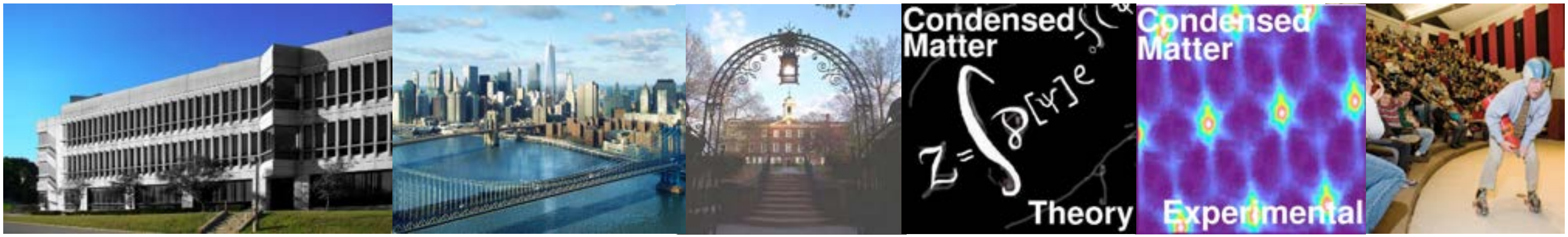
The Physics of Heavy Fermion Superconductivity

Lecture II. BCS meets Kondo: mean-field approach to the Kondo Lattice.

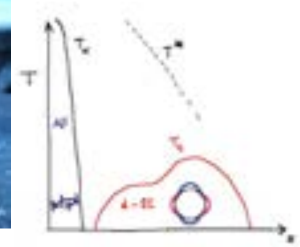


Piers Coleman

Center for Materials Theory, Rutgers.

Boulder School 2014: Modern Aspects of Superconductivity

June 30-July 25, 2014



14-17 July 2014

The Physics of Heavy Fermion Superconductivity

1. Introduction: Heavy Fermions and the Kondo Lattice.
2. BCS meets Kondo: mean-field approach to the Kondo Lattice.
3. Glue vs Fabric: Good, Bad and Ugly Heavy Fermion Superconductors.
4. Composite vs AFM induced pairing.

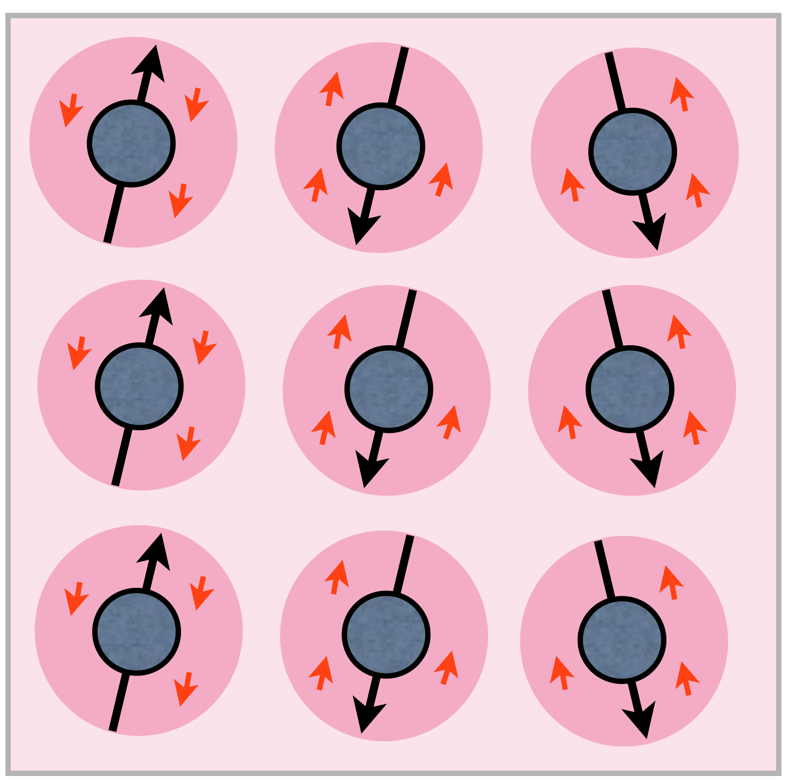
<u>Last Time: Lecture 1 Introduction to Heavy Fermions and the Kondo Lattice.</u>

1. Magnetism and SC: a remarkable converegence.
2. Electrons on the Brink of Localization.
3. Cartoon introduction to Heavy Fermions.
4. Lev Landau versus Ken Wilson: Criticality as a driver of Superconductivity.
5. Anderson, Kondo and Doniach.

