# STRONGLY CORRELATED SUPERCONDUCTIVITY

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# *Outline*

- Can Strong Correlation "help" Superconductivity?
- Mott Transition to a Zero-Entropy Mott Insulator
- Superconductivity close to the MIT
- Strong Enhancement of $\Delta$ due to Repulsion
- Key:
  Screened Repulsion, Unscreened Attraction
- Relevance for t-J Model

# *Superconductivity and e-e Correlation*

- In Conventional Superconductors $\rightarrow$ Coulomb interaction opposes to SC
- High T$_c$ Superconductors (Cuprates and Fullerene) $\rightarrow$ Strong Electron Correlation $U \gg W$
- The Cuprates are doped Mott Insulators
- Fullerene is considered an Electron-phonon Superconductor (s-wave), but it becomes a Mott Insulator by lattice expansion

- The Proximity to a Mott Transition can Strongly Enhance Superconductivity

# The Model

$$H = H_{kin} + \frac{U}{2}\sum_i n_i^2 - J\sum_i (2S_i^2 + \frac{1}{2}L_i^2)$$

- Three-Orbitals Hubbard Model ($L = 1$)
- Mott Transition for every $n = 1 \ldots 5$
- "Pure" Hubbard model ($J = 0$) $\rightarrow$
  "Usual" Mott Transition in DMFT
- Introducing an Interaction between Orbitals the Story may be Really Different!

✔ We take $J < 0$ (Due to phonons in $C_{60}$)

⬇

**Lowest Spin and Orbital Momentum**

- We study the Mott Transition for $\langle n \rangle = 2$
  (Relevant to $A_4C_{60}$ Compounds)

*M. Capone, M. Fabrizio, and E. Tosatti, Phys. Rev. Lett.* **86, 5361 (2001).**

# *Weak and Strong Coupling Limits*

✓ We vary $U/W$ keeping fixed $J/U = -0.02$ (Pressure-driven Mott Transition)

## Weak Coupling $U \ll W$

- Metal with 1/3 filled bands
- Attraction $J$ + Repulsion $U$
  Acting on different degrees of freedom
- The attraction would form an s-wave Order Parameter

Who wins?

Scattering Amplitude in Cooper channel

$$A = U + \frac{10}{3} J > 0$$

↓

REPULSION → Metal, No Superconductor

## Strong Coupling $U \gg W$

- Strong Correlation $\rightarrow$ Mott Insulator $\rightarrow$ 2 electrons localized on each site
- The Atomic Physics ($J$ term) is still effective and splits the multiplets
- The multiplets for two electrons are

$$S = 1,\ L = 1$$
$$S = 0,\ L = 2$$
$$\boxed{S = 0,\ L = 0}$$

- For $J < 0$ the Mott insulator prefers $S = 0$ and $L = 0$
- This State is Non-degenerate

**ZERO-ENTROPY MOTT INSULATOR**

# The Transition is not Direct

- A Continuous Transition from the Metal to the Nondegenerate Insulator is Not Possible
- Problem: the Zero Entropy of the Insulator (or, equivalently, the Spin-Gap)

## Two Possibilities:

1. First-Order Transition $\rightarrow$ NO!
2. Some Other Phase Appears

- What is the Possible Novel Phase?
- We use Dynamical Mean-Field Theory (DMFT) to solve this problem
- Bethe Lattice $t_{ij}^{\alpha,\beta} \equiv \delta_{\alpha\beta}$
- ED to solve the Impurity Model at $T = 0$

