2239-2241
DOI: 10.1126/science.1069947

$$A_l = \int_0^{\Omega} \sigma(\omega) d\omega \quad \Omega/2\pi c = 10000 \text{ cm}^{-1}$$

$$A_h = \int_{\Omega}^{2\Omega} \sigma(\omega) d\omega \quad \Omega/2\pi c = 10000 \text{ cm}^{-1}$$

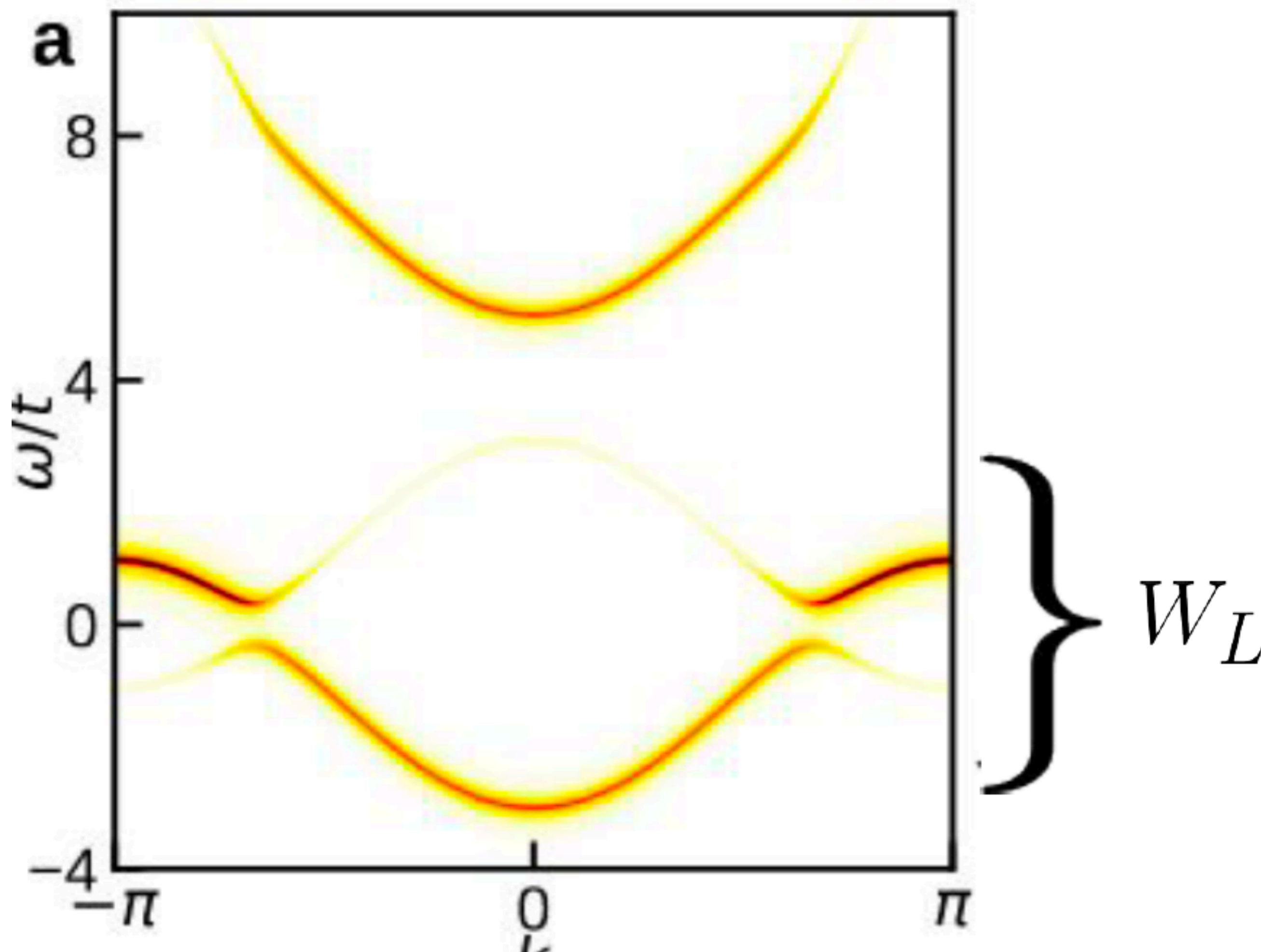
$$\frac{\Delta A_l}{A_l} \propto 3\%$$



condensation energy

Optical data are reported on a spectral weight transfer over a broad frequency range of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$, when this material became superconducting. Using spectroscopic ellipsometry, we observed the removal of a small amount of spectral weight in a broad frequency band from 10^4 cm^{-1} to at least $2 \times 10^4 \text{ cm}^{-1}$, due to the onset of superconductivity. We observed a blue shift of the *ab*-plane plasma frequency when the material became superconducting, indicating that the spectral weight was transferred to the infrared range. Our observations are in agreement with models in which superconductivity is accompanied by an increased charge carrier spectral weight. The measured spectral weight transfer is large enough to account for the condensation energy in these compounds.