THE KONDO LATTICE (From Lecture I)

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{\mathcal{N}} \sum_j \vec{S}_j \cdot c^\dagger_{\mathbf{k}\alpha} \vec{\sigma}_{\alpha\beta} c_{\mathbf{k}'\beta} e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{R}_j}$$

T. Kasuya (1951)



"Kondo Lattice"

Note: can also write Kondo interaction in the "Coqblin Schrieffer" form

$$H_K = -J \sum_{j,\alpha,\beta} (c^\dagger_{j\alpha} f_{j\alpha})(f^\dagger_{j\beta} c_{j\beta})$$

Physics of Heavy Fermion Superconductivity Lecture II:

1. The large N approach to the Kondo lattice.

2. Heavy Fermion Metals.

3. Optical Conductivity of Heavy Fermion Metals

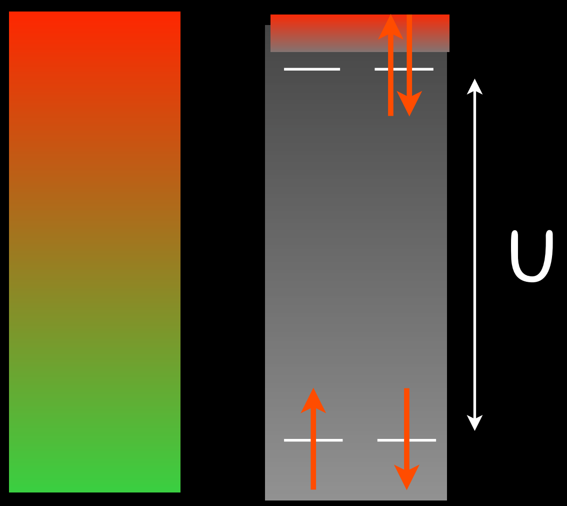
4. Kondo Insulators

Rutgers
Center for Materials Theory

Gauge Theories and Strong Correlation.

Strong correlation $\leftrightarrow$ Constrained Hilbert space

$\leftrightarrow$ Gauge theories



e^- spin

Φ λ

$U(1)_{\mathrm{global}} \times U(1)_{\mathrm{local}}$

e.g. $$\vec{S}_j = f^\dagger_{j\alpha}\left(\frac{\vec{\sigma}}{2}\right)_{\alpha\beta} f_{j\beta},$$

$$f_j \longrightarrow e^{i\phi_j} f_j,$$

$U(1)_{\mathrm{local}}$

$$\boxed{H = \sum \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \frac{J}{N}\sum_j c^\dagger_{j\alpha} c_{j\beta} S_{\beta\alpha}(j) + H_g}$$

$$S_{\alpha\beta} = f^\dagger_\alpha f_\beta - \delta_{\alpha\beta} n_f/N$$

$$\begin{aligned} H_g &= (\Phi-\mu)c^\dagger_j c_j + \lambda_j(f^\dagger_j f_j - Q), \\ (Q &= qN = 1) \end{aligned}$$

Strongly correlated electron physics: no small parameter

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Large N : family of models with “N” spin components, which retain the key physics and can be solved in the large N limit.