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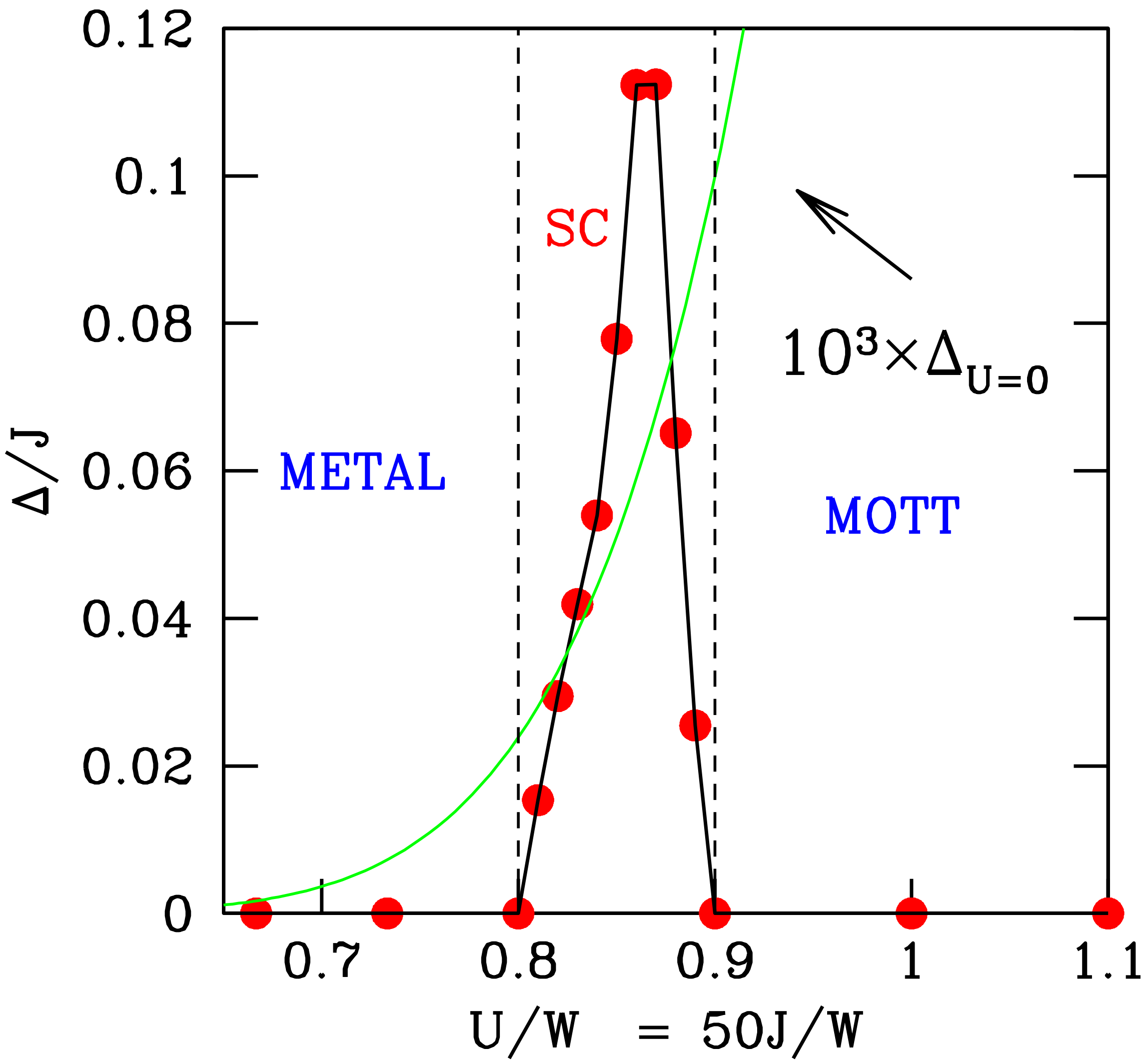
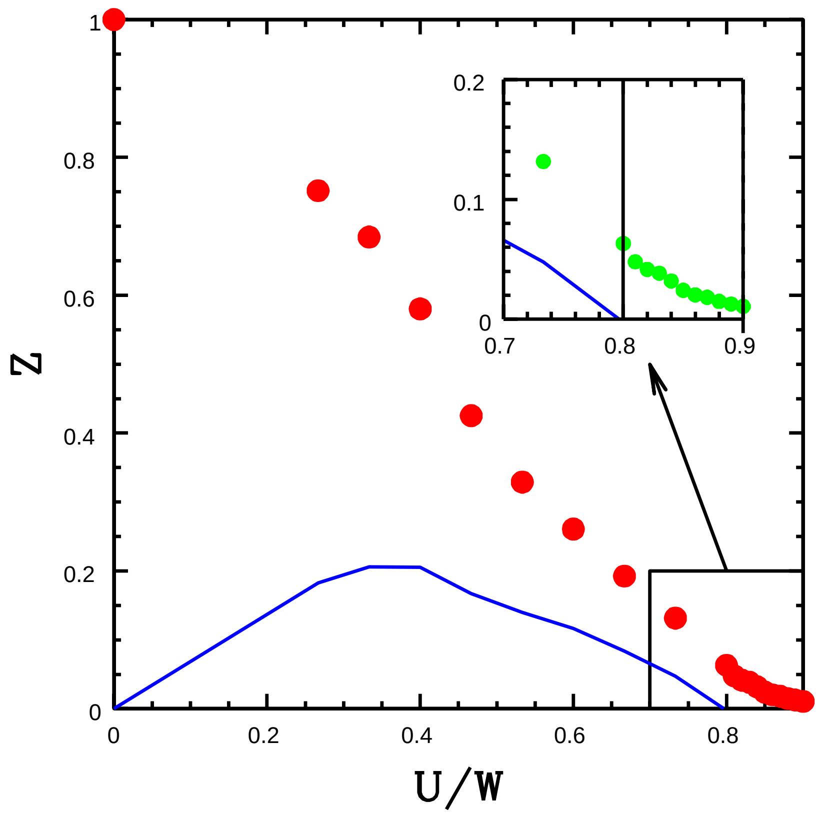
# *The DMFT Phase Diagram*




