Outline of the Topics

1. Trends in the periodic table.
2. Introduction: Heavy Fermions and the Kondo Lattice.
3. From Anderson to Kondo
4. Kondo Insulators: the simplest heavy fermions.
5. Oshikawa's Theorem.
6. **<u>Large N expansion for the Kondo Lattice</u>**
7. Heavy Fermion Superconductivity
8. Topological Kondo Insulators
9. Co-existing magnetism and the Kondo Effect.

Please ask questions!

Rutgers
Center for Materials Theory

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

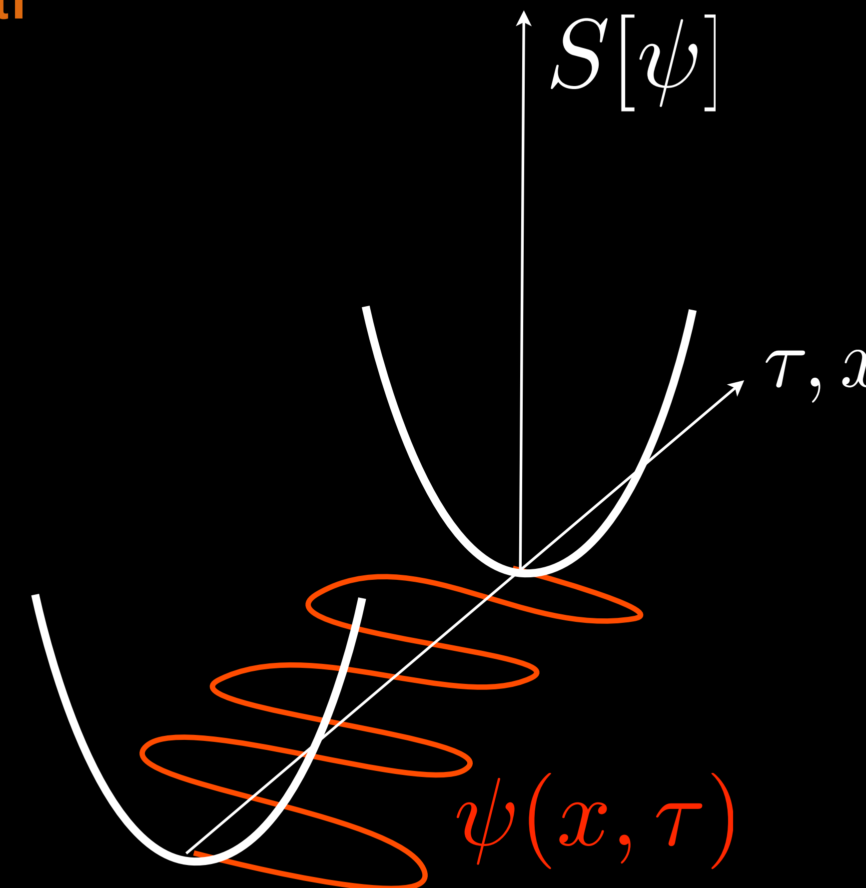
Local Wannier state:

$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Path Integral

$$Z = \int_{\text{Fields}} e^{-S[\psi]}$$



$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_j c^{\dagger}_a(j) c_b(j) S^{ba}(j)$$

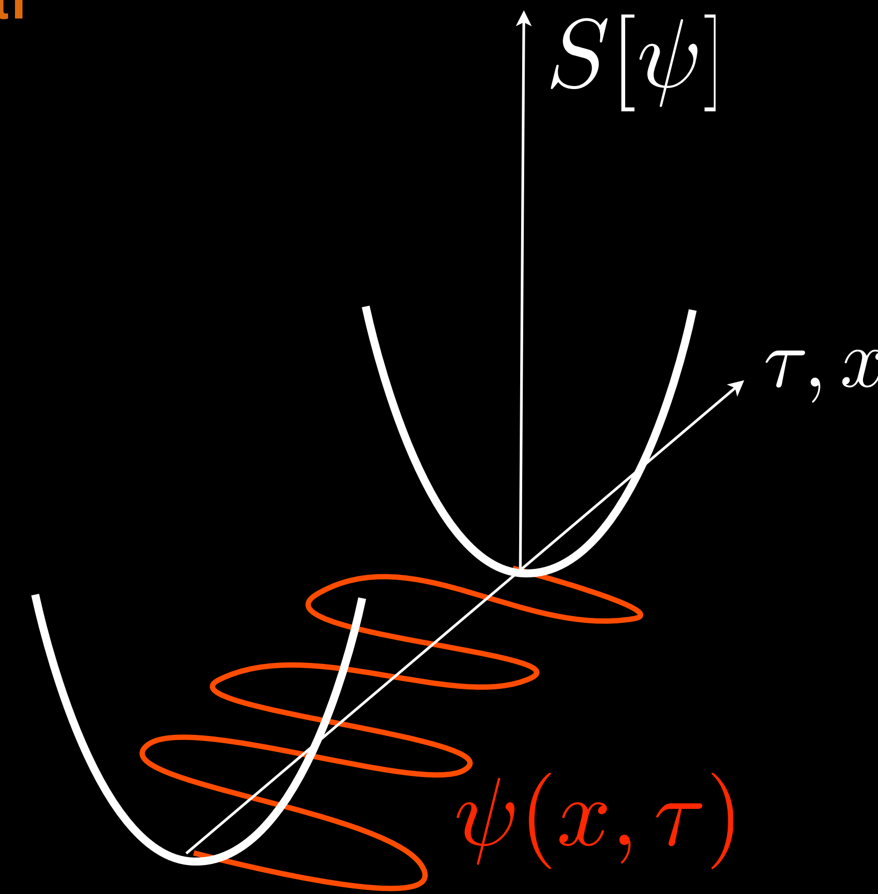
Local Wannier state:

$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Path Integral

$$Z = \int_{\text{Fields}} e^{-S[\psi]}$$



Wild quantum fluctuations!

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

Local Wannier state:

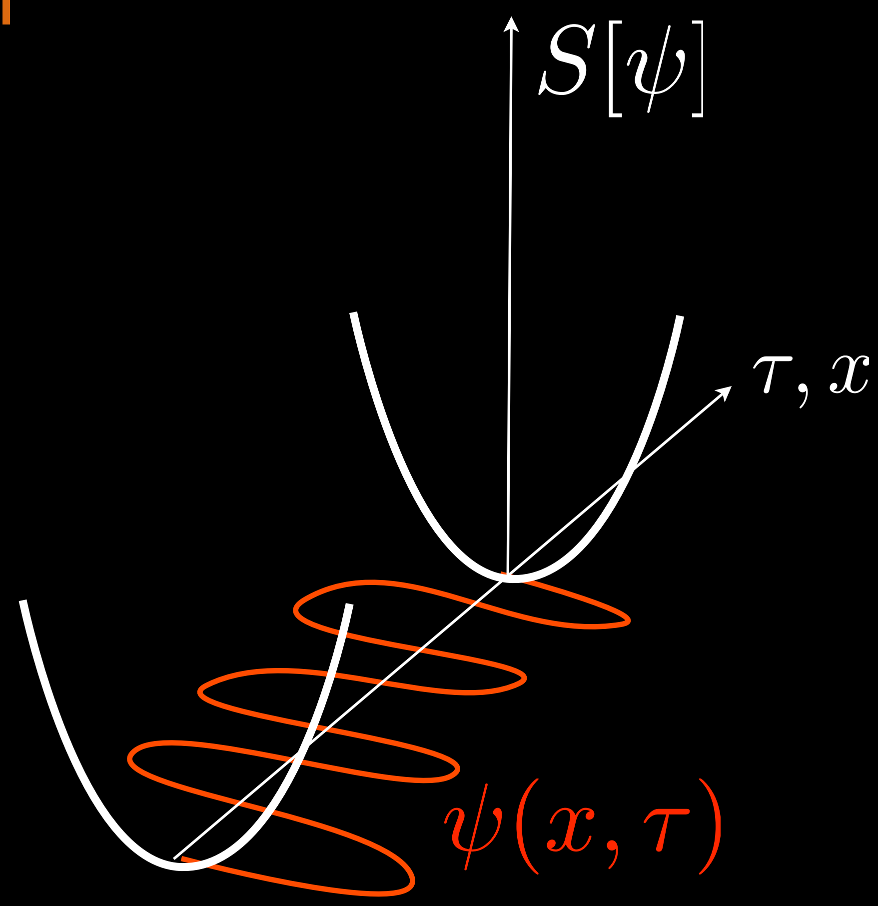
$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

How can we tame the wild Quantum fluctuations?

Path Integral

$$Z = \int_{\text{Fields}} e^{-S[\psi]}$$



$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

Local Wannier state:

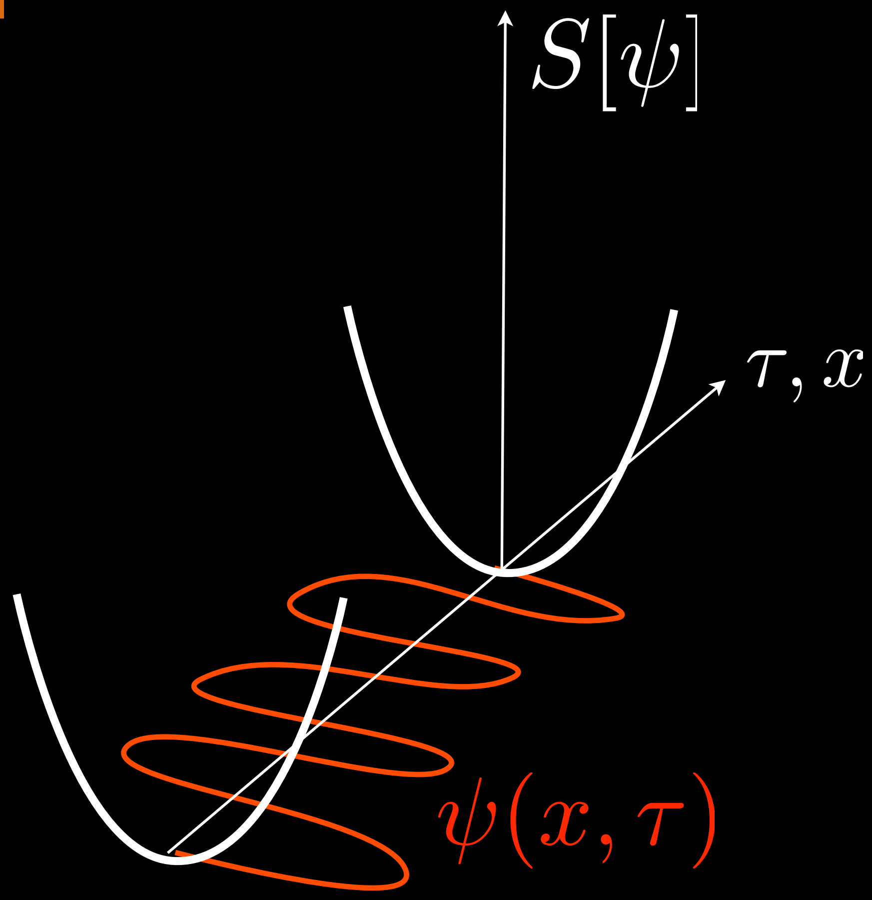
$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

Path Integral

$$Z = \int_{\mathrm{Fields}} e^{- \quad S[\psi]}$$



$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

Local Wannier state:

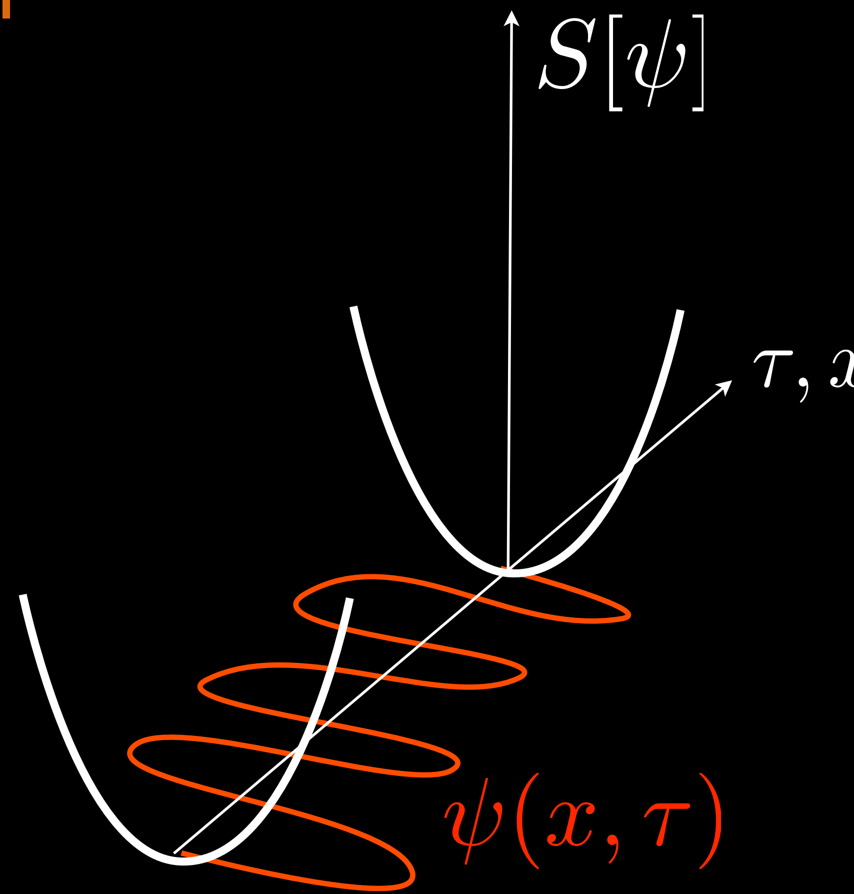
$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

Path Integral

$$Z = \int_{\text{Fields}} e^{-\quad S[\psi]}$$



$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N} \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

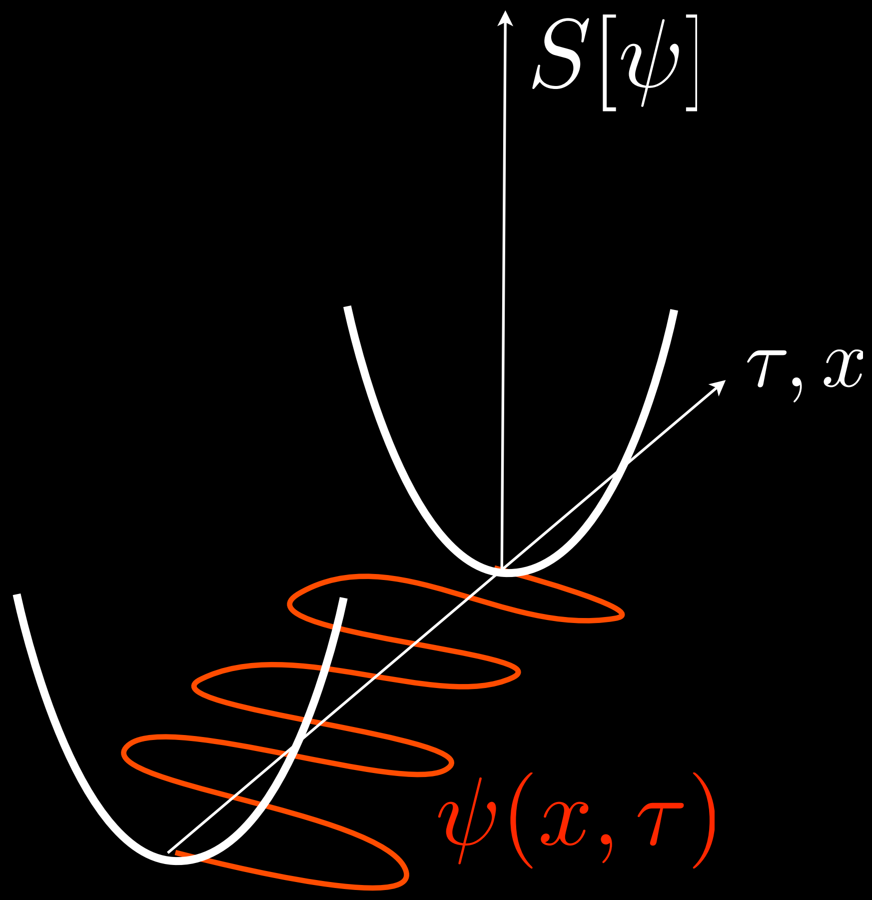
Local Wannier state:

$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

$$Z = \int_{\mathrm{Fields}} e^{-NS[\psi]}$$



$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N} \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

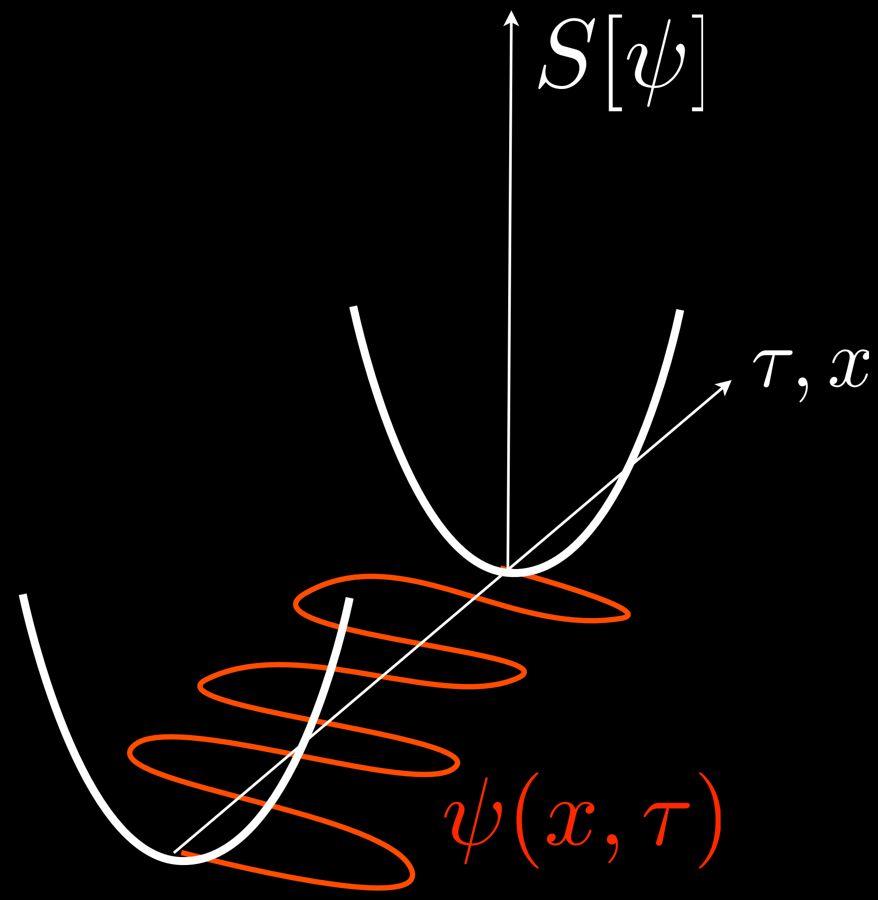
Local Wannier state:

$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

$$Z = \int_{\text{Fields}} e^{-\frac{S[\psi]}{1/N}}$$



$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N} \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

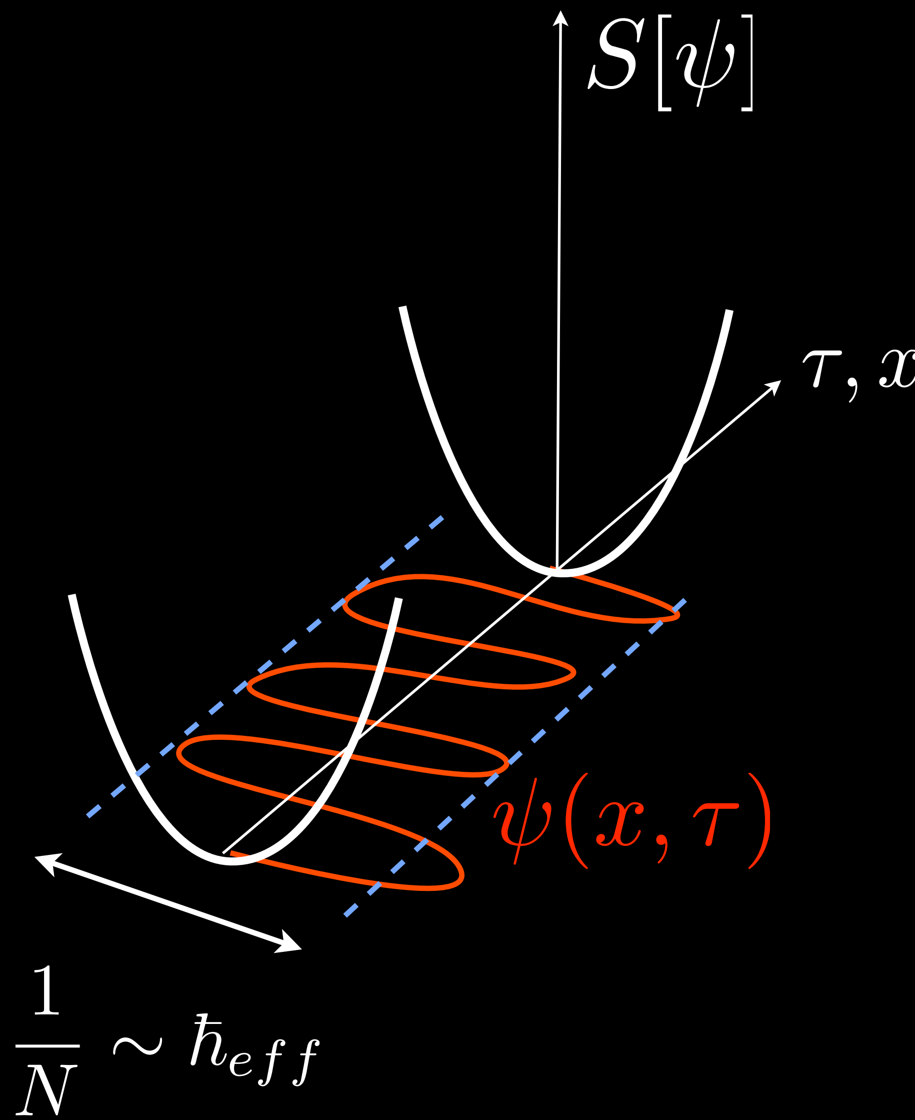
Local Wannier state:

$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

$$Z = \int_{\text{Fields}} e^{-\frac{S[\psi]}{1/N}}$$



$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N} \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

Local Wannier state:

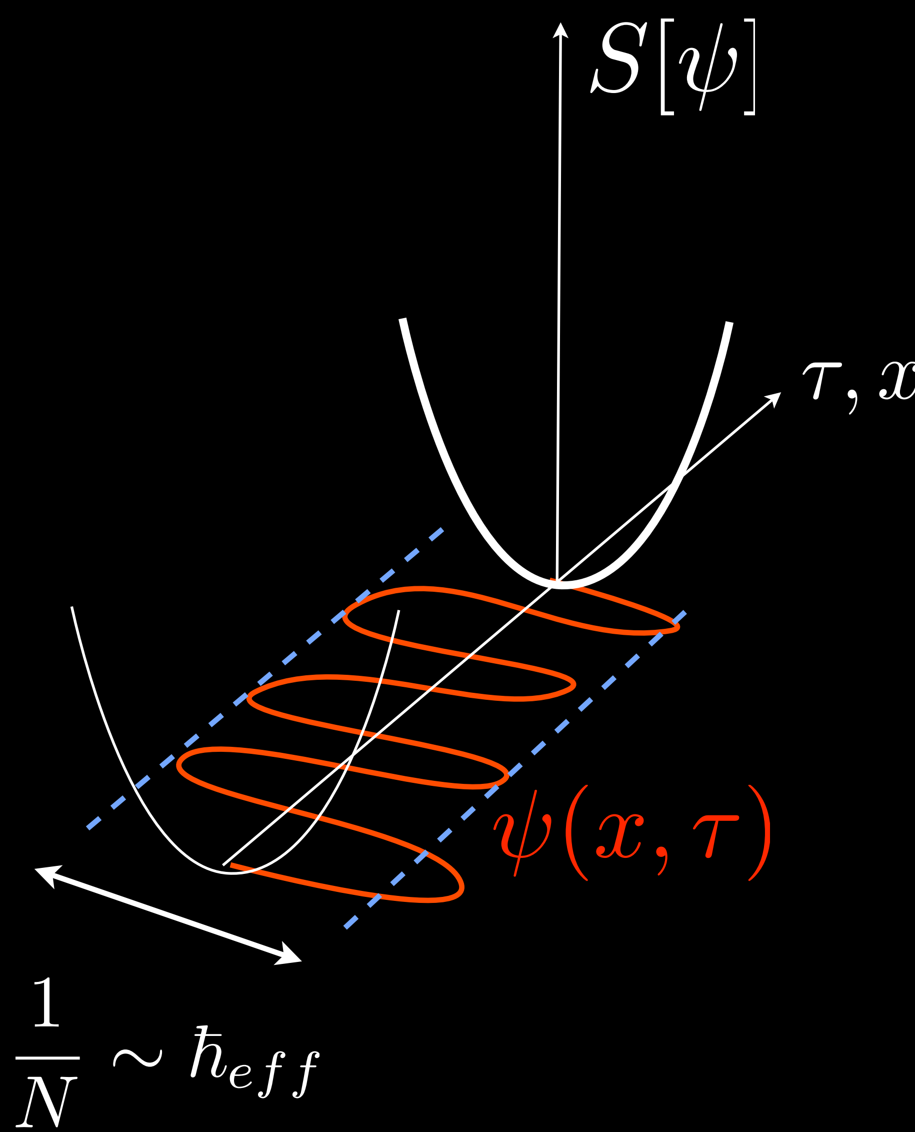
$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