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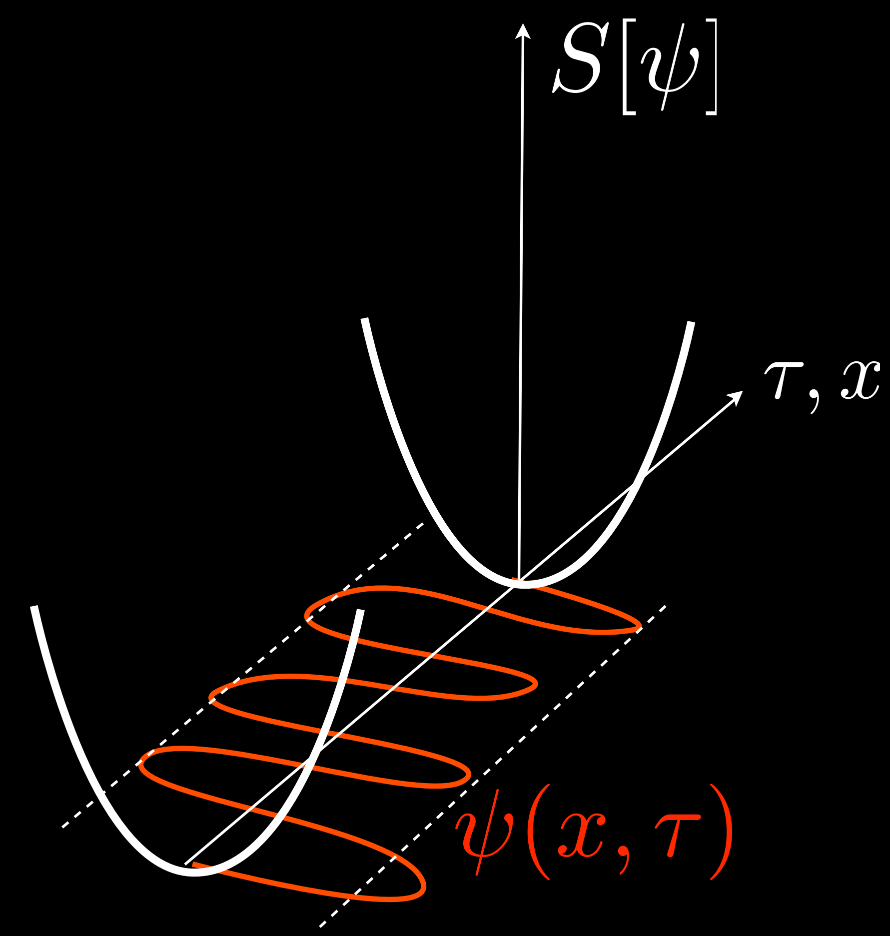

$$\frac{1}{N} \sim \hbar_{eff}$$

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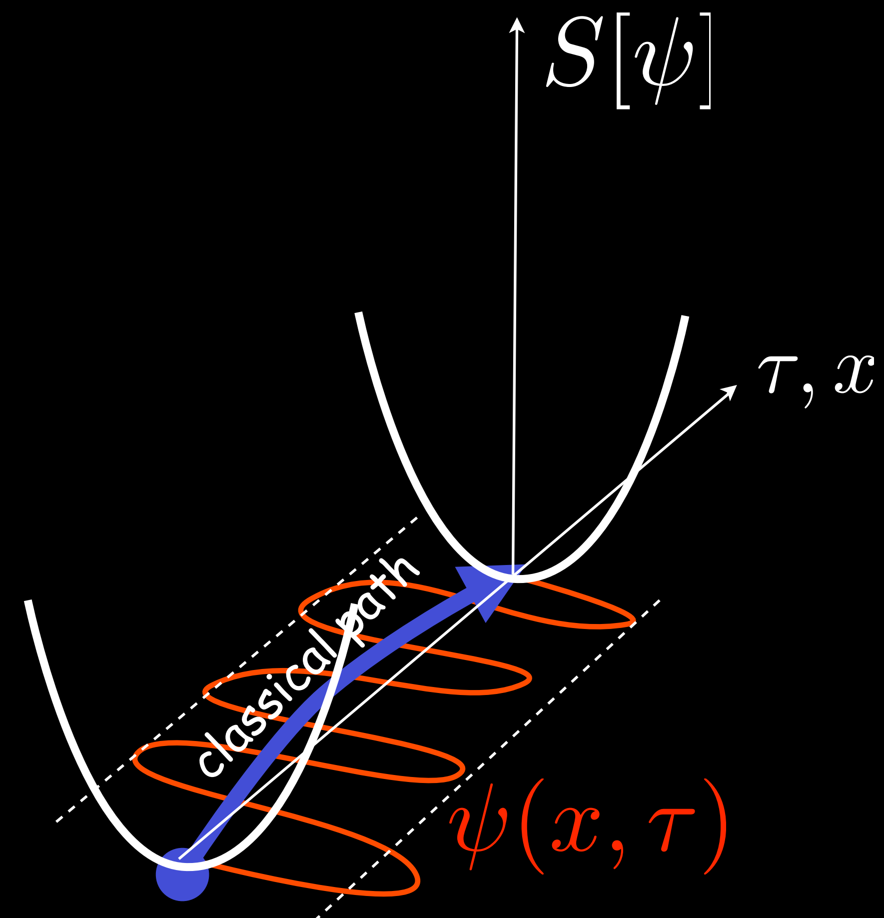