UV-IR mixing



why?

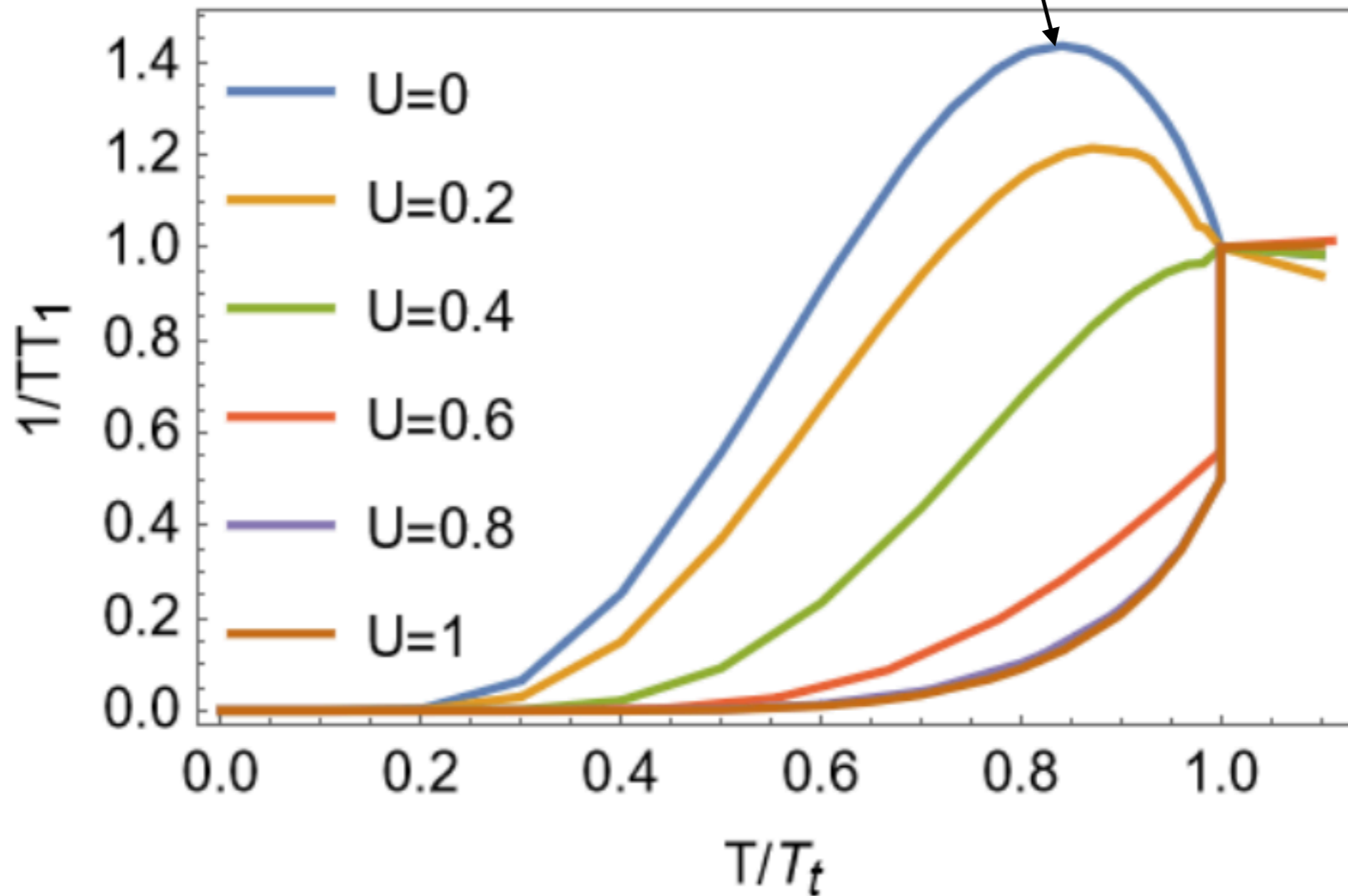
$$H = H_{\text{HK}} + H_p$$

$$[H_{\text{HK}}, H_p] \neq 0$$



dynamical
spectral weight
transfer

Hebel-Slichter
peak killed by
Mottness



Superconductivity

observable

$$\chi \rightarrow \infty$$

$$\Delta \neq 0$$

$$\lim_{g \rightarrow 0} 2\Delta_0/k_B T_c$$

quasi – particles

t_G (Ginzburg)

$$1/TT_1$$

Landau Expansion

$$E_{\text{cond}}/N(0)\Delta^2$$

BCS/FL

$$T_c$$

$$T_c$$

$$3.52$$

Bogoliubons

$$\approx 10^{-12}$$

HS peak

$$a = \alpha t, b > 0$$

$$-1$$

Mottness



HM

HK

PYHons

violation of Luttinger

non-BCS
superconductivity