$N \longrightarrow \infty$

$$Z = \int_{\text{Fields}} e^{-\frac{S[\psi]}{1/N}}$$



$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N} \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

Local Wannier state:

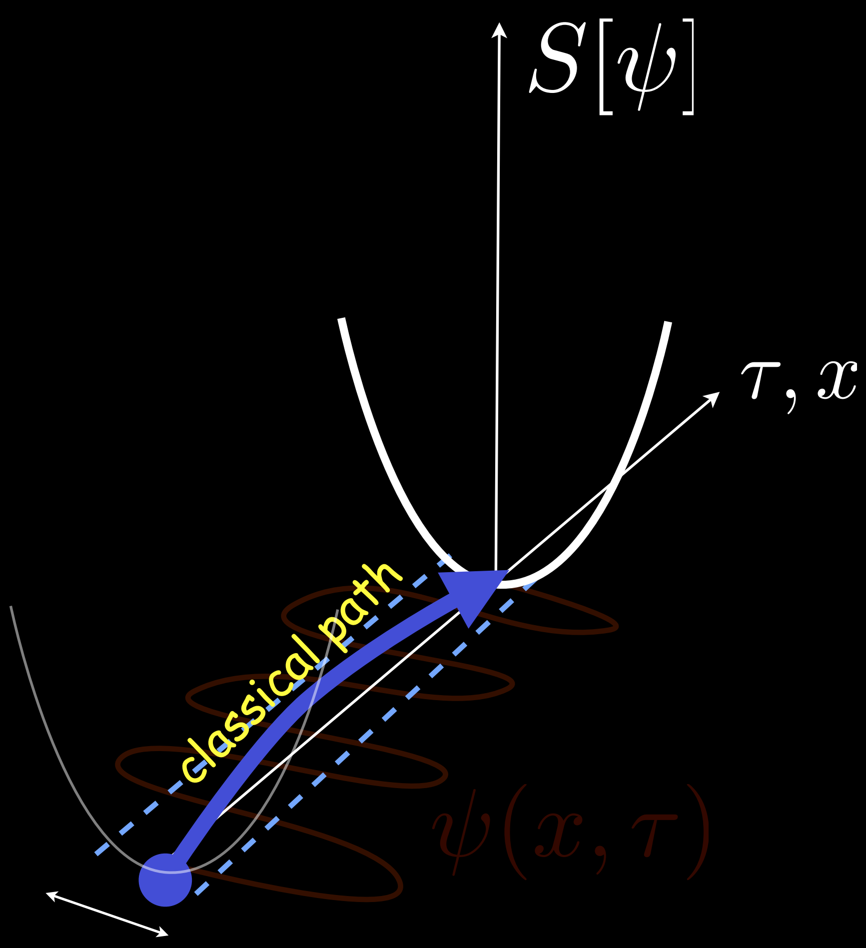
$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

$N \rightarrow \infty$

$$Z = \int_{\text{Fields}} e^{-\frac{S[\psi]}{1/N}}$$



$$\frac{1}{N} \sim \hbar_{eff}$$

$$\sigma \in \left(-\frac{1}{2}, \frac{1}{2}\right) \longrightarrow \left(-\frac{N}{2}, \frac{N}{2}\right)$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N} \sum_{j} c^{\dagger}_{a}(j) c_{b}(j) S^{ba}(j)$$

Local Wannier state:

$$c^{\dagger}_{\sigma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

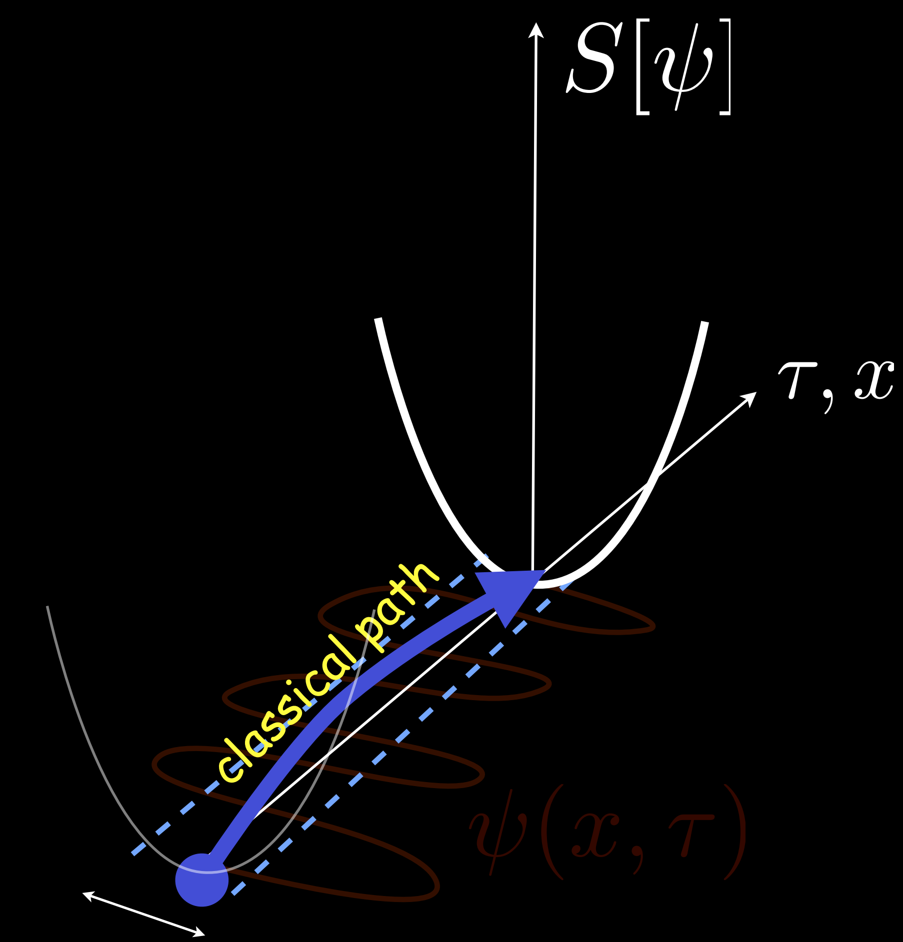
Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large *N* expansion.

$$N \rightarrow \infty$$

$$Z = \int_{\text{Fields}} e^{-\frac{S[\psi]}{1/N}}$$

$$S^{ba} = f_b^\dagger f_a - \frac{n_f}{N}\delta_{ab}$$



$$\frac{1}{N} \sim \hbar_{eff}$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N}\sum_j c_a^\dagger(j) c_b(j) S^{ba}(j)$$

Local Wannier state:

$$c^\dagger_\sigma(j) = \frac{1}{\sqrt{V}}\sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large N expansion.

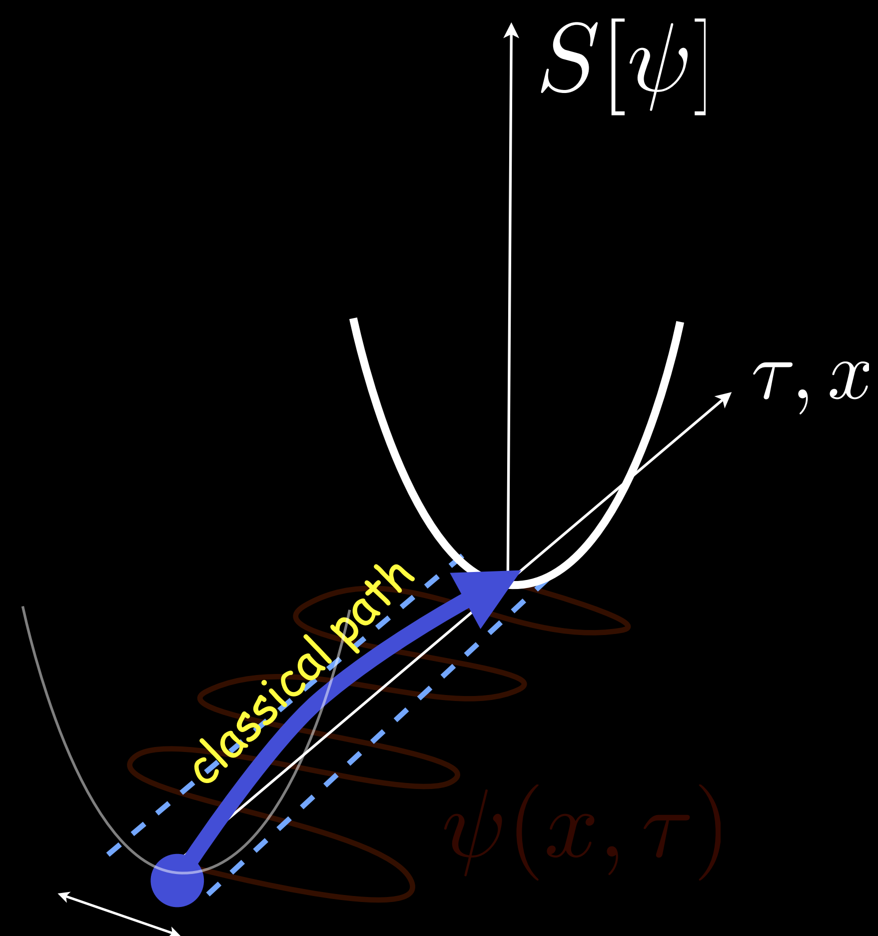
$N \rightarrow \infty$

$$Z = \int_{\text{Fields}} e^{-\frac{S[\psi]}{1/N}}$$

$$S^{ba} = f_b^\dagger f_a - \frac{n_f}{N}\delta_{ab}$$

$$H_I \rightarrow -\frac{J}{N}(f^\dagger_{j\alpha} c_{j\alpha})(c^\dagger_{j\beta} f_{j\beta})$$

$$\rightarrow \bar{V}\left(c^\dagger_{j\beta} f_\beta\right) + \left(f^\dagger_{j\alpha} c_{j\alpha}\right) V + N\frac{\bar{V}V}{J}$$



$$\frac{1}{N} \sim \hbar_{eff}$$

$$H = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{N}\sum_j c_a^\dagger(j) c_b(j) S^{ba}(j)$$

Local Wannier state:

$$c_\sigma^\dagger(j) = \frac{1}{\sqrt{V}}\sum_{\mathbf{k}} c_{\mathbf{k}\sigma} e^{i\mathbf{k}\cdot\mathbf{R}_j}$$

Doniach 77, Lacroix and Cyrot 79, Coleman 83, Read and Newns 83, Auerbach and Levin 86.

Large N Approach.

Read and Newns '83.

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j H_I(j)$$

$$H_I(j) = -\frac{J}{N} \left(c^\dagger_{j\beta} f_{j\beta} \right) \left(f^\dagger_{j\alpha} c_{j\alpha} \right)$$

Large N Approach.

Read and Newns '83.

$$c^\dagger_{j\alpha} = \frac{1}{\sqrt{\mathcal{N}_s}} \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} e^{-i\mathbf{k}\cdot\vec{R}_j}$$

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j H_I(j)$$

$$H_I(j) = -\frac{J}{N}\left(c^\dagger_{j\beta} f_{j\beta}\right)\left(f^\dagger_{j\alpha} c_{j\alpha}\right)$$

Large N Approach.

Read and Newns '83.

$$c^\dagger_{j\alpha} = \frac{1}{\sqrt{N_s}} \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} e^{-i\mathbf{k}\cdot\vec{R}_j}$$

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j H_I(j)$$

$$H_I(j) = -\frac{J}{N} \left(c^\dagger_{j\beta} f_{j\beta} \right) \left(f^\dagger_{j\alpha} c_{j\alpha} \right)$$

Constraint $n_f = Q = qN$

all terms extensive in N

Large N Approach.

Read and Newns '83.

$$c^\dagger_{j\alpha} = \frac{1}{\sqrt{N_s}} \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} e^{-i\mathbf{k}\cdot\vec{R}_j}$$

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j H_I(j)$$

$$H_I(j) = -\frac{J}{N}\left(c^\dagger_{j\beta} f_{j\beta}\right)\left(f^\dagger_{j\alpha} c_{j\alpha}\right)$$

Constraint n_f = Q=qN

all terms extensive in N

$$-gA^\dagger A \rightarrow A^\dagger V + \bar{V}A + \frac{\bar{V}V}{g}$$

Large N Approach.

Read and Newns '83.

$$c^\dagger_{j\alpha} = \frac{1}{\sqrt{N_s}} \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} e^{-i\mathbf{k}\cdot\vec{R}_j}$$

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j H_I(j)$$

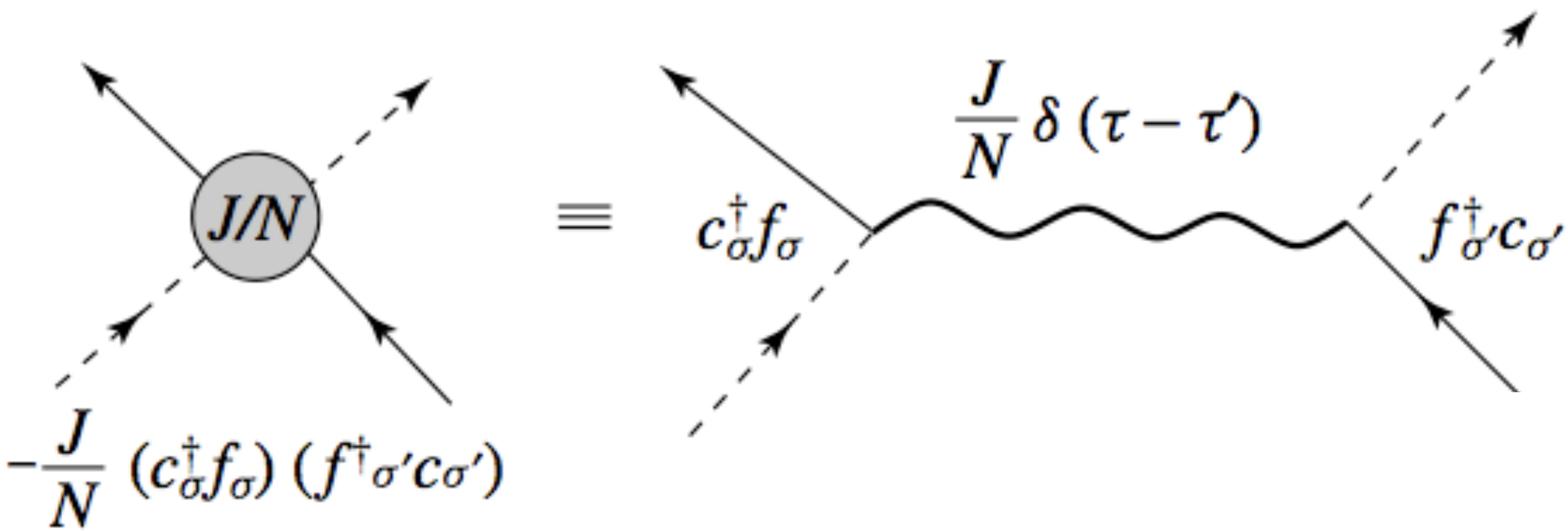
$$H_I(j) = -\frac{J}{N}\left(c^\dagger_{j\beta} f_{j\beta}\right)\left(f^\dagger_{j\alpha} c_{j\alpha}\right)$$

Constraint n_f = Q=qN

all terms extensive in N

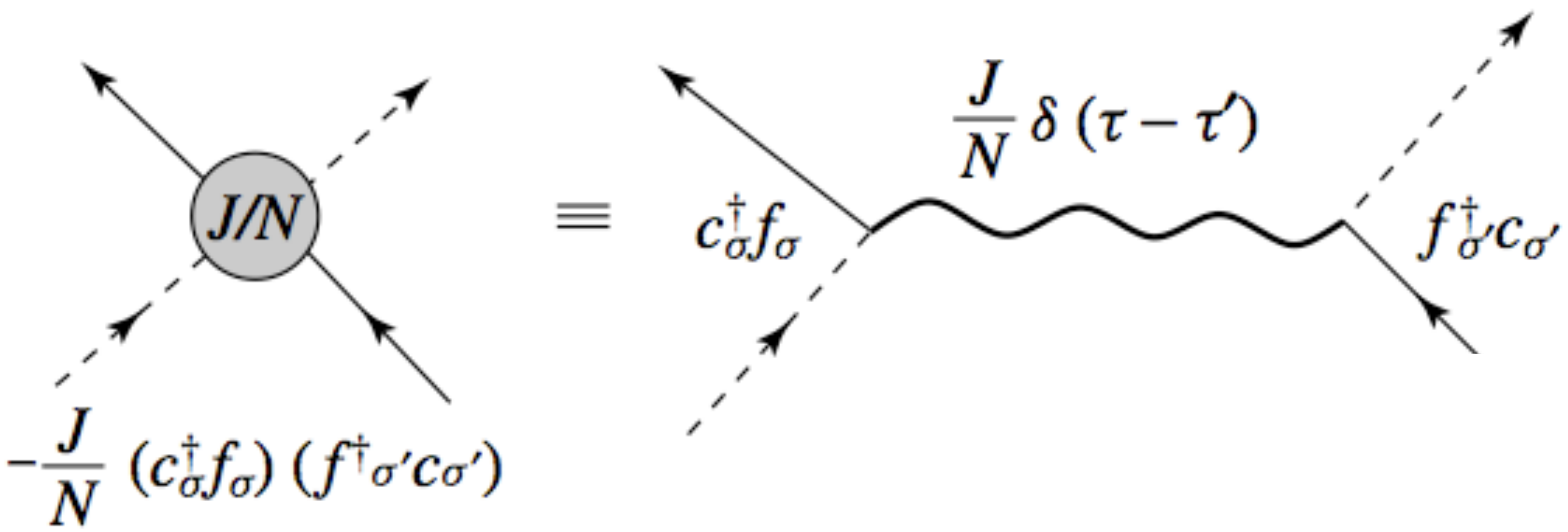
$$-gA^\dagger A \rightarrow A^\dagger V + \bar{V} A + \frac{\bar{V} V}{g}$$

$$H_I(j) \rightarrow H_I[V,j] = \bar{V}_j \left(c^\dagger_{j\alpha} f_{j\alpha}\right) + \left(f^\dagger_{j\alpha} c_{j\alpha}\right) V_j + N \frac{\bar{V}_j V_j}{J}.$$



Large N Approach

Read and Newns '83.

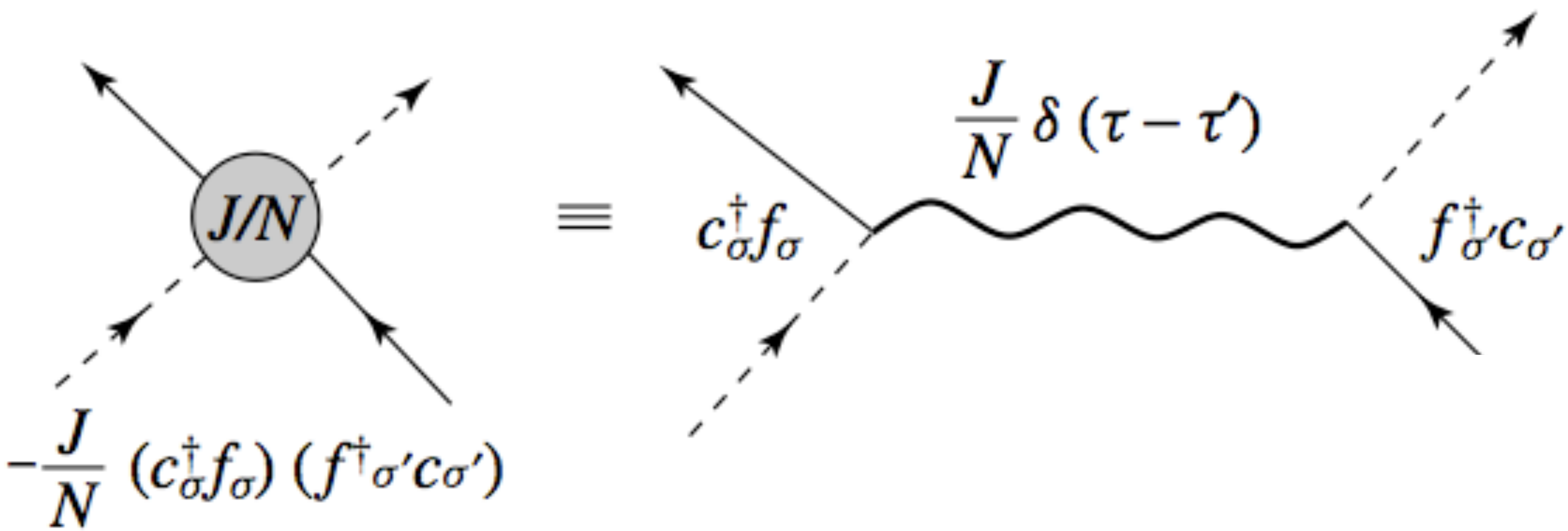


Large N Approach

Read and Newns '83.

$$H[V,\lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j \left(H_I[V_j, j] + \lambda_j [n_f(j) - Q]\right),$$

$$H_I[V,j] = \bar{V}_j \left(c^\dagger_{j\alpha} f_{j\alpha}\right) + \left(f^\dagger_{j\alpha} c_{j\alpha}\right) V_j + N \frac{\bar{V}_j V_j}{J}.$$

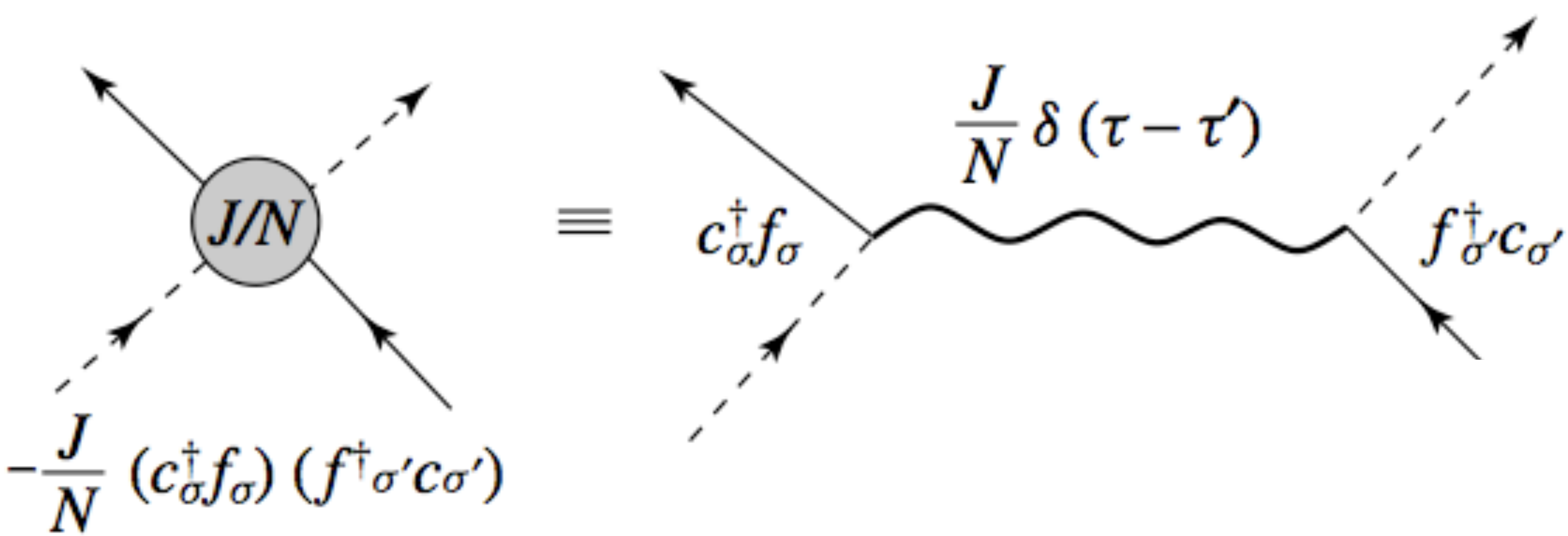


Large N Approach

Read and Newns '83.