- SUPERCONDUCTIVITY appears close to the Mott transition
- $\Delta \equiv S(\omega = 0) \rightarrow \Delta_{SC}$ in BCS
- $\Delta \sim 1000\ \Delta(U = 0)$ !!!!!

# *How Can Correlation Enhance $T_c$?*

- For $U = 0$ the maximum $\Delta$ is for $W \sim J$
- Correlation reduces the coherent band $W \to W^* = ZW$




SUPERCONDUCTIVITY appears for $ZW \sim 10/3J \sim 0.06W$

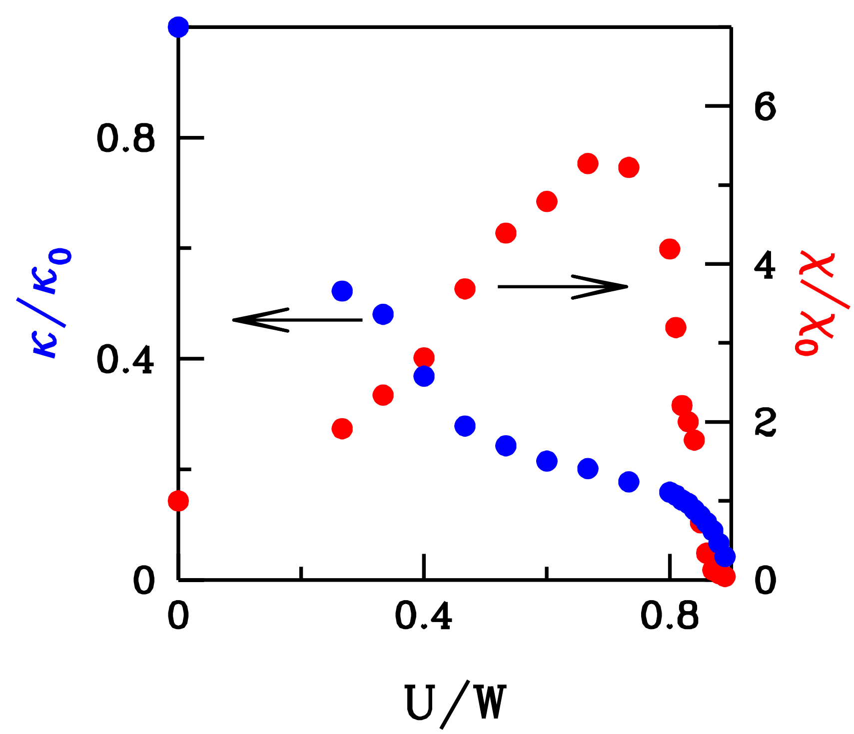
Heavy Quasiparticles with Unrenormalized Attraction?