$$H[V,\lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{j} \left(H_I[V_j, j] + \lambda_j [n_f(j) - Q] \right),$$
$$H_I[V,j] = \bar{V}_j \left(c^{\dagger}_{j\alpha} f_{j\alpha} \right) + \left(f^{\dagger}_{j\alpha} c_{j\alpha} \right) V_j + N \frac{\bar{V}_j V_j}{J}.$$

U(1) constraint: note $n_f = Q = (qN)$



Large N Approach

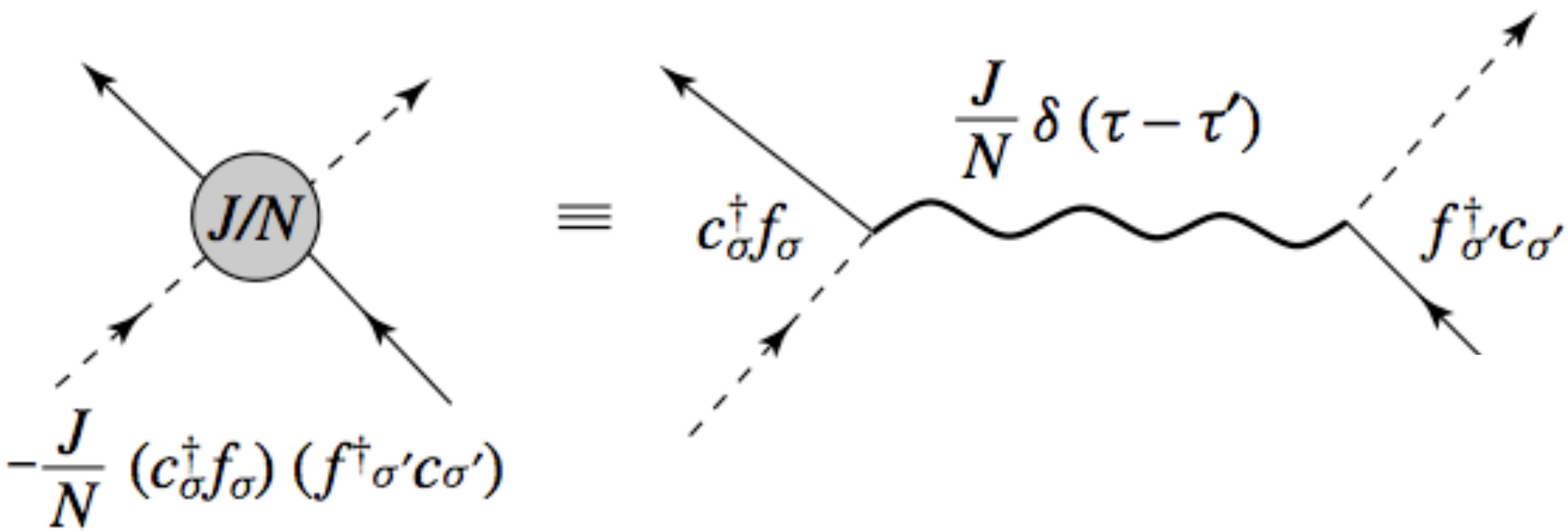
Read and Newns '83.

$$Z = \int \mathcal{D}[V,\lambda] \overbrace{\int \mathcal{D}[c,f] \exp\left[-\int_0^\beta \left(\sum_{k\sigma} c^\dagger_{\mathbf{k}\sigma} \partial_\tau c_{\mathbf{k}\sigma} + \sum_{j\sigma} f^\dagger_{j\sigma} \partial_\tau f_{j\sigma} + H[V,\lambda] \right) \right]}^{= \mathrm{Tr}\left[Texp\left(-\int_0^\beta H[V,\lambda] d\tau \right) \right]}$$

$$H[V,\lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j \left(H_I[V_j, j] + \lambda_j [n_f(j) - Q] \right),$$

$$H_I[V,j] = \bar{V}_j \left(c^\dagger_{j\alpha} f_{j\alpha} \right) + \left(f^\dagger_{j\alpha} c_{j\alpha} \right) V_j + N \frac{\bar{V}_j V_j}{J}.$$

U(1) constraint: note $n_f = Q = (qN)$



Large N Approach

Read and Newns '83.

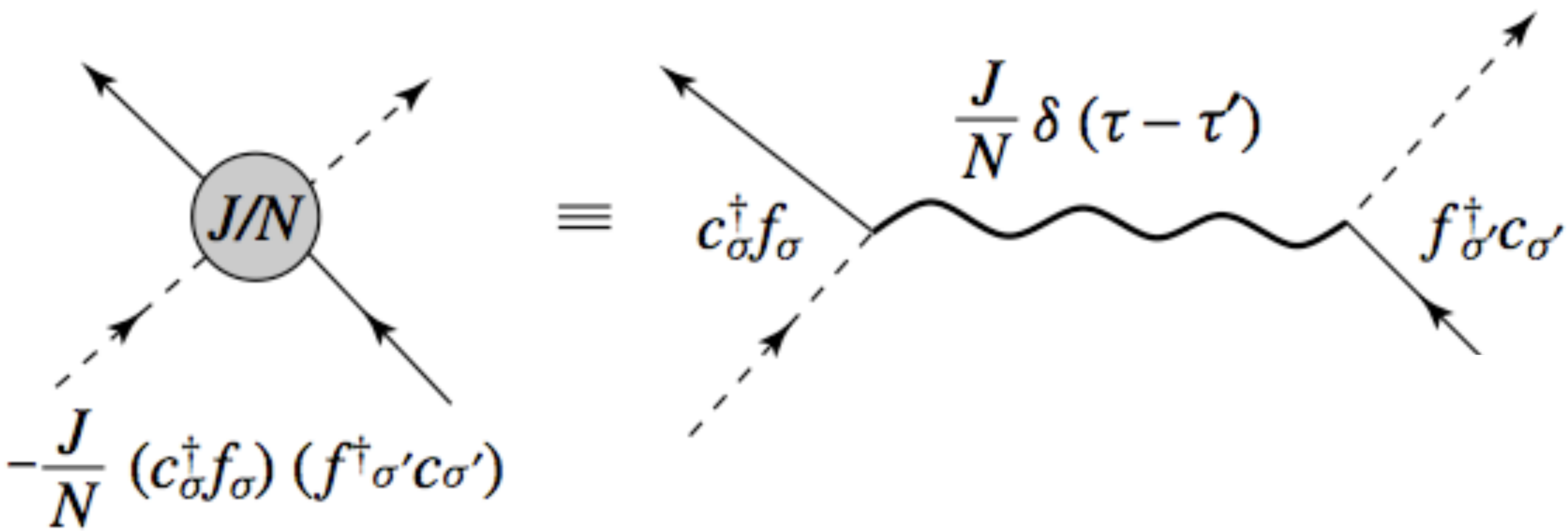
Extensive in N

$$Z = \int \mathcal{D}[V,\lambda] \overbrace{\int \mathcal{D}[c,f] \exp\left[-\int_0^\beta \left(\sum_{k\sigma} c^\dagger_{\mathbf{k}\sigma}\partial_\tau c_{\mathbf{k}\sigma} + \sum_{j\sigma} f^\dagger_{j\sigma}\partial_\tau f_{j\sigma} + H[V,\lambda]\right)\right]}^{=\mathrm{Tr}\left[T exp\left(-\int_0^\beta H[V,\lambda]d\tau\right)\right]}$$

$$H[V,\lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j \left(H_I[V_j,j] + \lambda_j[n_f(j) - Q]\right),$$

$$H_I[V,j] = \bar{V}_j\left(c^\dagger_{j\alpha} f_{j\alpha}\right) + \left(f^\dagger_{j\alpha} c_{j\alpha}\right) V_j + N\frac{\bar{V}_j V_j}{J}.$$

U(1) constraint: note n_f =Q =(qN)



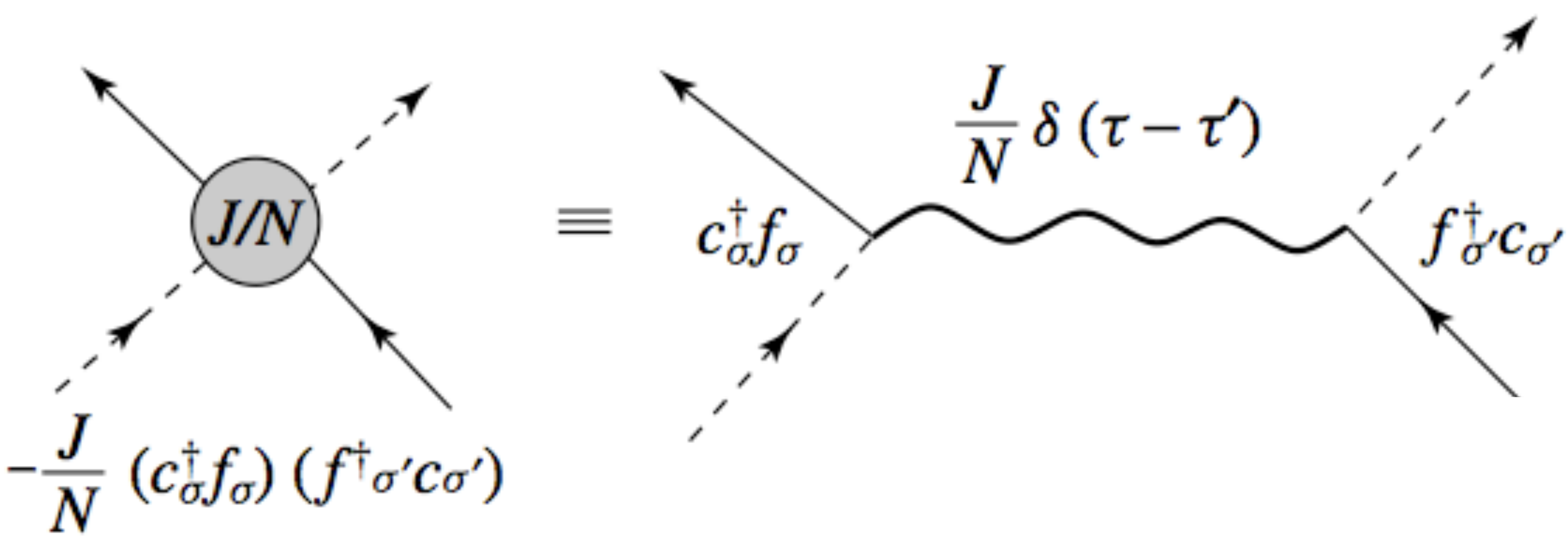
Large N Approach.

Read and Newns '83.

$$Z = \int \mathcal{D}[V,\lambda] \overbrace{\int \mathcal{D}[c,f] \exp\left[-\int_0^\beta \left(\sum_{k\sigma} c^\dagger_{\mathbf{k}\sigma}\partial_\tau c_{\mathbf{k}\sigma} + \sum_{j\sigma} f^\dagger_{j\sigma}\partial_\tau f_{j\sigma} + H[V,\lambda]\right)\right]}^{=\mathrm{Tr}\left[Texp\left(-\int_0^\beta H[V,\lambda]d\tau\right)\right]}$$

$$H[V,\lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j \left(H_I[V_j, j] + \lambda_j[n_f(j) - Q]\right),$$

$$H_I[V,j] = \bar{V}_j \left(c^\dagger_{j\alpha} f_{j\alpha}\right) + \left(f^\dagger_{j\alpha} c_{j\alpha}\right) V_j + N\frac{\bar{V}_j V_j}{J}.$$

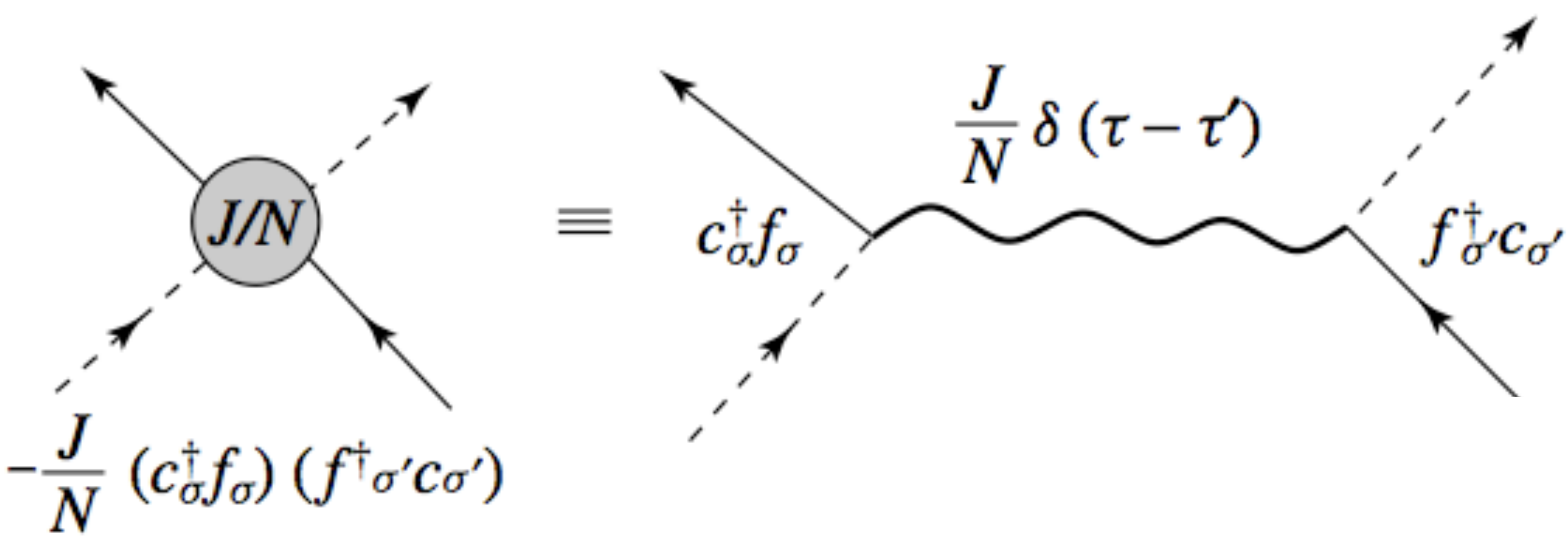


Large N Approach.

Read and Newns '83.

$$Z = \mathrm{Tr} e^{-\beta H_{MFT}}, \qquad (N \to \infty)$$

$$H[V,\lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_j \left(H_I[V_j, j] + \lambda_j [n_f(j) - Q]\right),$$
$$H_I[V,j] = \bar{V}_j \left(c^{\dagger}_{j\alpha} f_{j\alpha}\right) + \left(f^{\dagger}_{j\alpha} c_{j\alpha}\right) V_j + N \frac{\bar{V}_j V_j}{J}.$$



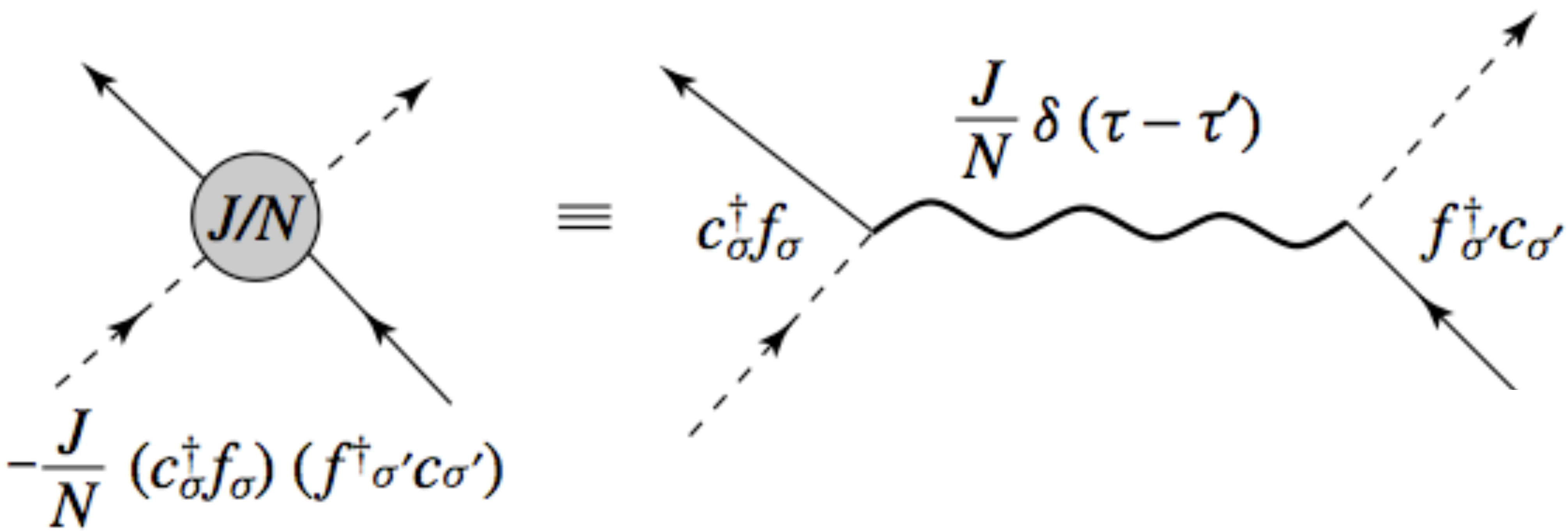
Large N Approach.

Read and Newns '83.

$$Z = \mathrm{Tr} e^{-\beta H_{MFT}}, \qquad (N \to \infty)$$

$$H[V,\lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{j} \left(H_I[V_j, j] + \lambda_j [n_f(j) - Q] \right),$$

$$H_I[V,j] = \bar{V}_j \left(c^{\dagger}_{j\alpha} f_{j\alpha} \right) + \left(f^{\dagger}_{j\alpha} c_{j\alpha} \right) V_j + N \frac{\bar{V}_j V_j}{J}.$$



Large N Approach.

Read and Newns ’83.

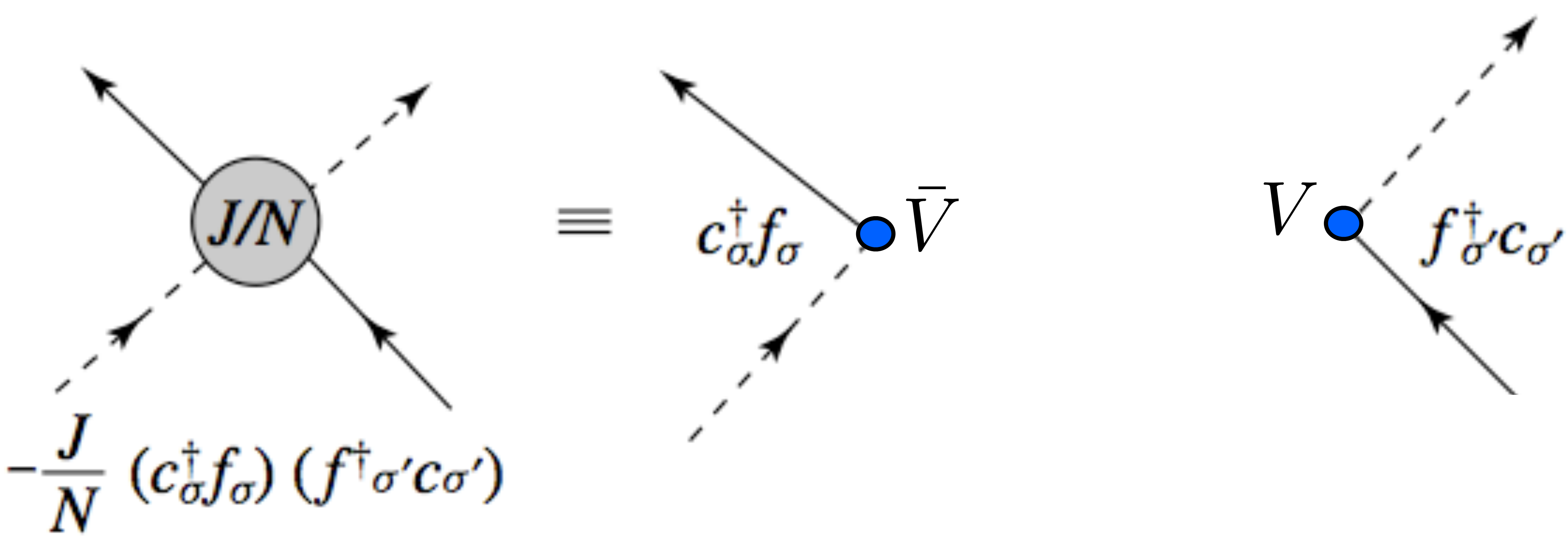
$$Z = \mathrm{Tr} e^{-\beta H_{MFT}}, \qquad (N \rightarrow \infty)$$

$V_j = V$

at each site

$$H[V, \lambda] = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{j} \left(H_I[V_j, j] + \lambda_j [n_f(j) - Q] \right),$$

$$H_I[V, j] = \bar{V}_j \left(c^{\dagger}_{j\alpha} f_{j\alpha} \right) + \left(f^{\dagger}_{j\alpha} c_{j\alpha} \right) V_j + N \frac{\bar{V}_j V_j}{J}.$$



Detailed calcn.

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(c^\dagger{}_{\mathbf{k}\sigma}, f^\dagger{}_{\mathbf{k}\sigma}\right) \overbrace{\begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix}}^{\underline{h}(\mathbf{k})} \begin{pmatrix} c_{\mathbf{k}\sigma} \\ f_{\mathbf{k}\sigma} \end{pmatrix} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q\right)$$

$$= \sum_{\mathbf{k}\sigma} \psi^\dagger{}_{\mathbf{k}\sigma}\, \underline{h}(\mathbf{k})\, \psi_{\mathbf{k}\sigma} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q\right).$$

Detailed calcn.

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(c^{\dagger}{}_{\mathbf{k}\sigma}, f^{\dagger}{}_{\mathbf{k}\sigma}\right) \overbrace{\begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix}}^{\underline{h}(\mathbf{k})} \begin{pmatrix} c_{\mathbf{k}\sigma} \\ f_{\mathbf{k}\sigma} \end{pmatrix} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right)$$

$$= \sum_{\mathbf{k}\sigma} \psi^{\dagger}{}_{\mathbf{k}\sigma}\, \underline{h}(\mathbf{k})\, \psi_{\mathbf{k}\sigma} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right).$$

$$f^{\dagger}{}_{\vec{k}\sigma} = \frac{1}{\sqrt{n}} \sum_j f^{\dagger}{}_{j\sigma} e^{i\vec{k}\cdot\vec{R}_j}$$

Detailed calcn.

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(c^{\dagger}{}_{\mathbf{k}\sigma}, f^{\dagger}{}_{\mathbf{k}\sigma}\right) \overbrace{\begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix}}^{\underline{h}(\mathbf{k})} \begin{pmatrix} c_{\mathbf{k}\sigma} \\ f_{\mathbf{k}\sigma} \end{pmatrix} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right)$$

$$= \sum_{\mathbf{k}\sigma} \psi^{\dagger}{}_{\mathbf{k}\sigma}\, \underline{h}(\mathbf{k})\, \psi_{\mathbf{k}\sigma} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right).$$

$$f^{\dagger}{}_{\vec{k}\sigma} = \frac{1}{\sqrt{n}} \sum_j f^{\dagger}{}_{j\sigma} e^{i\vec{k}\cdot\vec{R}_j}$$

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(a^{\dagger}{}_{\mathbf{k}\sigma}, b^{\dagger}{}_{\mathbf{k}\sigma}\right) \begin{pmatrix} E_{\mathbf{k}^+} & 0 \\ 0 & E_{\mathbf{k}^-} \end{pmatrix} \begin{pmatrix} a_{\mathbf{k}\sigma} \\ b_{\mathbf{k}\sigma} \end{pmatrix} + Nn \left(\frac{\bar{V}V}{J} - \lambda q \right).$$

Detailed calcn.

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(c^\dagger{}_{\mathbf{k}\sigma}, f^\dagger{}_{\mathbf{k}\sigma}\right) \overbrace{\begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix}}^{\underline{h}(\mathbf{k})} \begin{pmatrix} c_{\mathbf{k}\sigma} \\ f_{\mathbf{k}\sigma} \end{pmatrix} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right)$$

$$= \sum_{\mathbf{k}\sigma} \psi^\dagger{}_{\mathbf{k}\sigma}\, \underline{h}(\mathbf{k})\, \psi_{\mathbf{k}\sigma} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right).$$

$$f^\dagger{}_{\vec{k}\sigma} = \frac{1}{\sqrt{n}} \sum_j f^\dagger{}_{j\sigma} e^{i\vec{k}\cdot\vec{R}_j}$$

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(a^\dagger{}_{\mathbf{k}\sigma}, b^\dagger{}_{\mathbf{k}\sigma}\right) \begin{pmatrix} E_{\mathbf{k}^+} & 0 \\ 0 & E_{\mathbf{k}^-} \end{pmatrix} \begin{pmatrix} a_{\mathbf{k}\sigma} \\ b_{\mathbf{k}\sigma} \end{pmatrix} + Nn \left(\frac{\bar{V}V}{J} - \lambda q \right).$$

$$\mathrm{Det}\left[E^{\pm}_{\mathbf{k}} \underline{1} - \begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix} \right] = (E_{\mathbf{k}\pm} - \epsilon_{\mathbf{k}})(E_{\mathbf{k}\pm} - \lambda) - |V|^2 = 0,$$

Detailed calcn.

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(c^\dagger{}_{\mathbf{k}\sigma}, f^\dagger{}_{\mathbf{k}\sigma}\right) \overbrace{\begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix}}^{\underline{h}(\mathbf{k})} \begin{pmatrix} c_{\mathbf{k}\sigma} \\ f_{\mathbf{k}\sigma} \end{pmatrix} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right)$$

$$= \sum_{\mathbf{k}\sigma} \psi^\dagger{}_{\mathbf{k}\sigma}\, \underline{h}(\mathbf{k})\, \psi_{\mathbf{k}\sigma} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right).$$

$$f^\dagger{}_{\vec{k}\sigma} = \frac{1}{\sqrt{n}} \sum_j f^\dagger{}_{j\sigma} e^{i\vec{k}\cdot\vec{R}_j}$$

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(a^\dagger{}_{\mathbf{k}\sigma}, b^\dagger{}_{\mathbf{k}\sigma}\right) \begin{pmatrix} E_{\mathbf{k}^+} & 0 \\ 0 & E_{\mathbf{k}^-} \end{pmatrix} \begin{pmatrix} a_{\mathbf{k}\sigma} \\ b_{\mathbf{k}\sigma} \end{pmatrix} + Nn \left(\frac{\bar{V}V}{J} - \lambda q \right).$$

$$\mathrm{Det}\left[E^\pm_{\mathbf{k}} \underline{1} - \begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix} \right] = (E_{\mathbf{k}\pm} - \epsilon_{\mathbf{k}})(E_{\mathbf{k}\pm} - \lambda) - |V|^2 = 0,$$

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$

Detailed calcn.

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(c^{\dagger}{}_{\mathbf{k}\sigma}, f^{\dagger}{}_{\mathbf{k}\sigma}\right) \overbrace{\begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix}}^{\underline{h}(\mathbf{k})} \begin{pmatrix} c_{\mathbf{k}\sigma} \\ f_{\mathbf{k}\sigma} \end{pmatrix} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right)$$

$$= \sum_{\mathbf{k}\sigma} \psi^{\dagger}{}_{\mathbf{k}\sigma}\, \underline{h}(\mathbf{k})\, \psi_{\mathbf{k}\sigma} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right).$$

$$f^{\dagger}{}_{\vec{k}\sigma} = \frac{1}{\sqrt{n}} \sum_j f^{\dagger}{}_{j\sigma} e^{i\vec{k}\cdot\vec{R}_j}$$

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(a^{\dagger}{}_{\mathbf{k}\sigma}, b^{\dagger}{}_{\mathbf{k}\sigma}\right) \begin{pmatrix} E_{\mathbf{k}^+} & 0 \\ 0 & E_{\mathbf{k}^-} \end{pmatrix} \begin{pmatrix} a_{\mathbf{k}\sigma} \\ b_{\mathbf{k}\sigma} \end{pmatrix} + Nn \left(\frac{\bar{V}V}{J} - \lambda q \right).$$

$$\mathrm{Det}\left[E^{\pm}_{\mathbf{k}} \underline{1} - \begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix} \right] = (E_{\mathbf{k}\pm} - \epsilon_{\mathbf{k}})(E_{\mathbf{k}\pm} - \lambda) - |V|^2 = 0,$$

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}} ,$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}} ,$$

$$a^{\dagger}{}_{\mathbf{k}\sigma} = u_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + v_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma}$$
$$b^{\dagger}{}_{\mathbf{k}\sigma} = -v_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma}$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$

$$a^{\dagger}{}_{\mathbf{k}\sigma} = u_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + v_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma}$$
$$b^{\dagger}{}_{\mathbf{k}\sigma} = -v_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma}$$

$$\left\{ \begin{array}{c} u_{\mathbf{k}} \\ v_{\mathbf{k}} \end{array} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_{\mathbf{k}} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_{\mathbf{k}}-\lambda}{2}\right)^2 + |V|^2}}\right]^{\frac{1}{2}}$$

Detailed calcn.

$$|MF\rangle = \prod_{|\mathbf{k}|<k_F,\sigma} b^\dagger_{\mathbf{k}\sigma} = \prod_{|\mathbf{k}|<k_F,\sigma} (-v_\mathbf{k} c^\dagger_{\mathbf{k}\sigma} + u_\mathbf{k} f^\dagger_{\mathbf{k}\sigma})|0\rangle$$

$$E_{\mathbf{k}\pm} = \frac{\epsilon_\mathbf{k} + \lambda}{2} \pm \left[\left(\frac{\epsilon_\mathbf{k} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$

$$a^\dagger{}_{\mathbf{k}\sigma} = u_\mathbf{k} c^\dagger{}_{\mathbf{k}\sigma} + v_\mathbf{k} f^\dagger{}_{\mathbf{k}\sigma}$$
$$b^\dagger{}_{\mathbf{k}\sigma} = -v_\mathbf{k} c^\dagger{}_{\mathbf{k}\sigma} + u_\mathbf{k} f^\dagger{}_{\mathbf{k}\sigma}$$

$$\left\{ \begin{array}{c} u_\mathbf{k} \\ v_\mathbf{k} \end{array} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_\mathbf{k} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_\mathbf{k}-\lambda}{2}\right)^2 + |V|^2}}\right]^{\frac{1}{2}}$$

Detailed calcn.

$$|MF\rangle = \prod_{|\mathbf{k}|<k_F,\sigma} b^\dagger_{\mathbf{k}\sigma} = \prod_{|\mathbf{k}|<k_F,\sigma} (-v_\mathbf{k} c^\dagger_{\mathbf{k}\sigma} + u_\mathbf{k} f^\dagger_{\mathbf{k}\sigma})|0\rangle$$

$$E_{\mathbf{k}\pm} = \frac{\epsilon_\mathbf{k} + \lambda}{2} \pm \left[\left(\frac{\epsilon_\mathbf{k} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$

$$\boxed{|GW\rangle = P_Q \prod_{|\mathbf{k}|<k_F,\sigma} (-v_\mathbf{k} c^\dagger_{\mathbf{k}\sigma} + u_\mathbf{k} f^\dagger_{\mathbf{k}\sigma})|0\rangle}$$

"Gutzwiller" wavefunction

$$a^\dagger{}_{\mathbf{k}\sigma} = u_\mathbf{k} c^\dagger{}_{\mathbf{k}\sigma} + v_\mathbf{k} f^\dagger{}_{\mathbf{k}\sigma}$$
$$b^\dagger{}_{\mathbf{k}\sigma} = -v_\mathbf{k} c^\dagger{}_{\mathbf{k}\sigma} + u_\mathbf{k} f^\dagger{}_{\mathbf{k}\sigma}$$

$$\left\{ \begin{array}{c} u_\mathbf{k} \\ v_\mathbf{k} \end{array} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_\mathbf{k} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_\mathbf{k}-\lambda}{2}\right)^2 + |V|^2}}\right]^{\frac{1}{2}}$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$

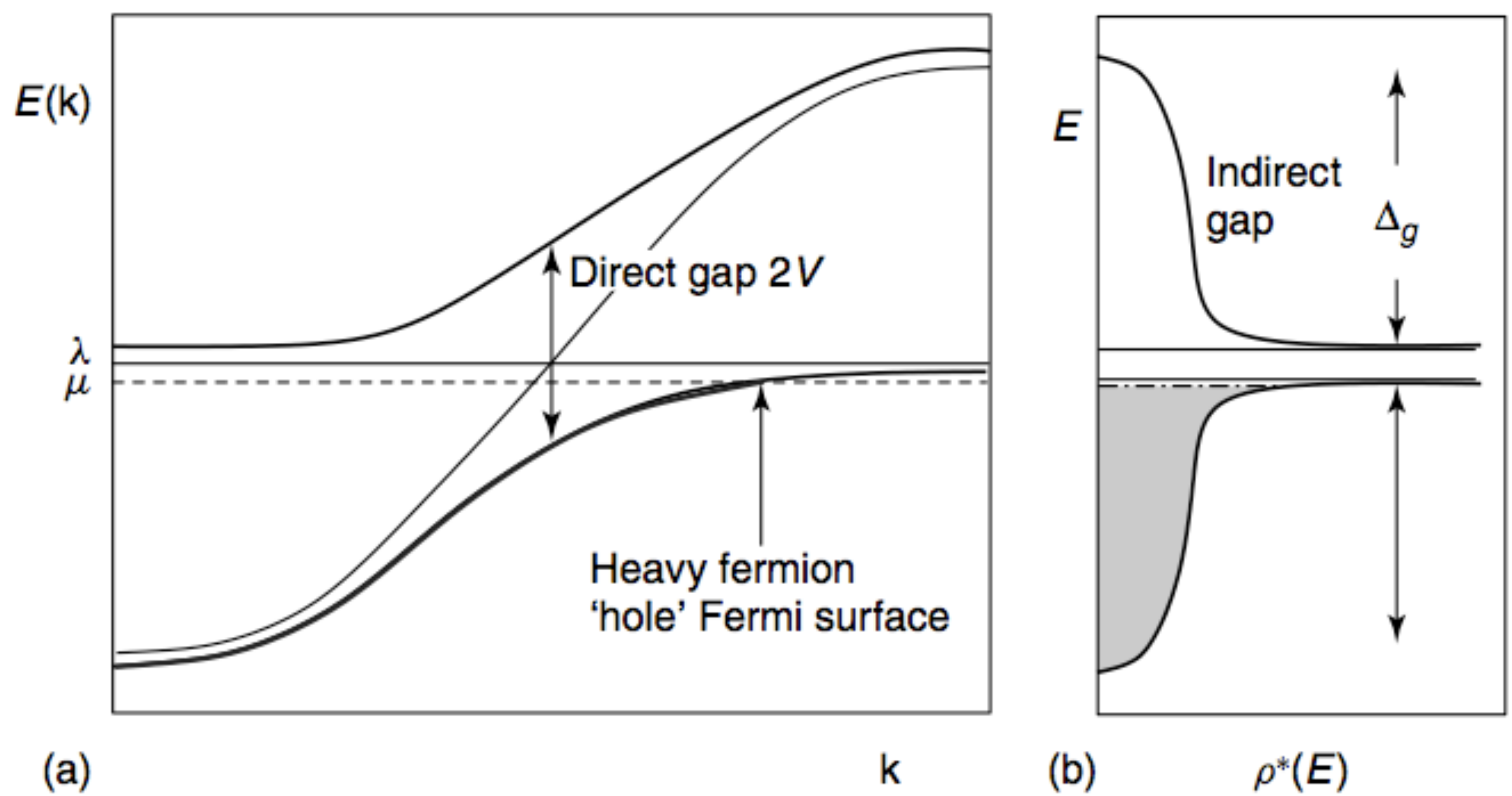
$$|MF\rangle = \prod_{|\mathbf{k}|<k_F,\sigma} b^\dagger_{\mathbf{k}\sigma} = \prod_{|\mathbf{k}|<k_F,\sigma} (-v_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^\dagger_{\mathbf{k}\sigma})|0\rangle$$

$$\boxed{|GW\rangle = P_Q \prod_{|\mathbf{k}|<k_F,\sigma} (-v_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^\dagger_{\mathbf{k}\sigma})|0\rangle}$$

"Gutzwiller" wavefunction

$$a^\dagger{}_{\mathbf{k}\sigma} = u_{\mathbf{k}} c^\dagger{}_{\mathbf{k}\sigma} + v_{\mathbf{k}} f^\dagger{}_{\mathbf{k}\sigma}$$
$$b^\dagger{}_{\mathbf{k}\sigma} = -v_{\mathbf{k}} c^\dagger{}_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^\dagger{}_{\mathbf{k}\sigma}$$

$$\left\{ \begin{array}{c} u_{\mathbf{k}} \\ v_{\mathbf{k}} \end{array} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_{\mathbf{k}} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_{\mathbf{k}}-\lambda}{2}\right)^2 + |V|^2}} \right]^{\frac{1}{2}}$$



Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$

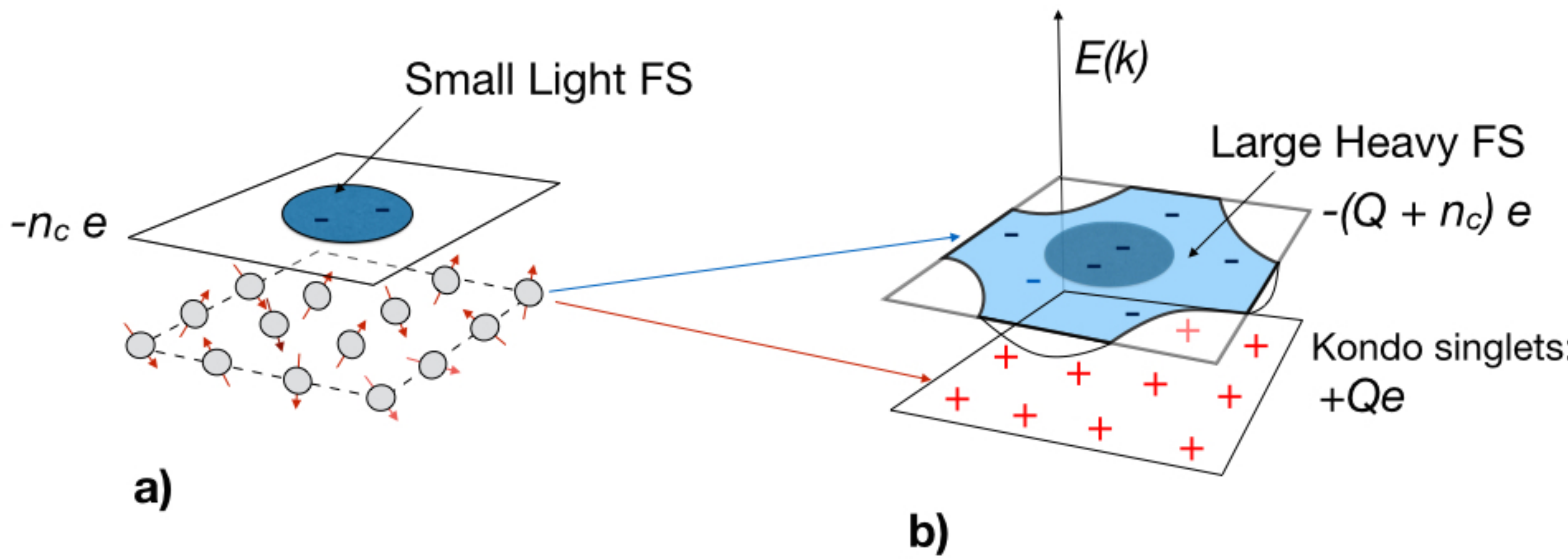
$$|MF\rangle = \prod_{|\mathbf{k}|<k_F,\sigma} b^{\dagger}_{\mathbf{k}\sigma} = \prod_{|\mathbf{k}|<k_F,\sigma} (-v_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}_{\mathbf{k}\sigma})|0\rangle$$

$$\boxed{|GW\rangle = P_Q \prod_{|\mathbf{k}|<k_F,\sigma} (-v_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}_{\mathbf{k}\sigma})|0\rangle}$$

"Gutzwiller" wavefunction

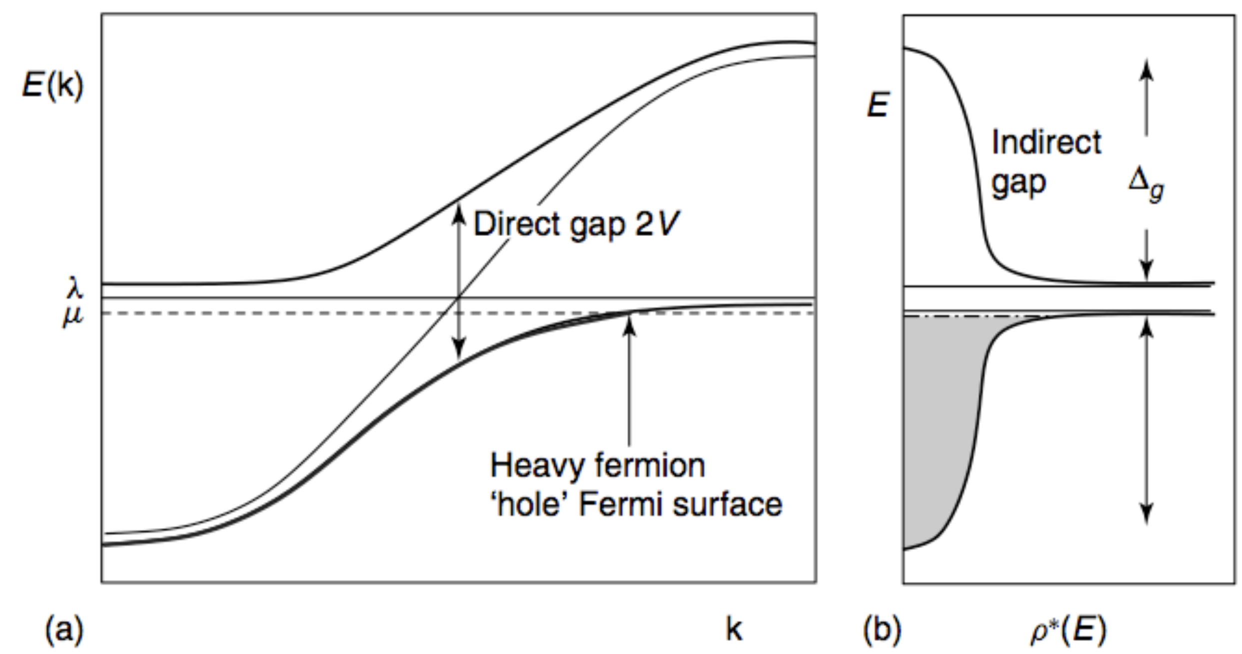
$$a^{\dagger}{}_{\mathbf{k}\sigma} = u_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + v_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma}$$
$$b^{\dagger}{}_{\mathbf{k}\sigma} = -v_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma}$$

$$\left\{ \begin{array}{c} u_{\mathbf{k}} \\ v_{\mathbf{k}} \end{array} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_{\mathbf{k}} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_{\mathbf{k}}-\lambda}{2}\right)^2 + |V|^2}} \right]^{\frac{1}{2}}$$



Detailed calcn.

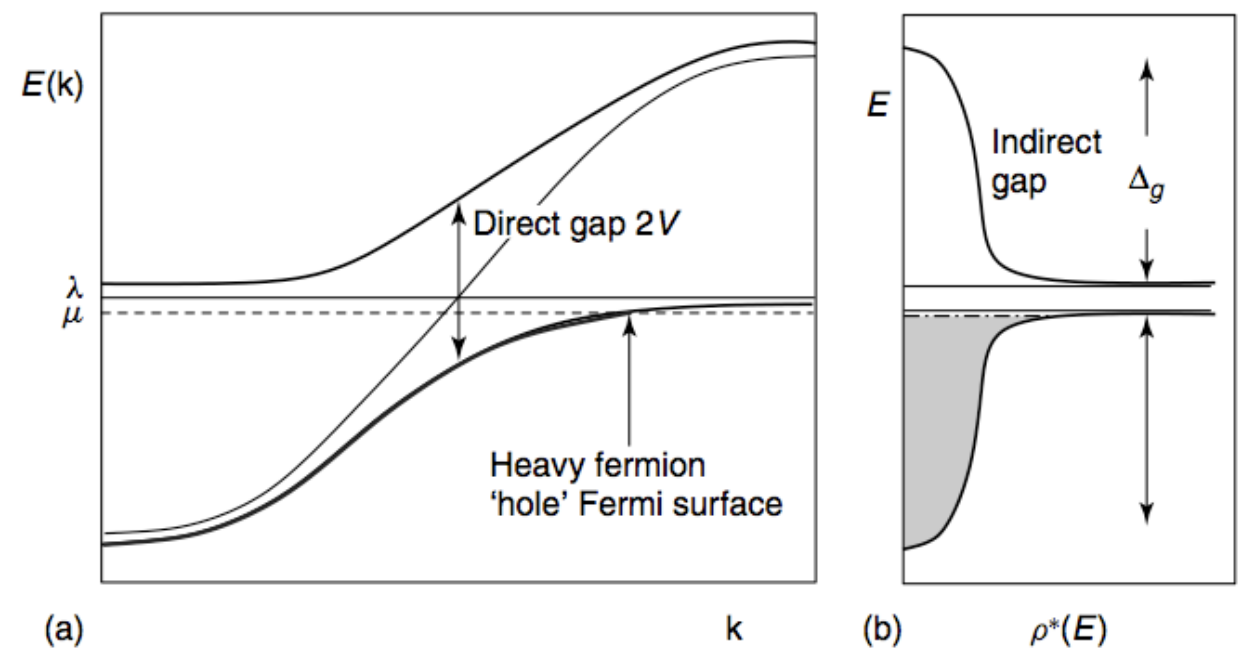
$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$



Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$

$$\frac{F}{N} = -T \sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s \left(\frac{V^2}{J} - \lambda q \right).$$