# *Landau Fermi-Liquid Theory*

- The Interacting system can be mapped onto a system of non-interacting Renormalized Quasi-particles
- The Model has SU(2) spin $\times$ O(3) orbital symmetry $\longrightarrow$ More parameters which measure the interaction between Quasi-particles:

- $F_0^S \leftrightarrow$ charge fluctuations $n$
- $F_0^A \leftrightarrow$ spin fluctuations $\sigma$
- $G_0^S \leftrightarrow W^k$ fluctuations in charge channel
- $G_0^A \leftrightarrow W^k$ fluctuations in spin channel
- $H_0^S \leftrightarrow$ orbital fluctuations $L$
- $H_0^A \leftrightarrow$ spin-orbital fluctuations $L - \sigma$

# *Response Functions → Landau Parameters*




- $\frac{\chi}{\chi_0} = \frac{m^*}{1+F_0^A} \to 0$
- $\frac{\kappa}{\kappa_0} = \frac{m^*}{1+F_0^S} \to 0$

ALL the Susceptibilities VANISH →

- No Charge-Spin-Orbital Instability
- Landau $F$, $G$, $H$ diverge FASTER THAN $m^*$

# *Quasiparticle Interactions*

S-wave Superconducting Amplitude

$$A = \frac{Z}{12\rho}\left(\frac{F_0^S}{1+F_0^S} - \frac{3F_0^A}{1+F_0^A} + \frac{2G_0^S}{1+G_0^S} - \frac{6G_0^A}{1+G_0^A}\right)$$

$A < 0 \rightarrow$ Superconducting Instability

$U \rightarrow U_c$ all $F$ diverge $\rightarrow$ $\boxed{A \rightarrow -\frac{Z}{2\rho}}$