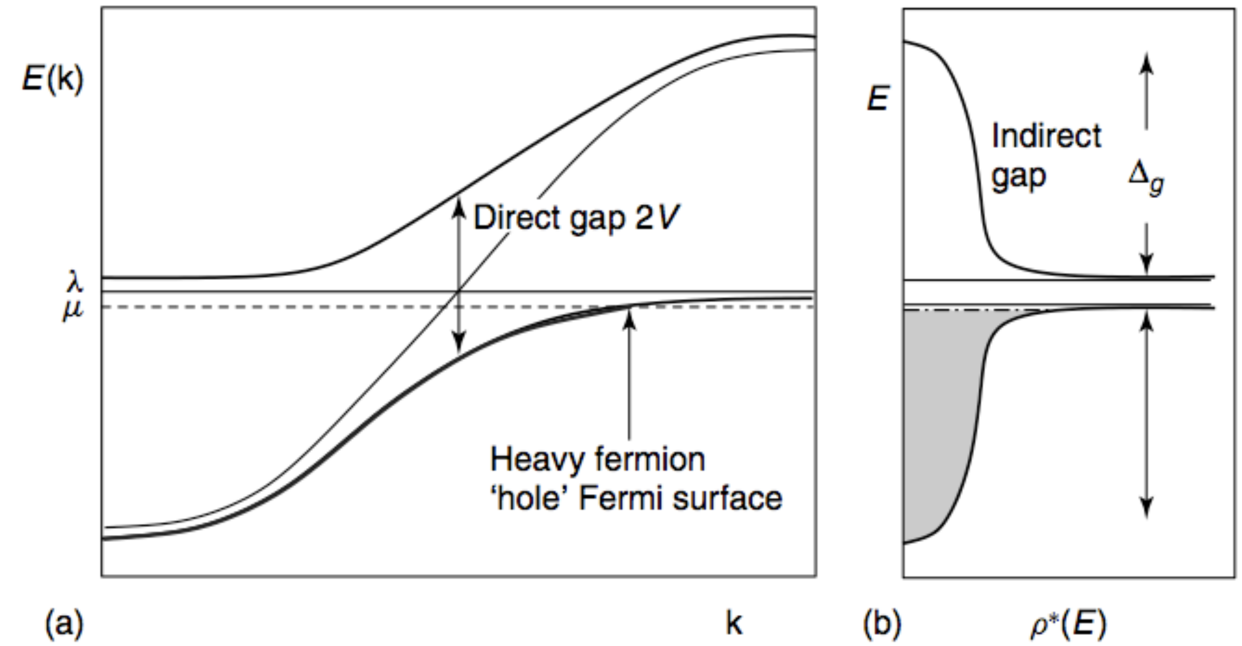


Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$

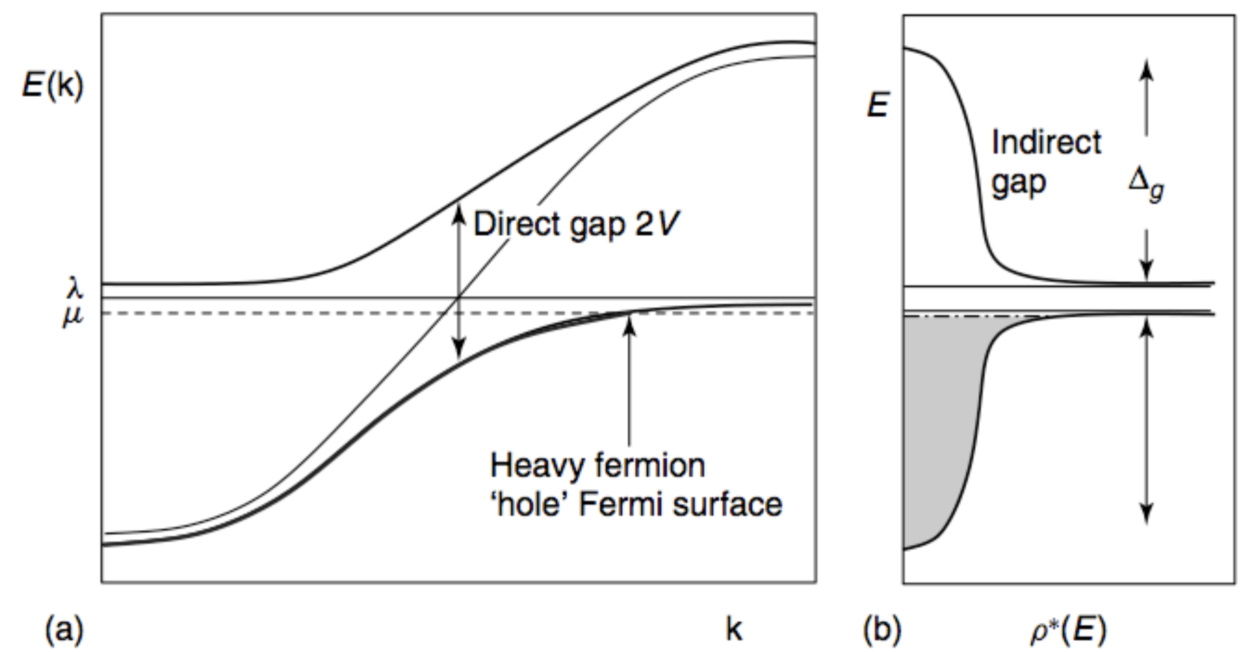
$$\frac{F}{N} = -T \sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s\left(\frac{V^2}{J} - \lambda q\right).$$

$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE \rho^*(E) E + \left(\frac{V^2}{J} - \lambda q\right)$$



Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2} \right)^2 + |V|^2 \right]^{\frac{1}{2}},$$



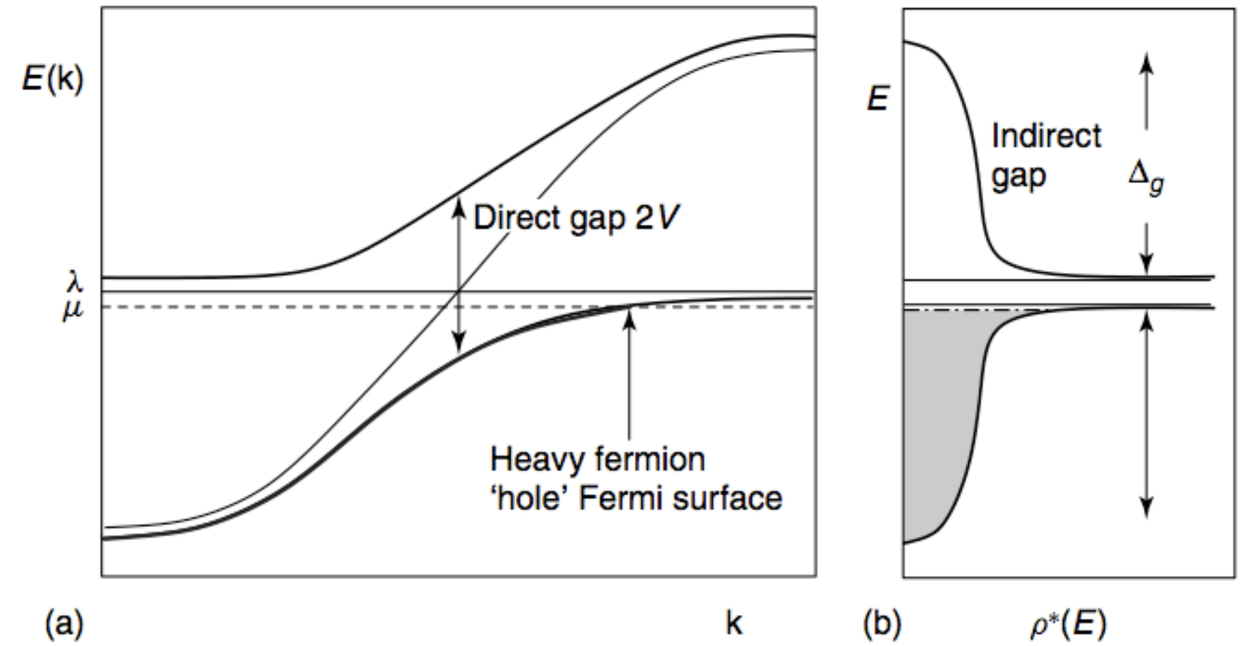
$$\frac{F}{N} = -T \sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s \left(\frac{V^2}{J} - \lambda q \right).$$

$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE \rho^*(E) E + \left(\frac{V^2}{J} - \lambda q \right)$$

$$E = \epsilon + \frac{V^2}{E - \lambda}$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$



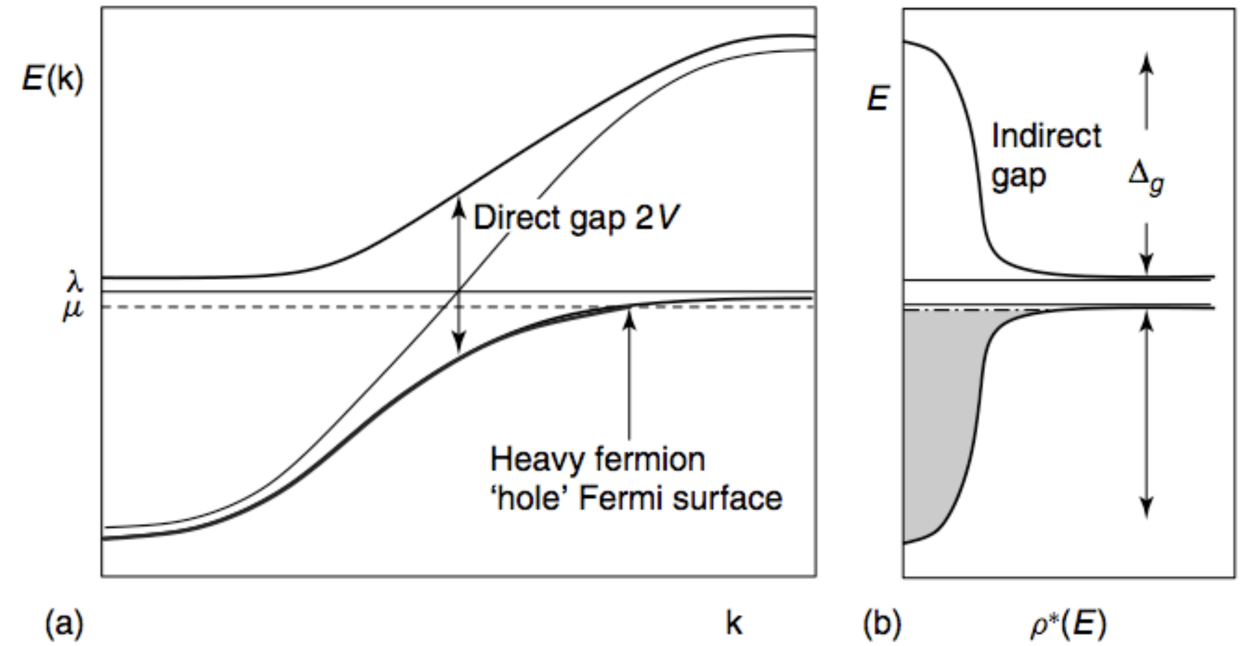
$$\frac{F}{N} = -T \sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s\left(\frac{V^2}{J} - \lambda q\right).$$

$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE\rho^*(E)E + \left(\frac{V^2}{J} - \lambda q\right)$$

$$E = \epsilon + \frac{V^2}{E - \lambda} \qquad \rho^*(E) = \rho\frac{d\epsilon}{dE} = \rho\left(1 + \frac{V^2}{(E - \lambda)^2}\right)$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$



$$\frac{F}{N} = -T \sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s\left(\frac{V^2}{J} - \lambda q\right).$$

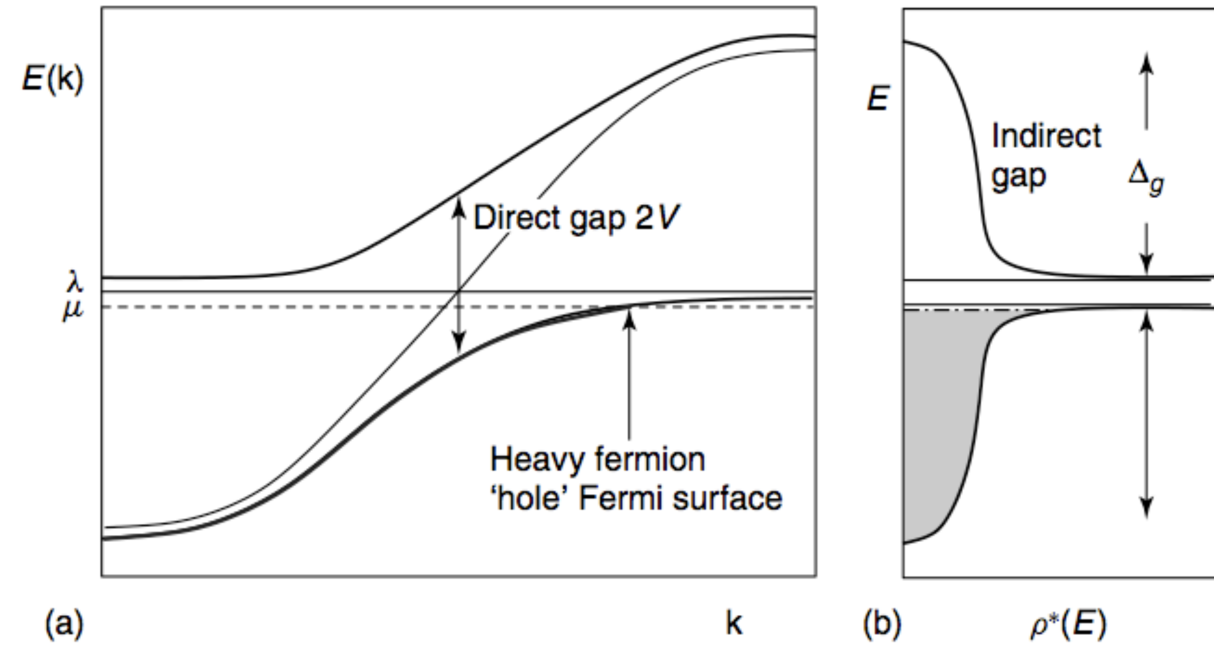
$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE\rho^*(E)E + \left(\frac{V^2}{J} - \lambda q\right)$$

$$E = \epsilon + \frac{V^2}{E - \lambda} \qquad \rho^*(E) = \rho\frac{d\epsilon}{dE} = \rho\left(1 + \frac{V^2}{(E-\lambda)^2}\right)$$

$$\frac{E_o}{N\mathcal{N}_s} = \rho\int_{-D-V^2/D}^{0} dEE\left(1 + \frac{V^2}{(E-\lambda)^2}\right) + \left(\frac{V^2}{J} - \lambda q\right)$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$



$$\frac{F}{N} = -T\sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s\left(\frac{V^2}{J} - \lambda q\right).$$

$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE\rho^*(E)E + \left(\frac{V^2}{J} - \lambda q\right)$$

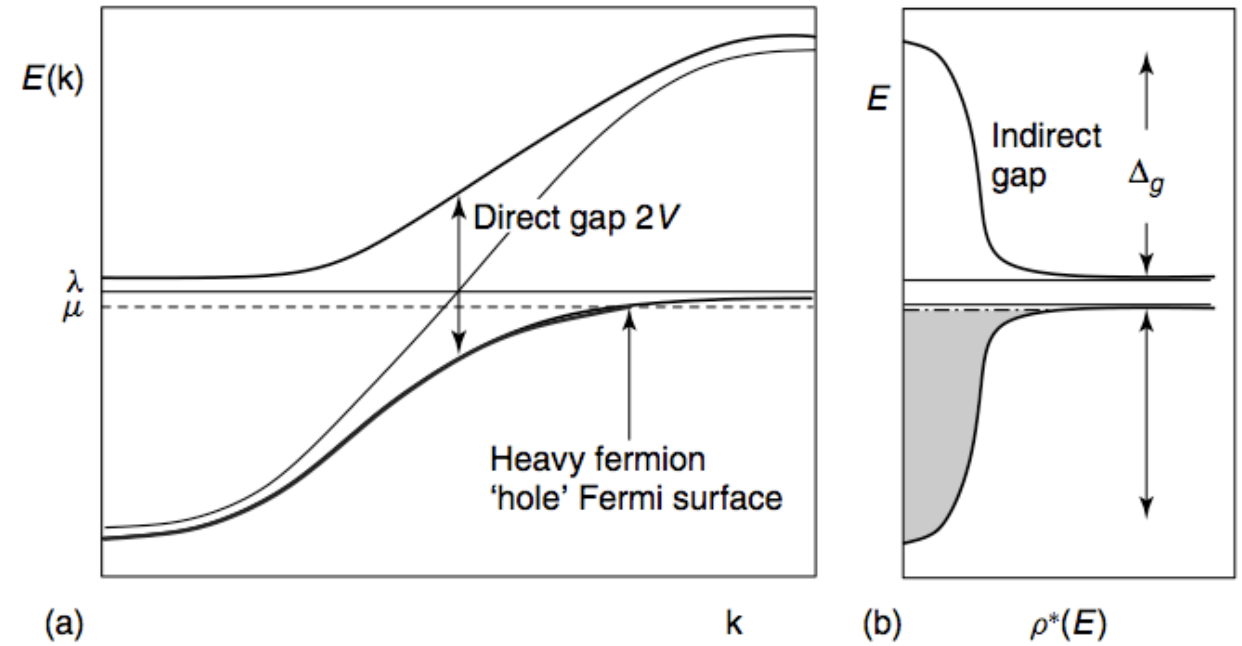
$$E = \epsilon + \frac{V^2}{E-\lambda} \qquad \rho^*(E) = \rho\frac{d\epsilon}{dE} = \rho\left(1 + \frac{V^2}{(E-\lambda)^2}\right)$$

$$\frac{E_o}{N\mathcal{N}_s} = \rho\int_{-D-V^2/D}^{0} dEE\left(1 + \frac{V^2}{(E-\lambda)^2}\right) + \left(\frac{V^2}{J} - \lambda q\right)$$

$$\begin{aligned}\frac{E_o}{N\mathcal{N}_s} &= -\frac{\rho}{2}\left(D + \frac{V^2}{D}\right)^2 + \frac{\Delta}{\pi}\int_{-D}^{0} dE\left(\frac{1}{E-\lambda} + \frac{\lambda}{(E-\lambda)^2}\right) + \left(\frac{V^2}{J} - \lambda q\right)\\ &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{V^2}{J} - \lambda q\right)\end{aligned} \qquad (\Delta = \pi\rho|V|^2)$$

Detailed calcn.

$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$



$$\frac{F}{N} = -T\sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s\left(\frac{V^2}{J} - \lambda q\right).$$

$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE\rho^*(E)E + \left(\frac{V^2}{J} - \lambda q\right)$$

$$E = \epsilon + \frac{V^2}{E-\lambda} \qquad \rho^*(E) = \rho\frac{d\epsilon}{dE} = \rho\left(1 + \frac{V^2}{(E-\lambda)^2}\right)$$

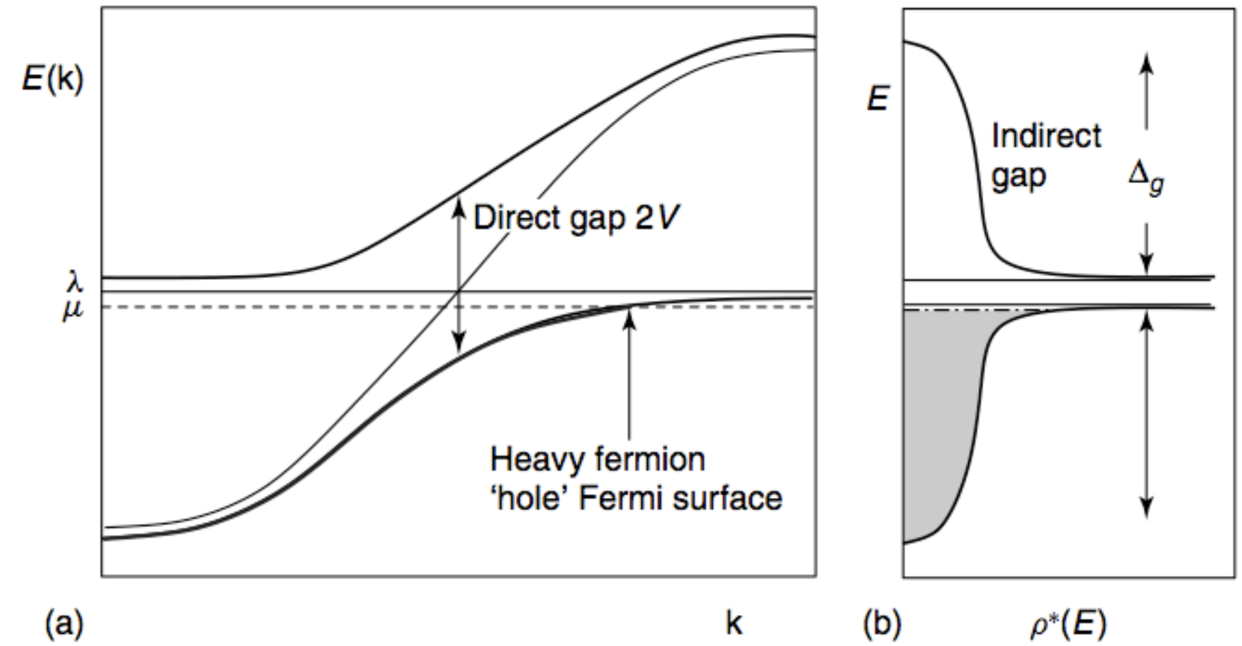
$$\frac{E_o}{N\mathcal{N}_s} = \rho\int_{-D-V^2/D}^{0} dEE\left(1 + \frac{V^2}{(E-\lambda)^2}\right) + \left(\frac{V^2}{J} - \lambda q\right)$$

$$\begin{aligned}\frac{E_o}{N\mathcal{N}_s} &= -\frac{\rho}{2}\left(D + \frac{V^2}{D}\right)^2 + \frac{\Delta}{\pi}\int_{-D}^{0} dE\left(\frac{1}{E-\lambda} + \frac{\lambda}{(E-\lambda)^2}\right) + \left(\frac{V^2}{J} - \lambda q\right)\\ &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{V^2}{J} - \lambda q\right)\end{aligned}$$

Detailed calcn.

$$\frac{E_o}{N\mathcal{N}_s} = -\frac{\rho}{2}\left(D + \frac{V^2}{D}\right)^2 + \frac{\Delta}{\pi}\int_{-D}^{0} dE\left(\frac{1}{E-\lambda} + \frac{\lambda}{(E-\lambda)^2}\right) + \left(\frac{V^2}{J} - \lambda q\right)$$

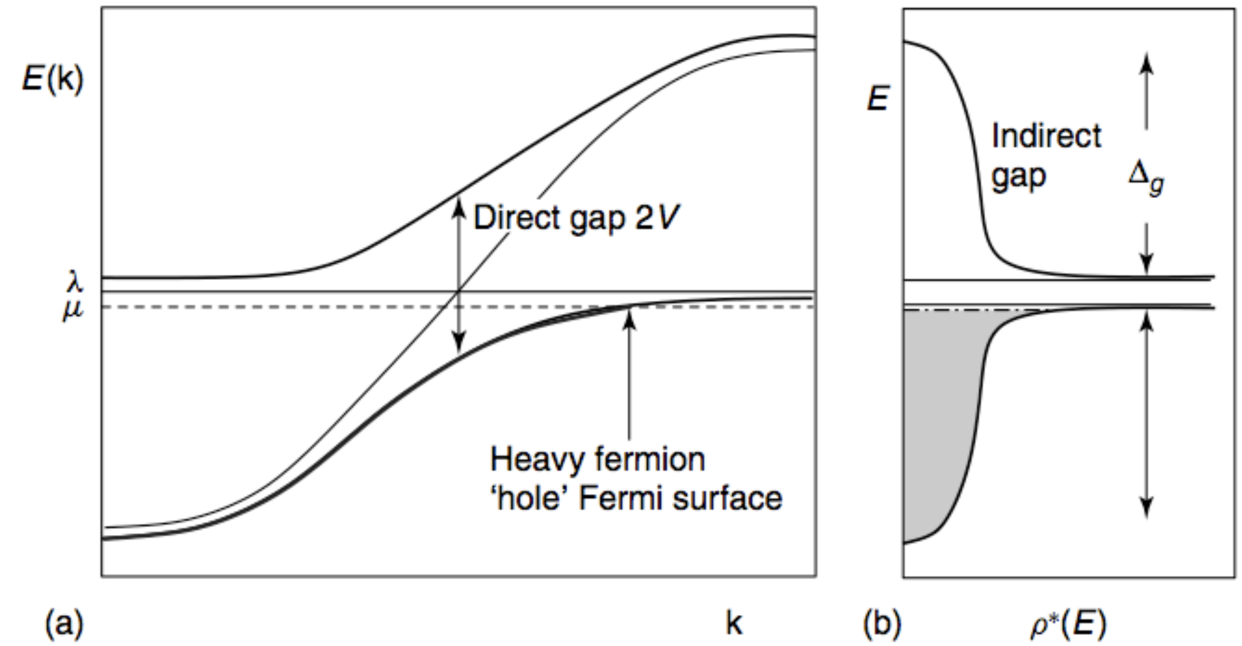
$$= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{V^2}{J} - \lambda q\right)$$



Detailed calcn.