↓

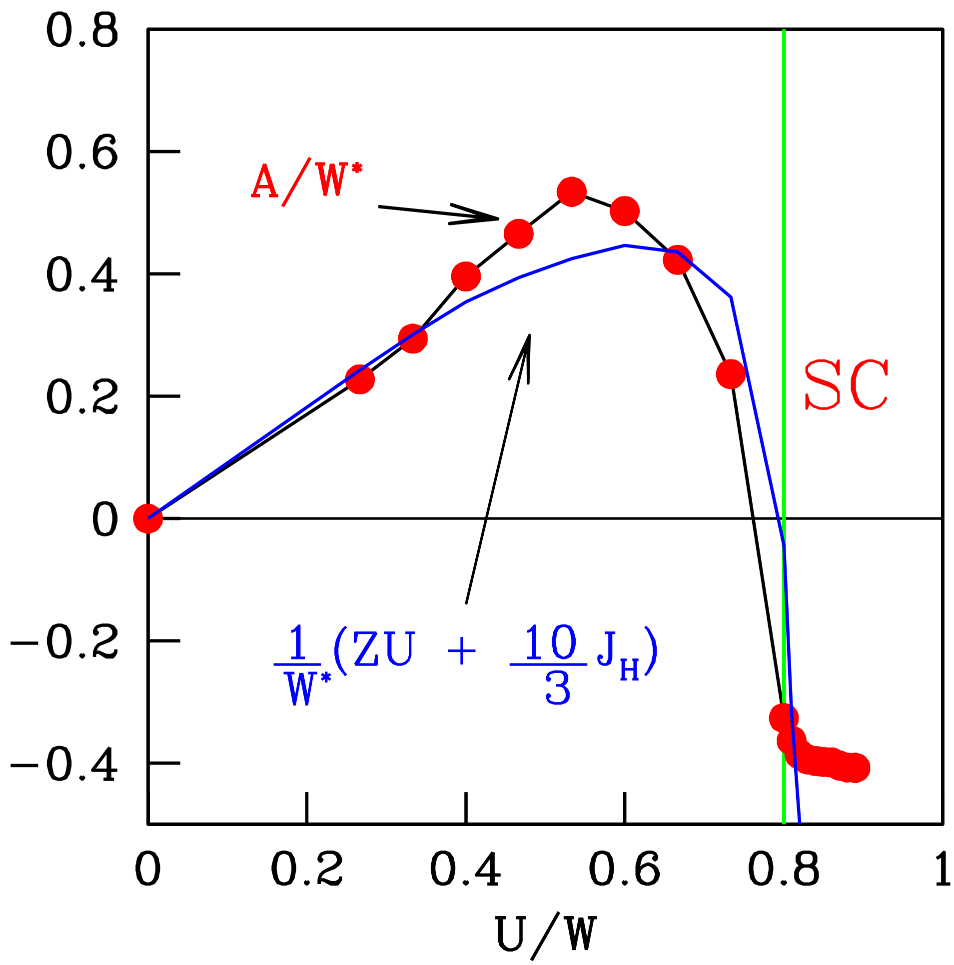
ATTRACTIVE close to $U_c$

REPULSIVE at Weak-Coupling!!!

↓

Repulsion gives rise to Superconductivity!

# DMFT Results




The True Attraction is Almost Equal to

$$A^{true} \simeq ZU - \frac{10}{3} J$$

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*Science* **296**, *2364 (2002) and cond-mat/0207058*

# The Scenario

- $U$ Strongly Renormalizes the Quasiparticles
  $\rightarrow$ Quasiparticle Repulsion is $ZU \ll U$
- The Attraction $J$ is NOT screened
  Since It Involves Different Degrees of Freedom

↓

$$A = ZU - \frac{10}{3}J$$

Superconductivity appears for
$A < 0 \rightarrow Z \simeq 0.06$ (Good Agreement with $Z$)

↓

Strongly Correlated Superconductivity of
Quasi-particles with large $m^* = 1/Z$
and Unrenormalized Attraction $J \sim ZW$

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# *Is This a Generic Mechanism?*

✓ Analogy with Anderson's RVB idea for the Cuprates

✓ In the $t - J$ Model

Using the Slave Bosons Approximation
$J(S_i \cdot S_j)$ is NOT Renormalized

Non-local $J$

↓

✓ d-wave superconductor

✓ DMFT is not enough

↓

CDMFT

# *What about $C_{60}$ compounds?*

- $W \simeq 0.5 eV$
- $U \simeq 1 - 1.2 eV$
- $J \simeq 0.02 eV$

✓ $U > U_c(n = 2) \rightarrow$ Non Magnetic Insulator

✓ $U < U_c(n = 3) \rightarrow$ Superconductor

$K_3(NH_3)C_{60}$ (lattice expanded) is an $S = 1/2$ Mott insulator (not $S = 3/2$)

The degeneracy is partially lifted:
RVB background + Spin 1/2 electrons
Is J still unaffected?

Moreover: $K_3C_{60}$ is 'more metallic' $\rightarrow$

- Critical values of $Z$ might be larger
- The Superconducting window should be larger

# *Conclusions*

- Mott Transition to the zero-entropy Mott Insulator gives rise to Superconductivity
- Strong Correlation $\rightarrow$ Strong Enhancement of Superconductivity
- Two Main Ingredients:
  - Unscreened Pairing Attraction $J$
  - Reduced Coherent Bandwidth $ZW \ll W$
- Superconductivity ONLY involves Quasi-particles on a Very Small Energy Range
- Similar to the RVB picture for the cuprates