$$(\Delta = \pi\rho|V|^2)$$

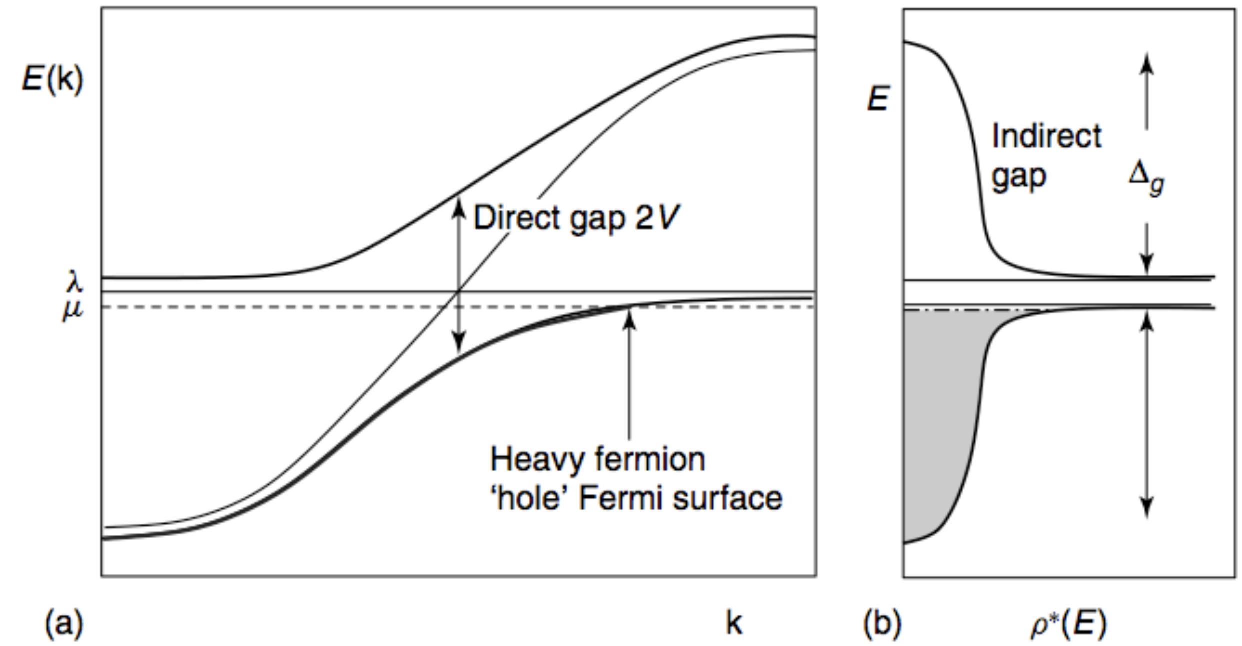
$$\frac{E_0}{N\mathcal{N}_s} = -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\pi\rho V^2}{\pi\rho J} - \lambda q\right)$$



Detailed calcn.

$$(\Delta = \pi\rho|V|^2)$$

$$\begin{aligned}
\frac{E_0}{N\mathcal{N}_s} &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\pi\rho V^2}{\pi\rho J} - \lambda q\right) \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\Delta}{\pi\rho J} - \lambda q\right) \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{De^{-\frac{1}{J\rho}}}\right) - \lambda q \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{T_K}\right) - \lambda q.
\end{aligned}$$

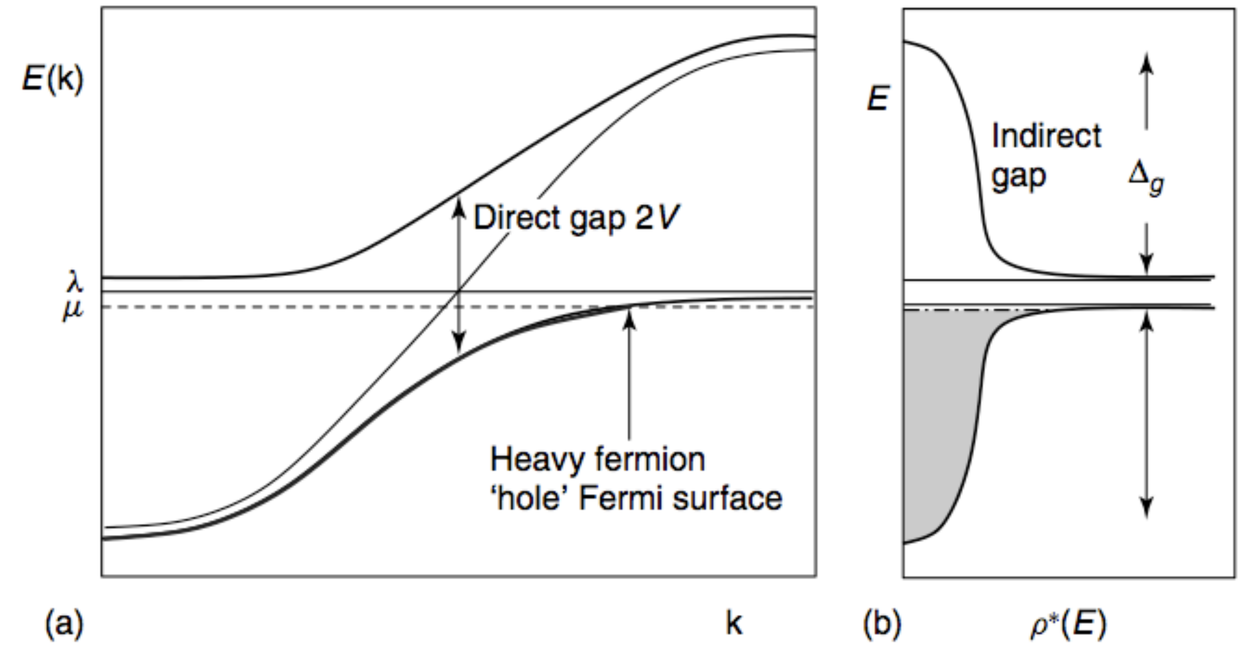


$$T_K = De^{-\frac{1}{J\rho}}$$

Detailed calcn.

$$(\Delta = \pi\rho|V|^2)$$

$$\begin{aligned}
\frac{E_0}{N\mathcal{N}_s} &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\pi\rho V^2}{\pi\rho J} - \lambda q\right) \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\Delta}{\pi\rho J} - \lambda q\right) \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{De^{-\frac{1}{J\rho}}}\right) - \lambda q \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{T_K}\right) - \lambda q.
\end{aligned}$$



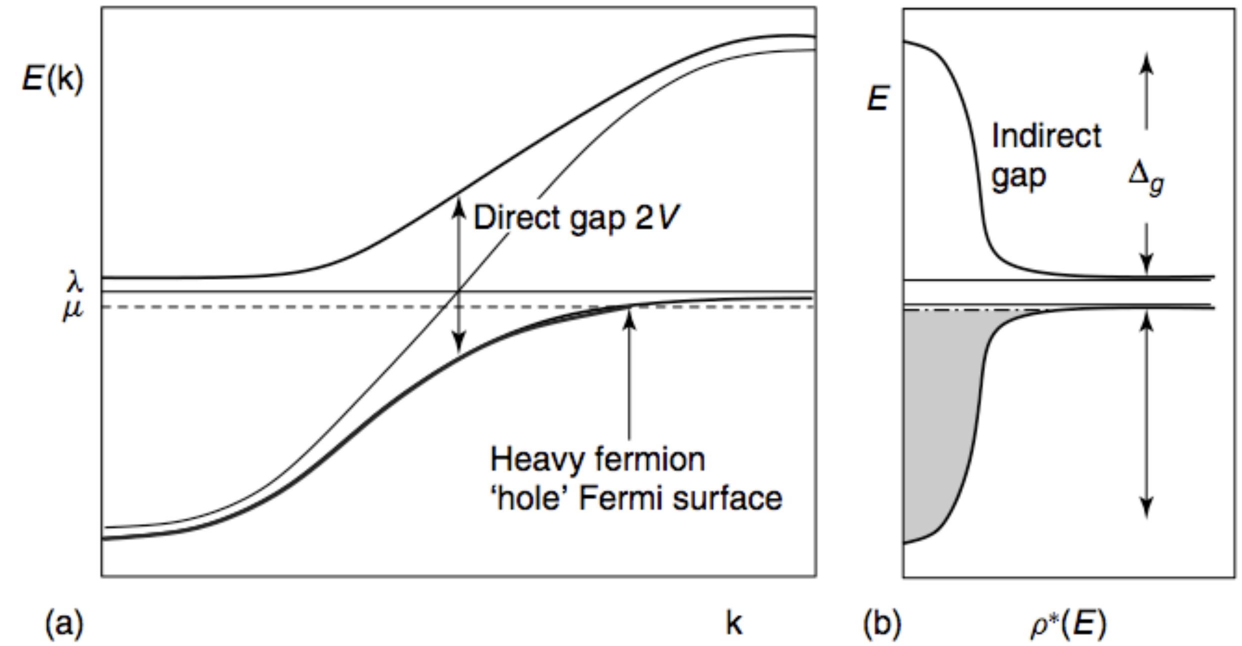
$$T_K = De^{-\frac{1}{J\rho}}$$

$$\frac{\partial E_0}{\partial \lambda} = \langle n_f \rangle - Q = 0$$

Detailed calcn.

$$(\Delta = \pi\rho|V|^2)$$

$$\begin{aligned}
\frac{E_0}{N\mathcal{N}_s} &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\pi\rho V^2}{\pi\rho J} - \lambda q\right) \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\Delta}{\pi\rho J} - \lambda q\right) \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{De^{-\frac{1}{J\rho}}}\right) - \lambda q \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{T_K}\right) - \lambda q.
\end{aligned}$$



$$T_K = De^{-\frac{1}{J\rho}}$$

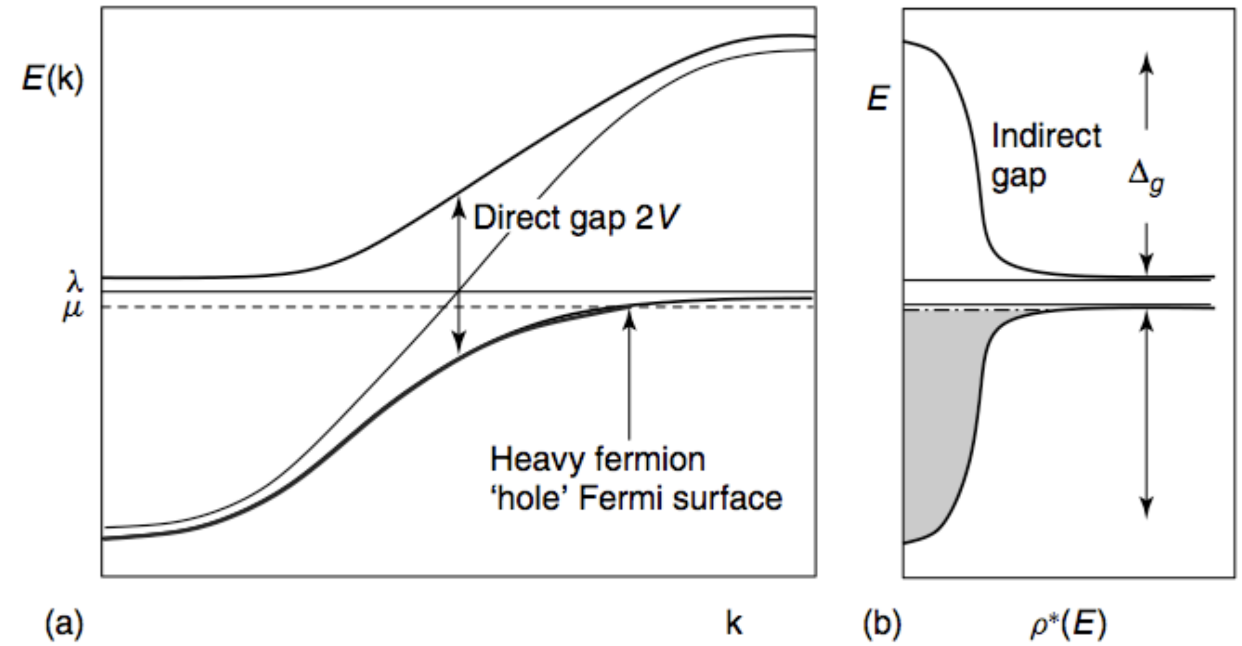
$$\frac{\partial E_0}{\partial \lambda} = \langle n_f \rangle - Q = 0 \qquad \frac{\Delta}{\pi\lambda} - q = 0$$

$$\frac{E_o(V)}{N\mathcal{N}_s} = \frac{\Delta}{\pi}\ln\left(\frac{\Delta}{\pi q e T_K}\right) - \frac{D^2\rho}{2},$$

Detailed calcn.

$(\Delta = \pi\rho|V|^2)$

$$\frac{E_0}{N\mathcal{N}_s} = -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\pi\rho V^2}{\pi\rho J} - \lambda q\right)$$
$$= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\Delta}{\pi\rho J} - \lambda q\right)$$
$$= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{De^{-\frac{1}{J\rho}}}\right) - \lambda q$$
$$= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{T_K}\right) - \lambda q.$$

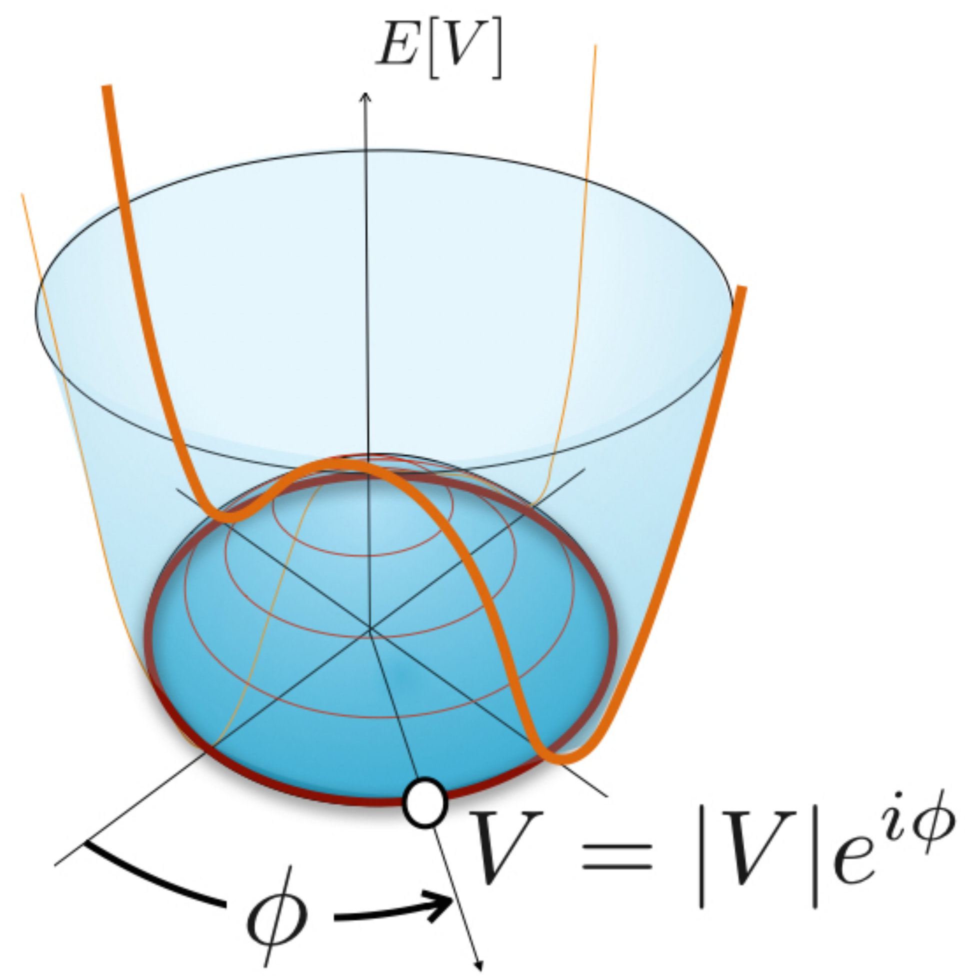


$$T_K = De^{-\frac{1}{J\rho}}$$

$$\frac{\partial E_0}{\partial \lambda} = \langle n_f \rangle - Q = 0 \qquad \frac{\Delta}{\pi\lambda} - q = 0$$

$$\frac{E_o(V)}{N\mathcal{N}_s} = \frac{\Delta}{\pi}\ln\left(\frac{\Delta}{\pi q e T_K}\right) - \frac{D^2\rho}{2},$$

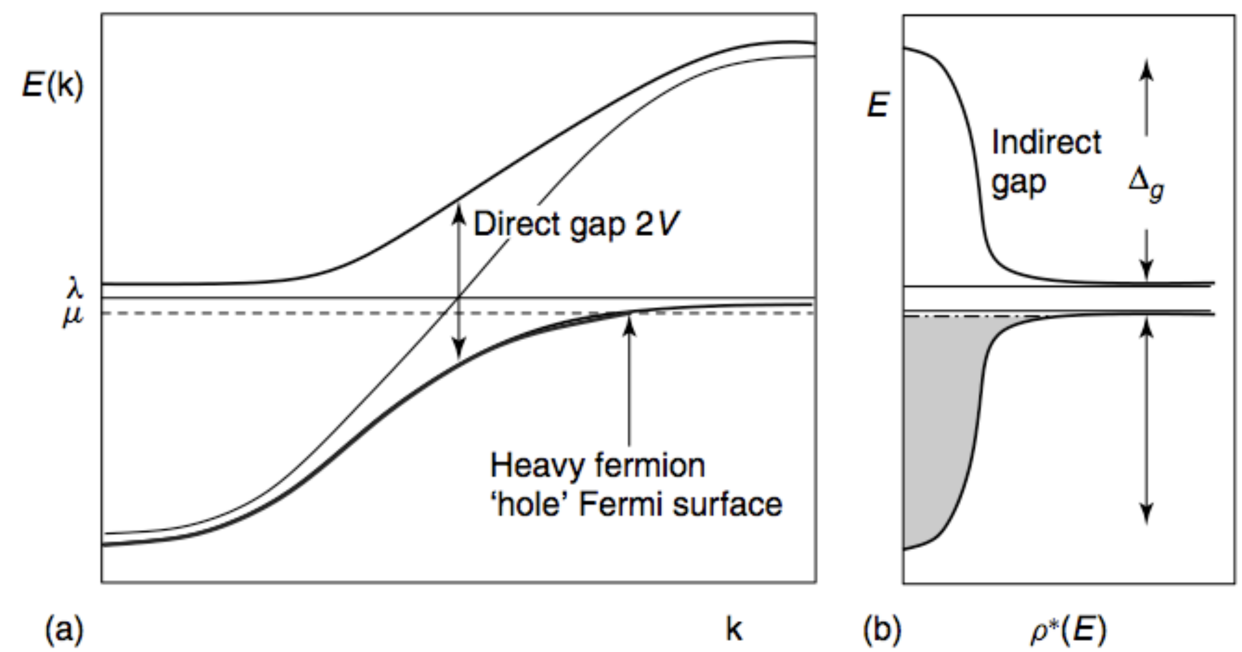
$$\frac{\partial E_0}{\partial \Delta} = 0$$



Detailed calcn.

$$(\Delta = \pi\rho|V|^2)$$

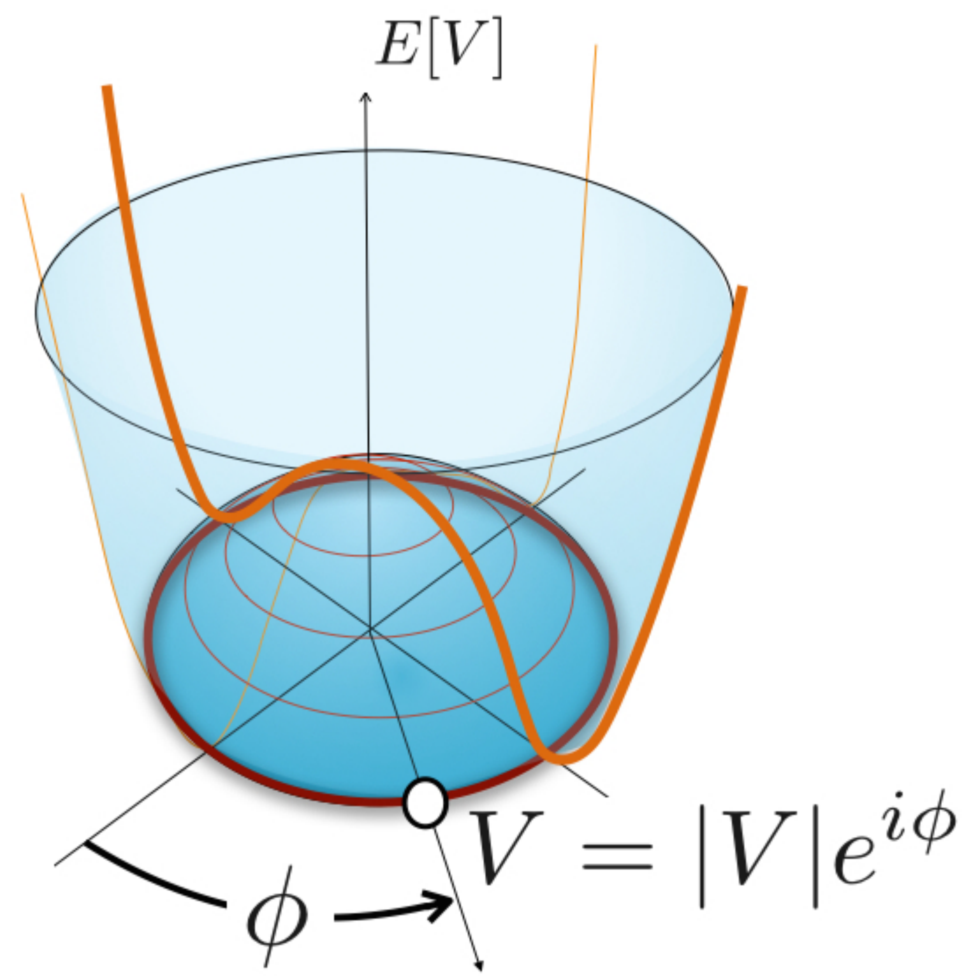
$$\begin{aligned}\frac{E_0}{N\mathcal{N}_s} &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\pi\rho V^2}{\pi\rho J} - \lambda q\right)\\ &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\Delta}{\pi\rho J} - \lambda q\right)\\ &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{De^{-\frac{1}{J\rho}}}\right) - \lambda q\\ &= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{T_K}\right) - \lambda q.\end{aligned}$$



$$T_K = De^{-\frac{1}{J\rho}}$$

$$\frac{\partial E_0}{\partial \lambda} = \langle n_f \rangle - Q = 0 \qquad \frac{\Delta}{\pi\lambda} - q = 0$$

$$\frac{E_o(V)}{N\mathcal{N}_s} = \frac{\Delta}{\pi}\ln\left(\frac{\Delta}{\pi q e T_K}\right) - \frac{D^2\rho}{2},$$

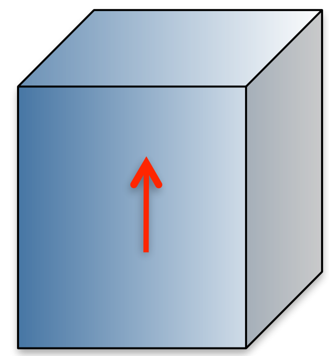


$$\frac{\partial E_0}{\partial \Delta} = 0$$

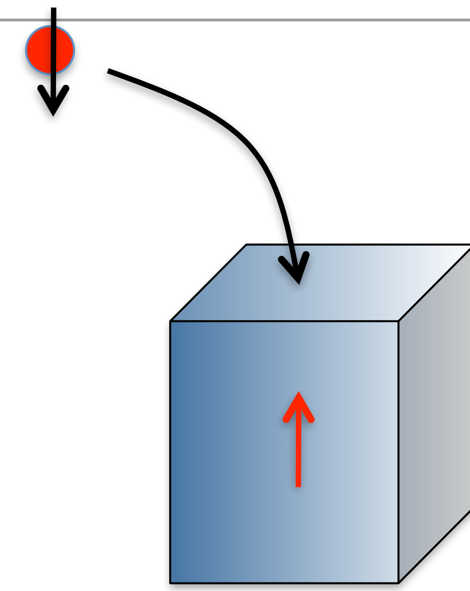
$$0 = \frac{1}{\pi}\ln\left(\frac{\Delta e^2}{\pi q T_K}\right)$$

$$\Delta = \frac{\pi q}{e^2} T_K$$

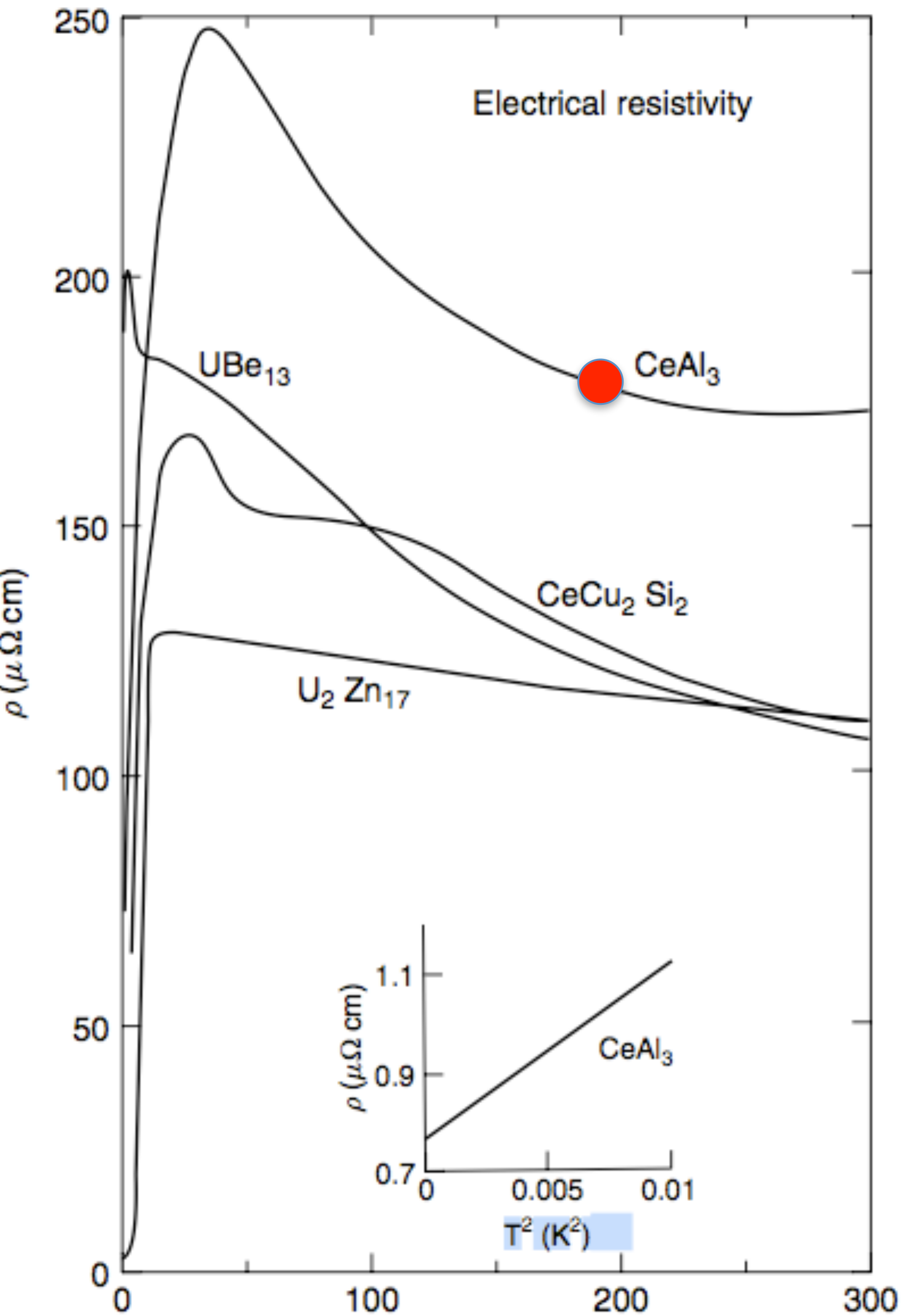
Coherence and composite fermions

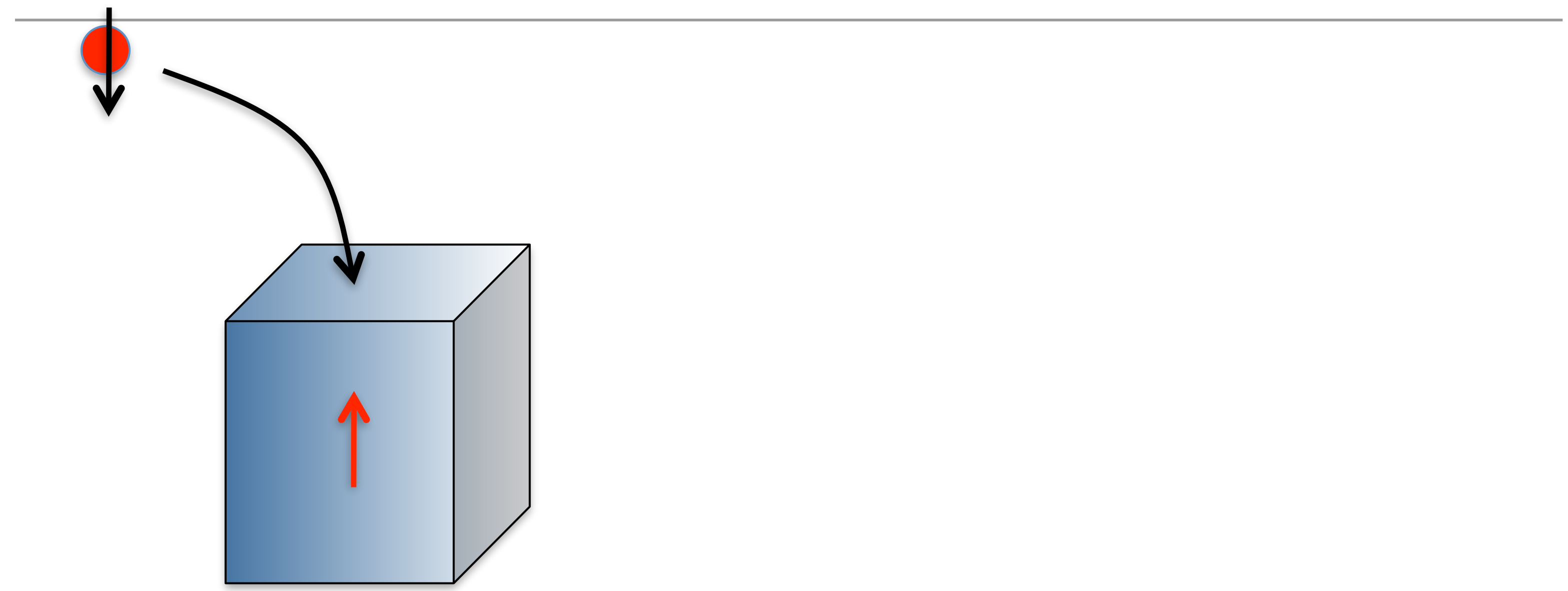


Coherence and composite fermions

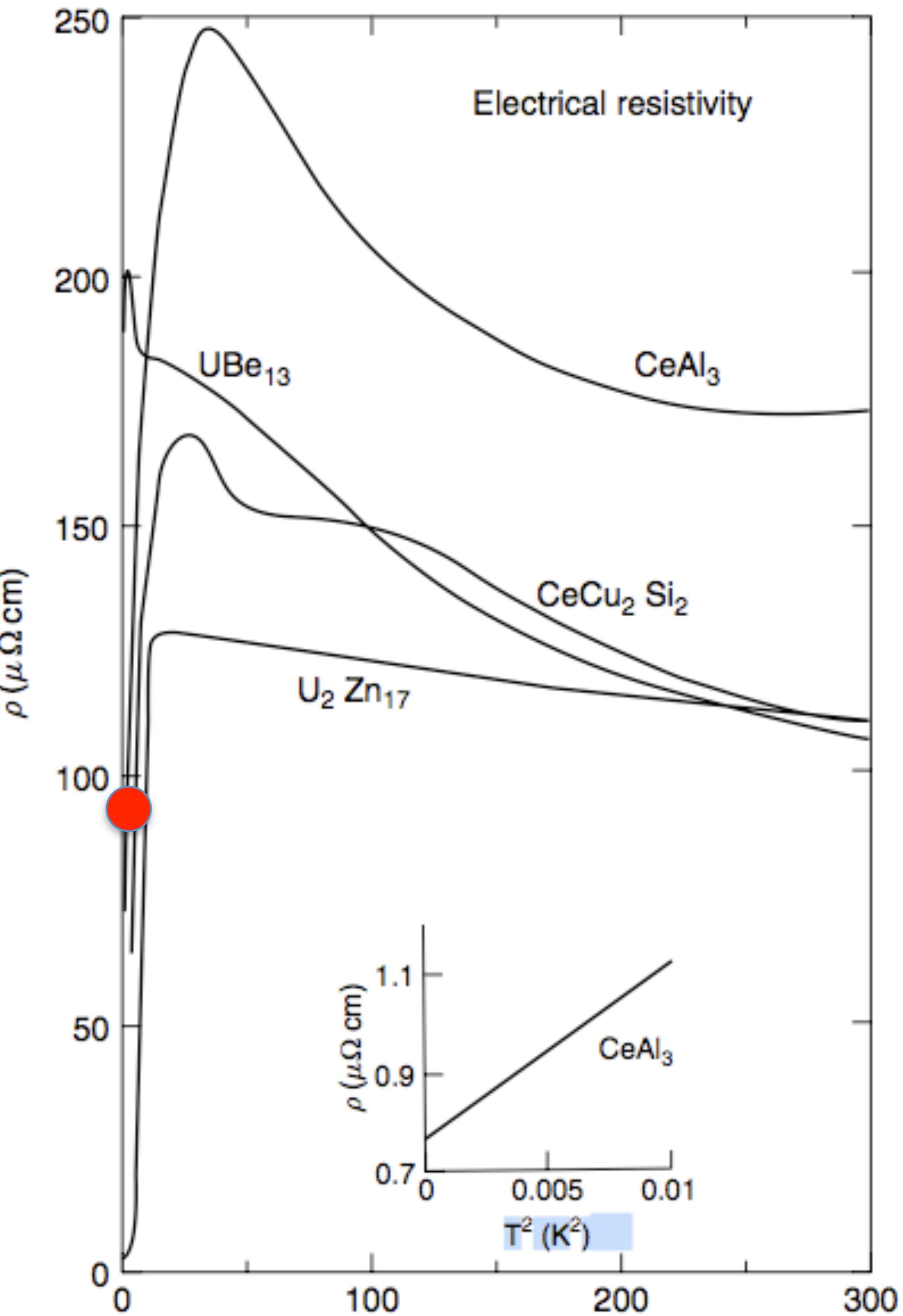


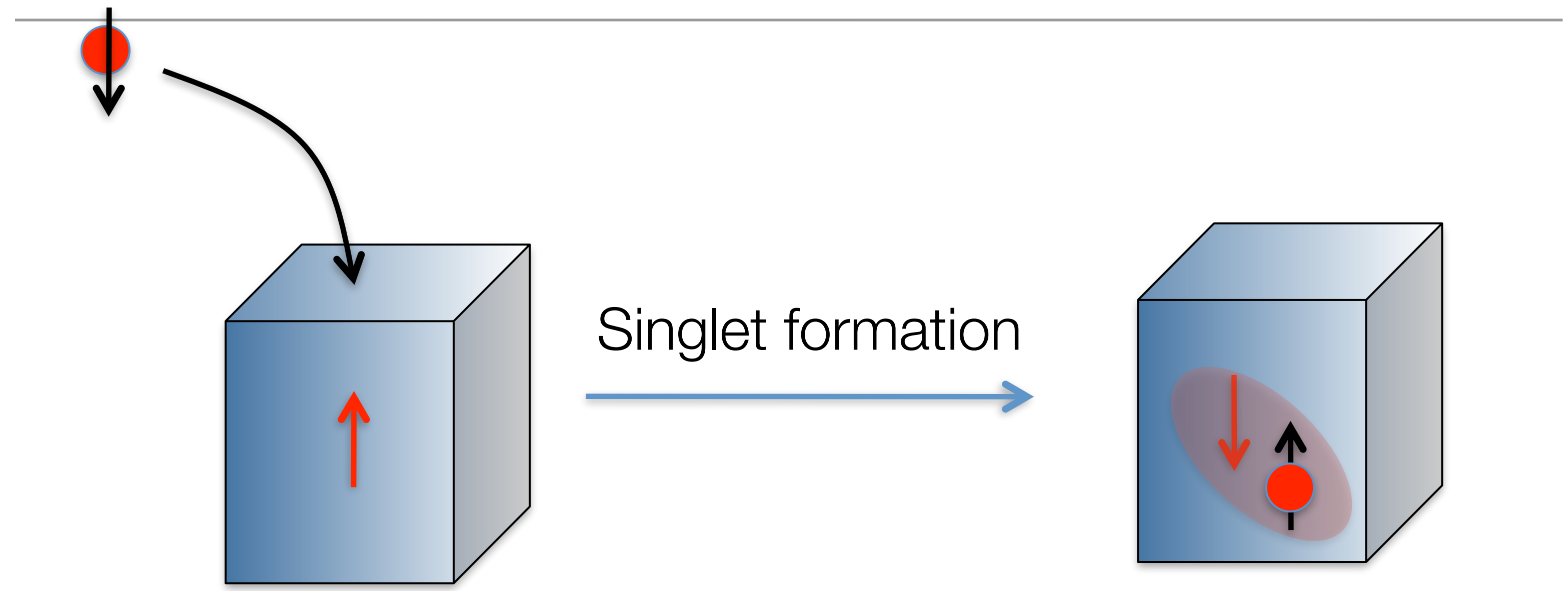
Coherence and composite fermions



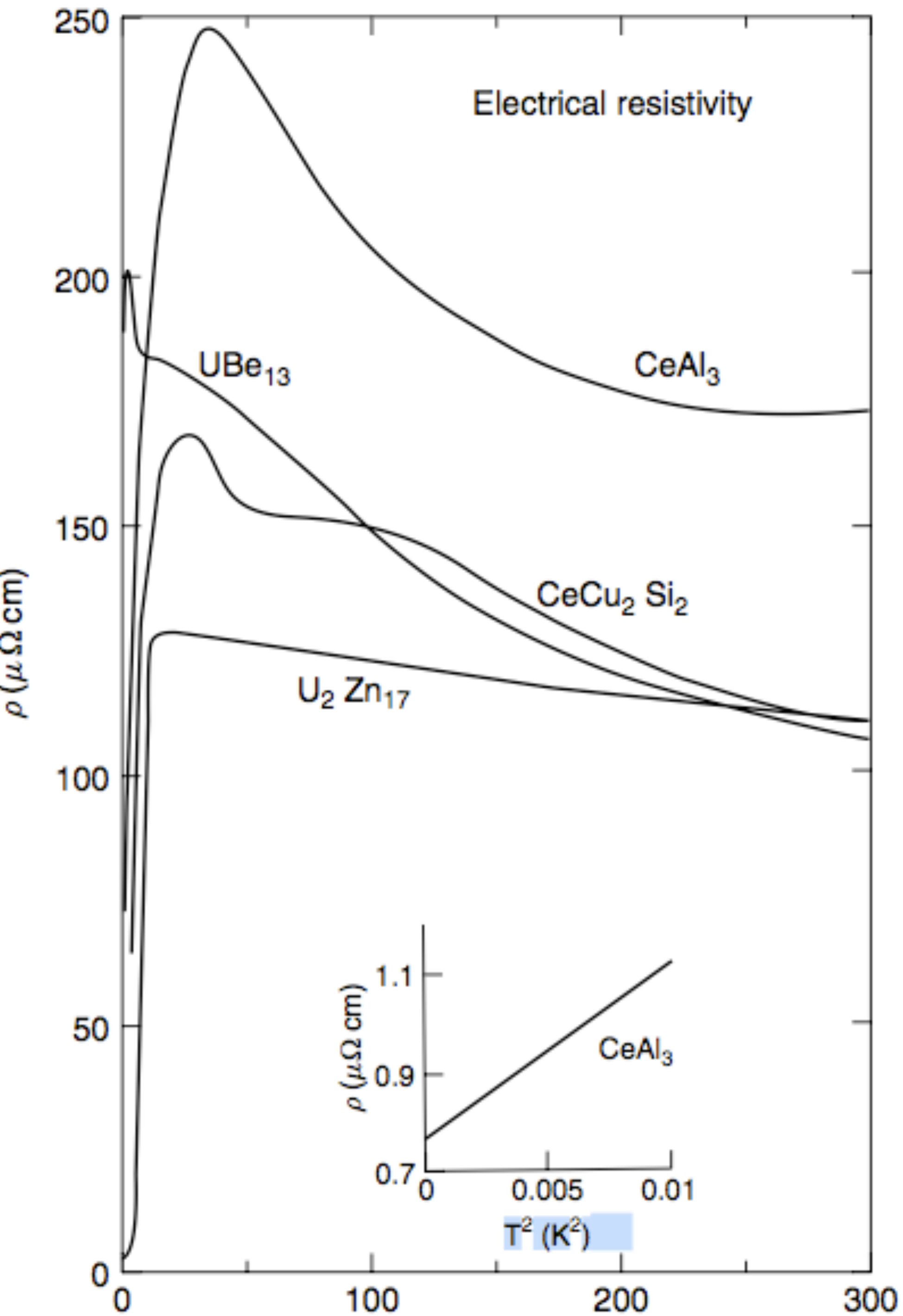


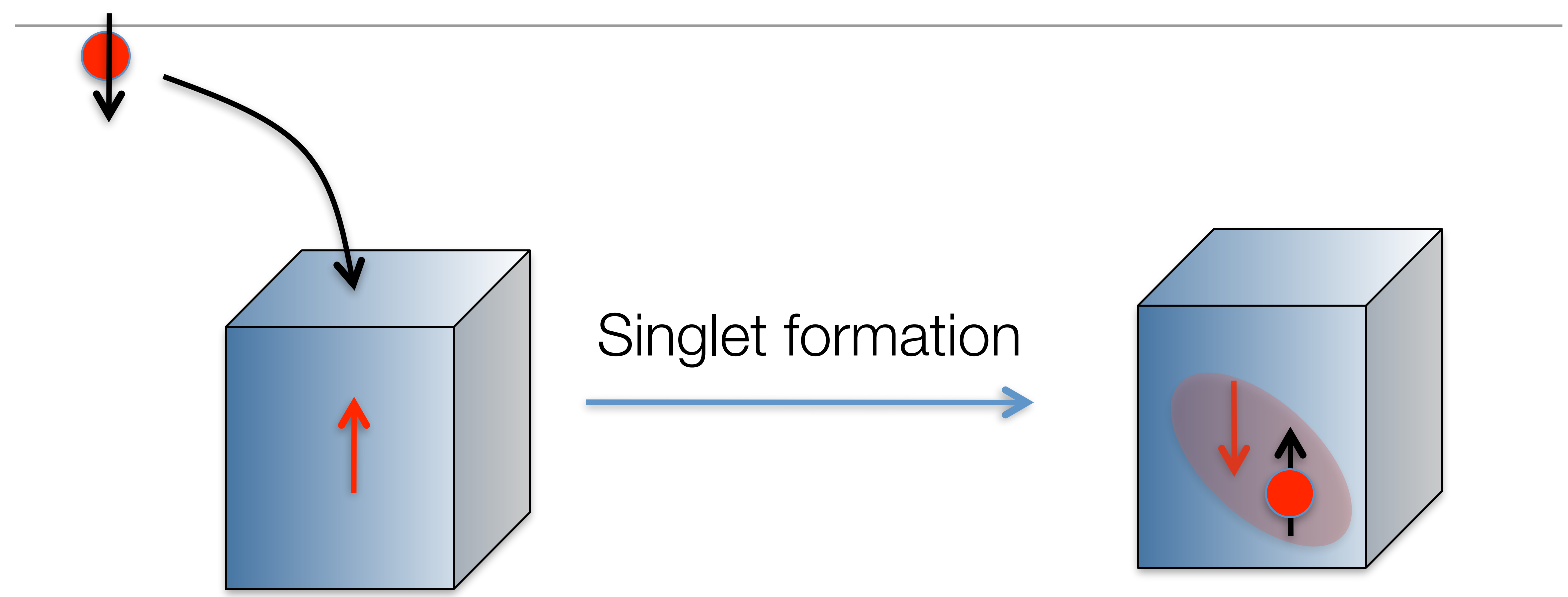
Coherence and composite fermions





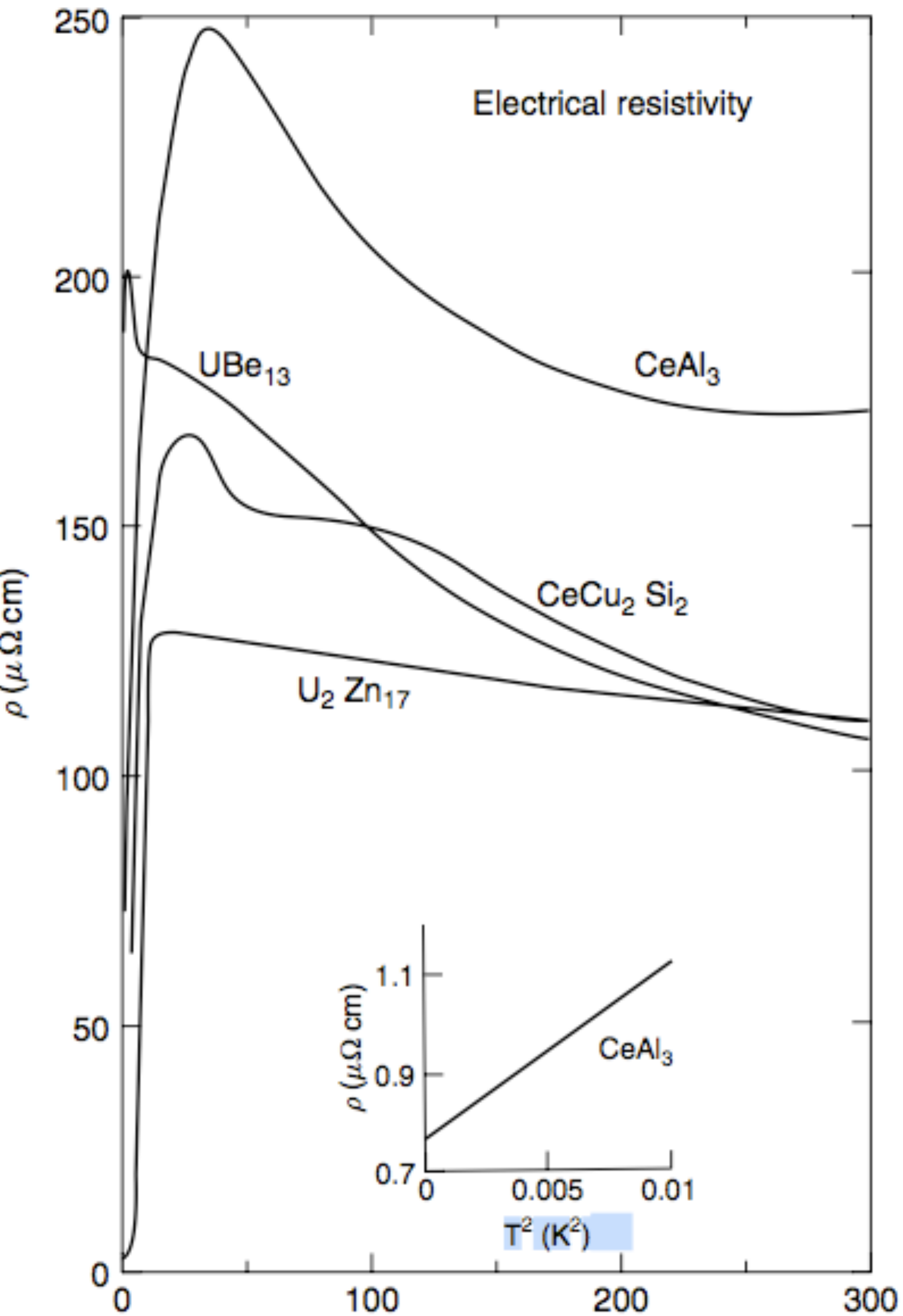
Coherence and composite fermions

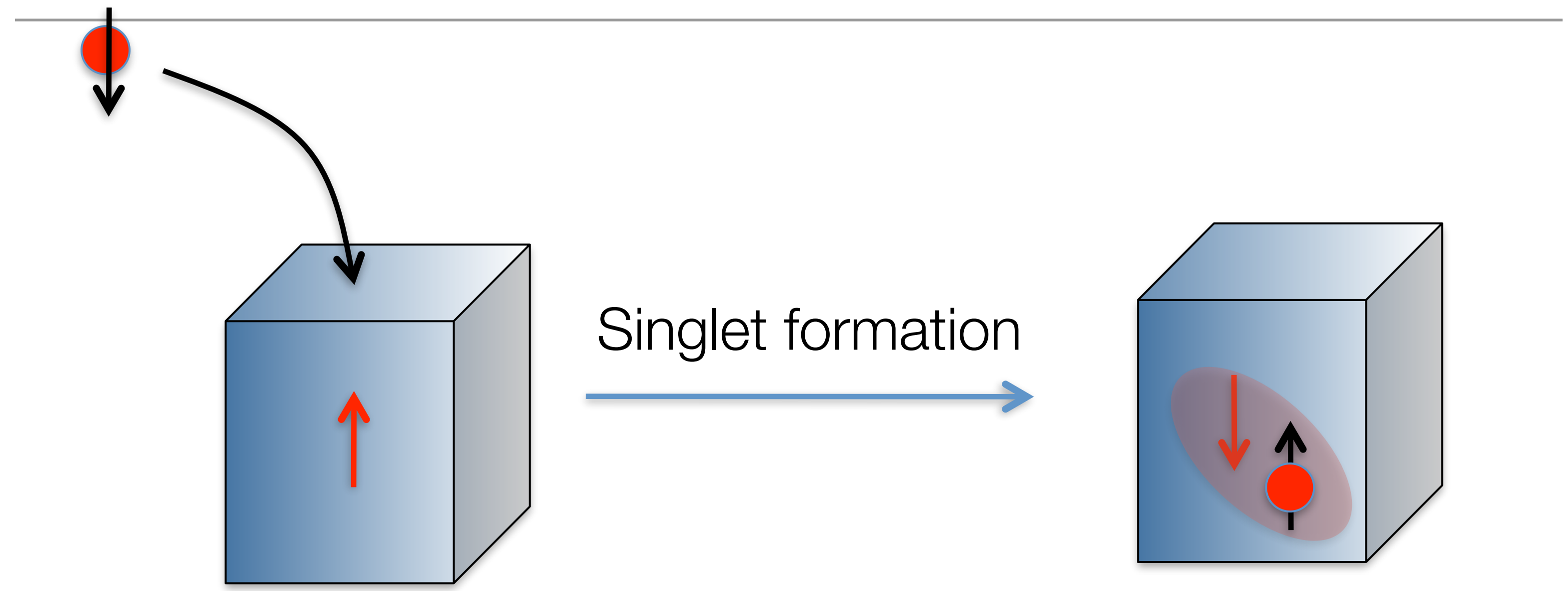




Heavy electron = (electron x spinflip)

Coherence and composite fermions

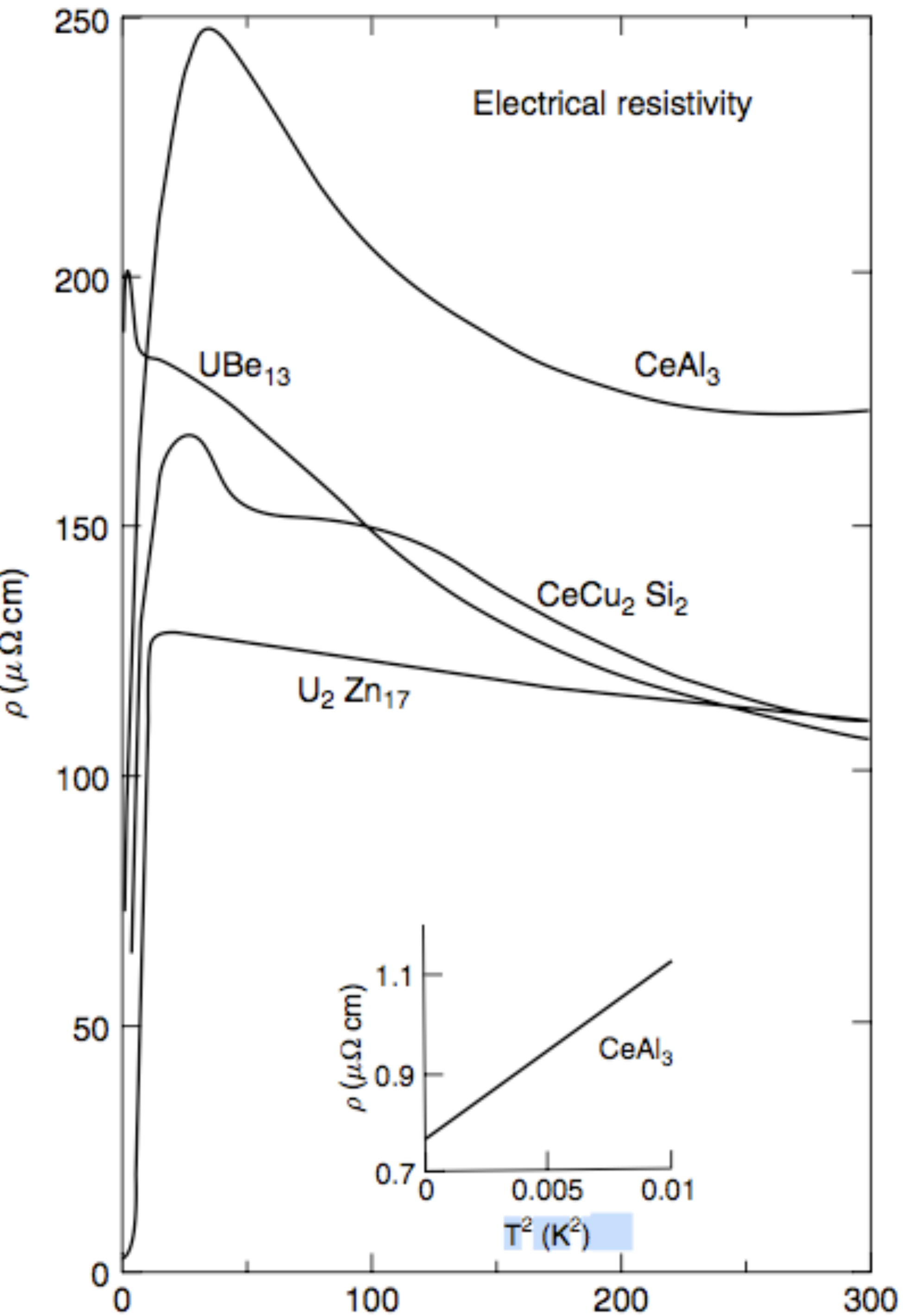


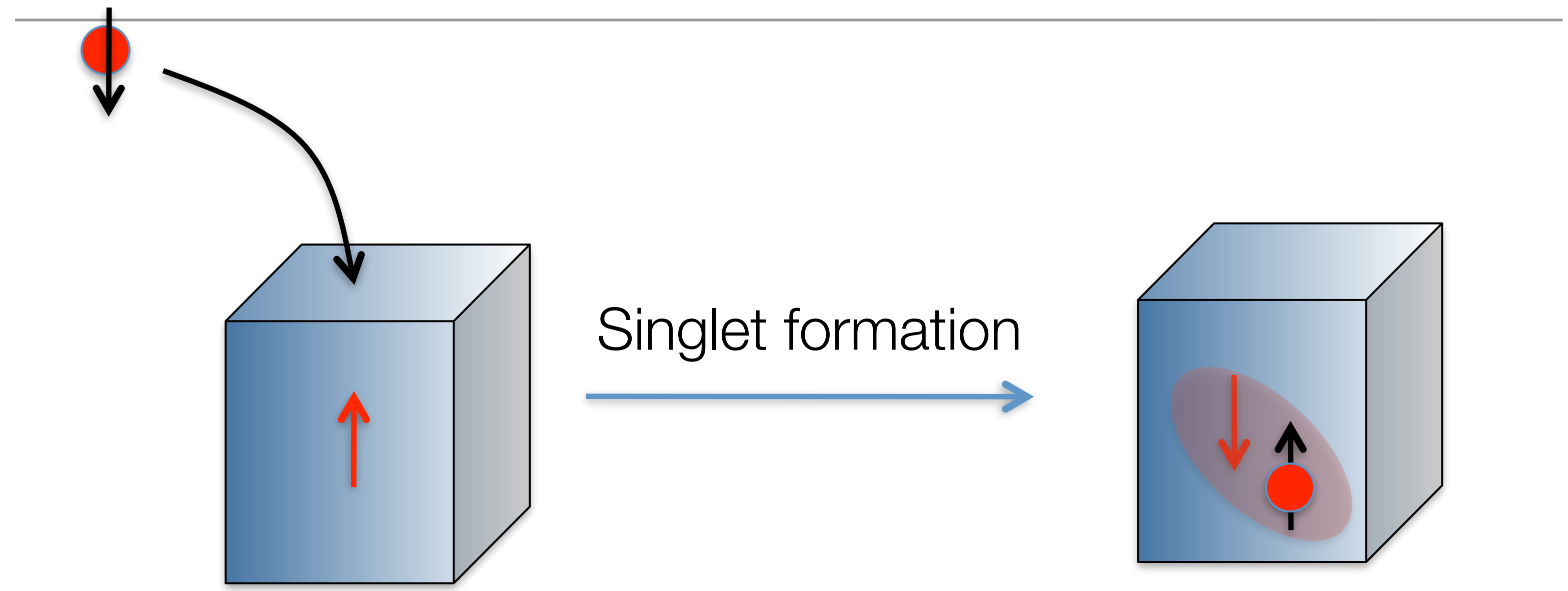


Heavy electron = (electron x spinflip)

- The large N approach to the Kondo lattice.
  Spin x conduction = composite fermion

Coherence and composite fermions



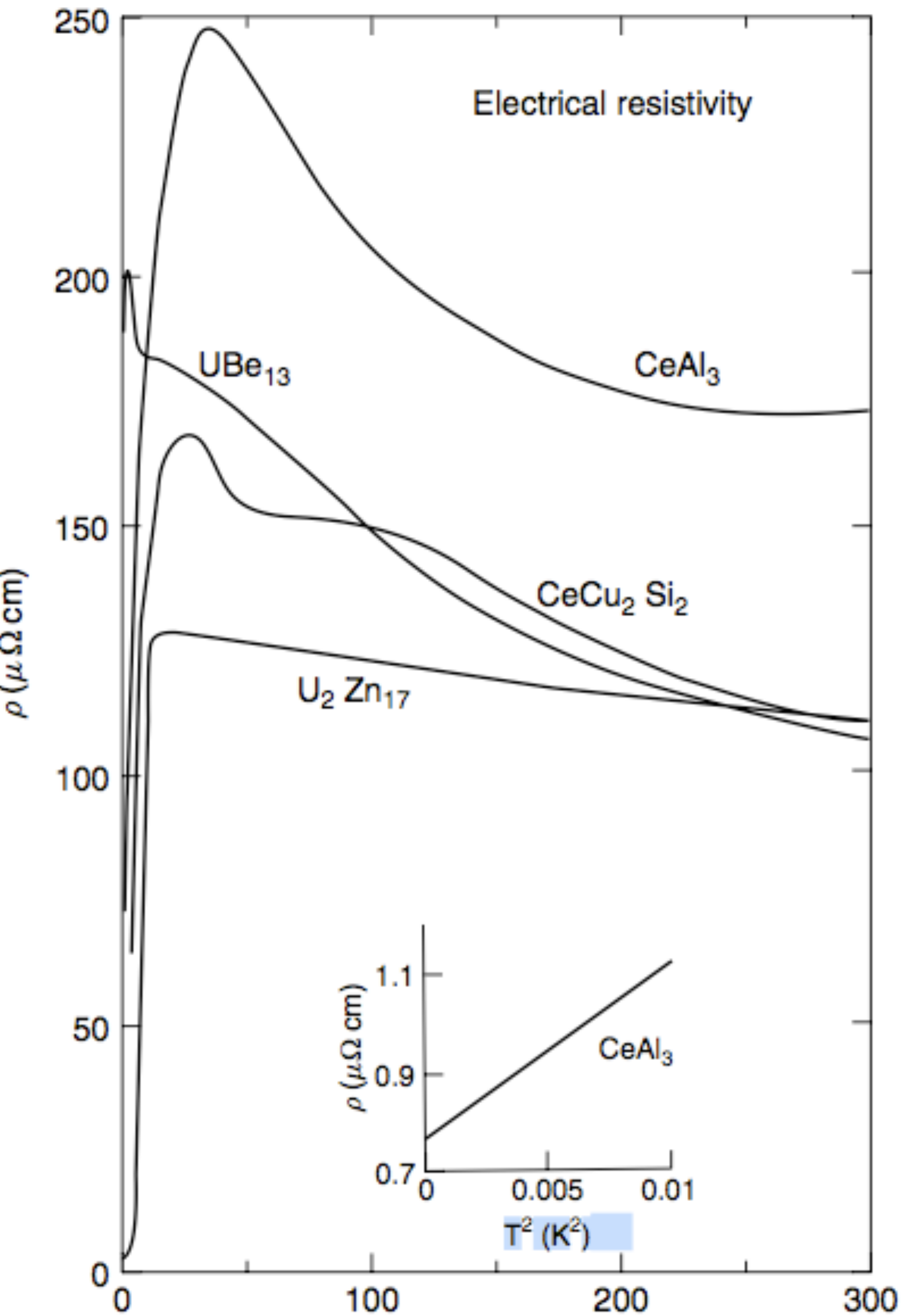


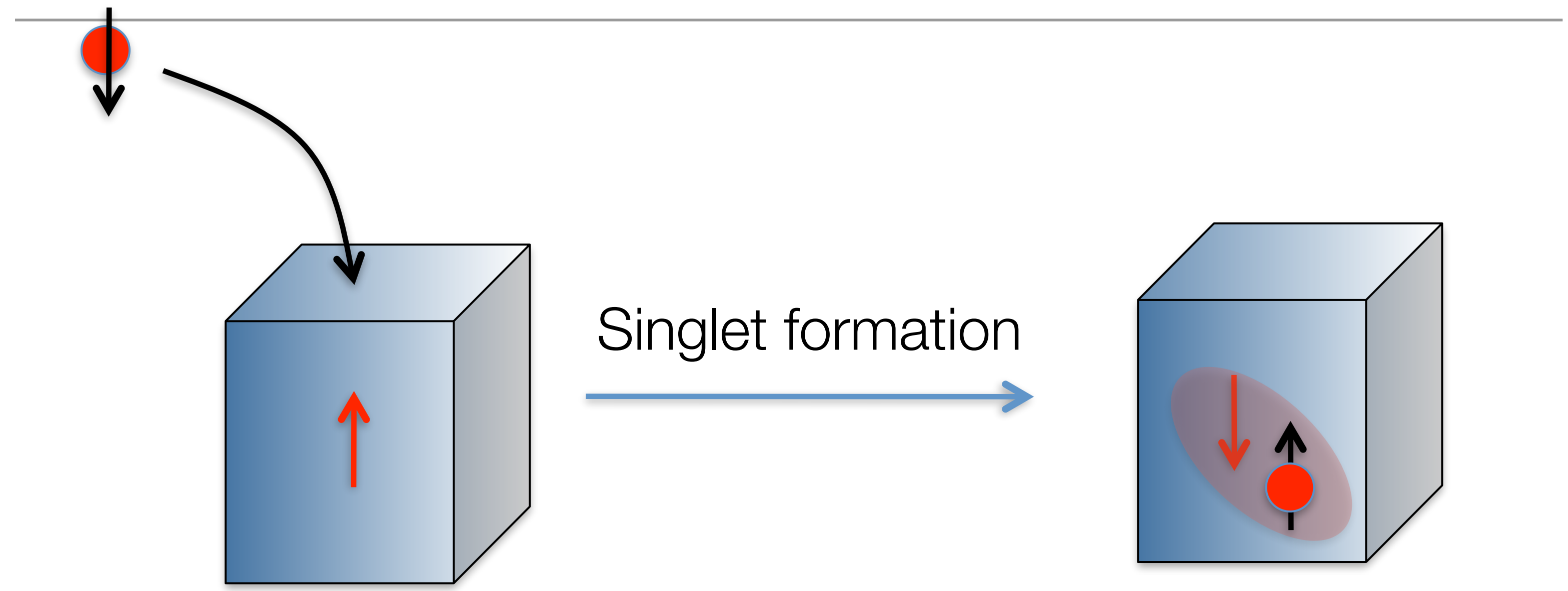
Heavy electron = (electron x spinflip)

- The large N approach to the Kondo lattice.
  Spin x conduction = composite fermion

$$\frac{J}{N} c^{\dagger}{}_{\beta} S_{\alpha\beta} c_{\alpha} \longrightarrow \bar{V}\left(c^{\dagger}{}_{\alpha} f_{\alpha}\right) + \left(f^{\dagger}{}_{\alpha} c_{\alpha}\right) V + N\frac{\bar{V}V}{J},$$

Coherence and composite fermions





Heavy electron = (electron x spinflip)

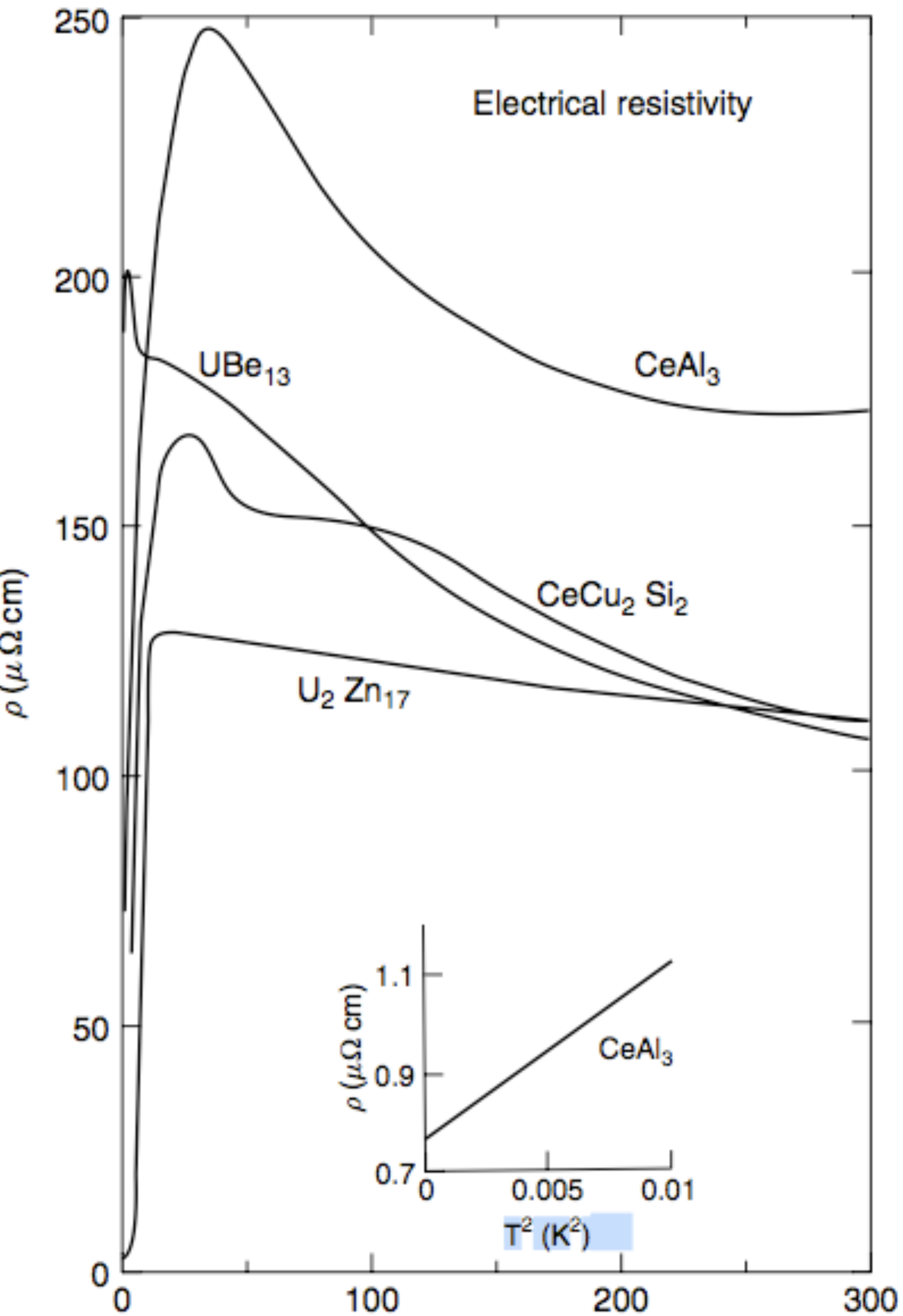
- The large N approach to the Kondo lattice.
  Spin x conduction = composite fermion

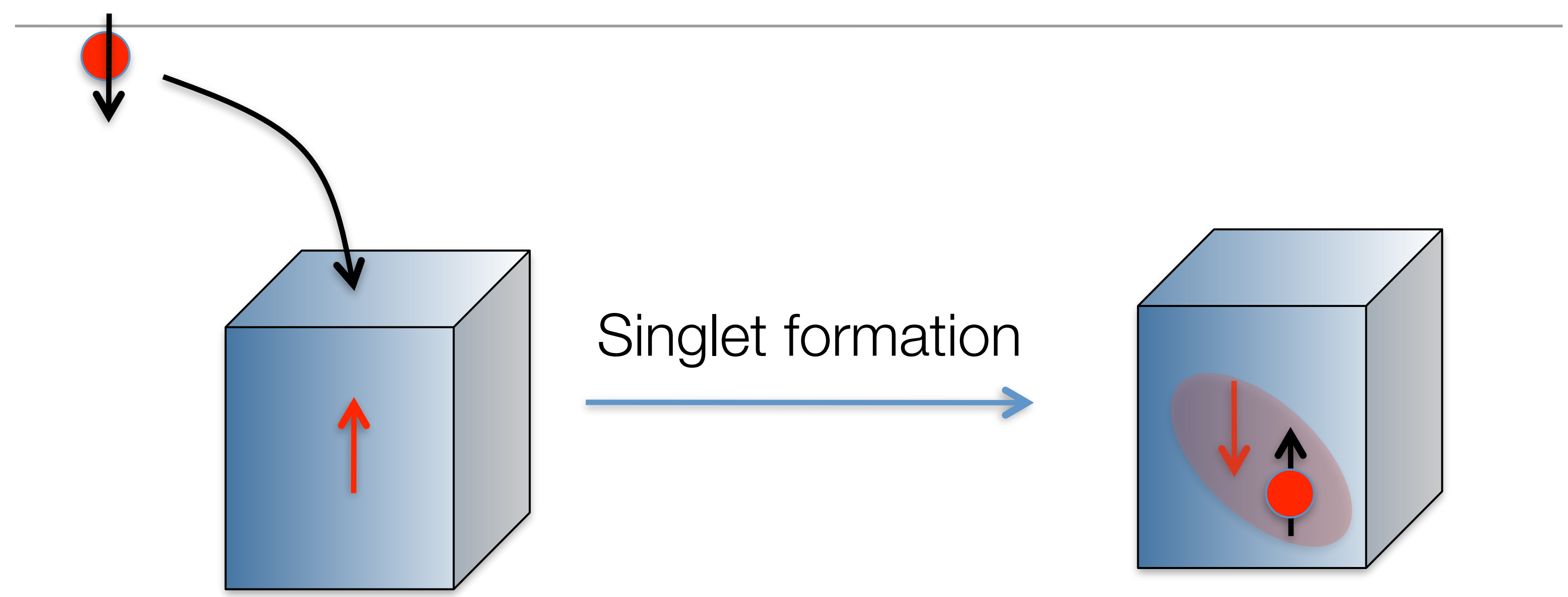
$$\frac{J}{N} c^{\dagger}{}_{\beta} S_{\alpha\beta} c_{\alpha} \longrightarrow \bar{V}\left(c^{\dagger}{}_{\alpha} f_{\alpha}\right) + \left(f^{\dagger}{}_{\alpha} c_{\alpha}\right) V + N \frac{\bar{V} V}{J},$$

Composite Fermion

$$\frac{J}{N} c^{\dagger}_{j\alpha} S_{\alpha\beta} \equiv \bar{V} f^{\dagger}_{j\beta}$$

Coherence and composite fermions





Heavy electron = (electron x spinflip)

- The large N approach to the Kondo lattice.
  Spin x conduction = composite fermion

$$\frac{J}{N} c^{\dagger}{}_{\beta} S_{\alpha\beta} c_{\alpha} \longrightarrow \bar{V}\left(c^{\dagger}{}_{\alpha} f_{\alpha}\right) + \left(f^{\dagger}{}_{\alpha} c_{\alpha}\right) V + N\frac{\bar{V}V}{J},$$

Composite Fermion

$$\frac{J}{N} c^{\dagger}_{j\alpha} S_{\alpha\beta} \equiv \bar{V} f^{\dagger}_{j\beta}$$