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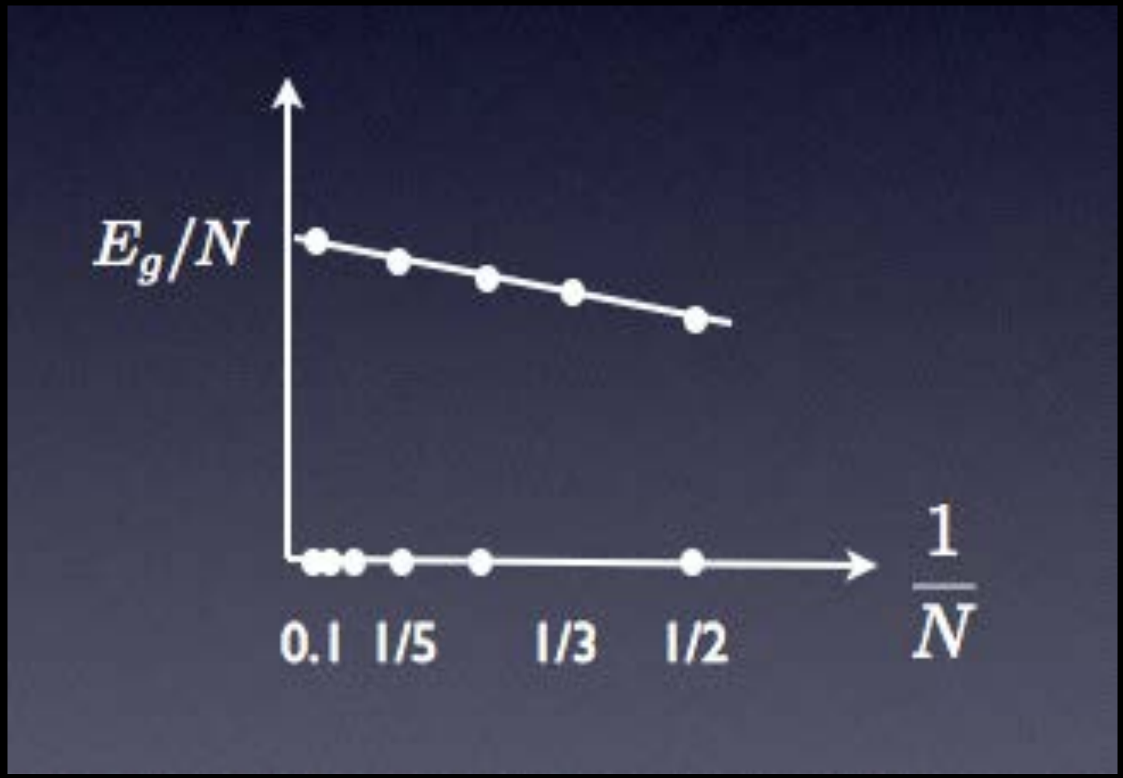

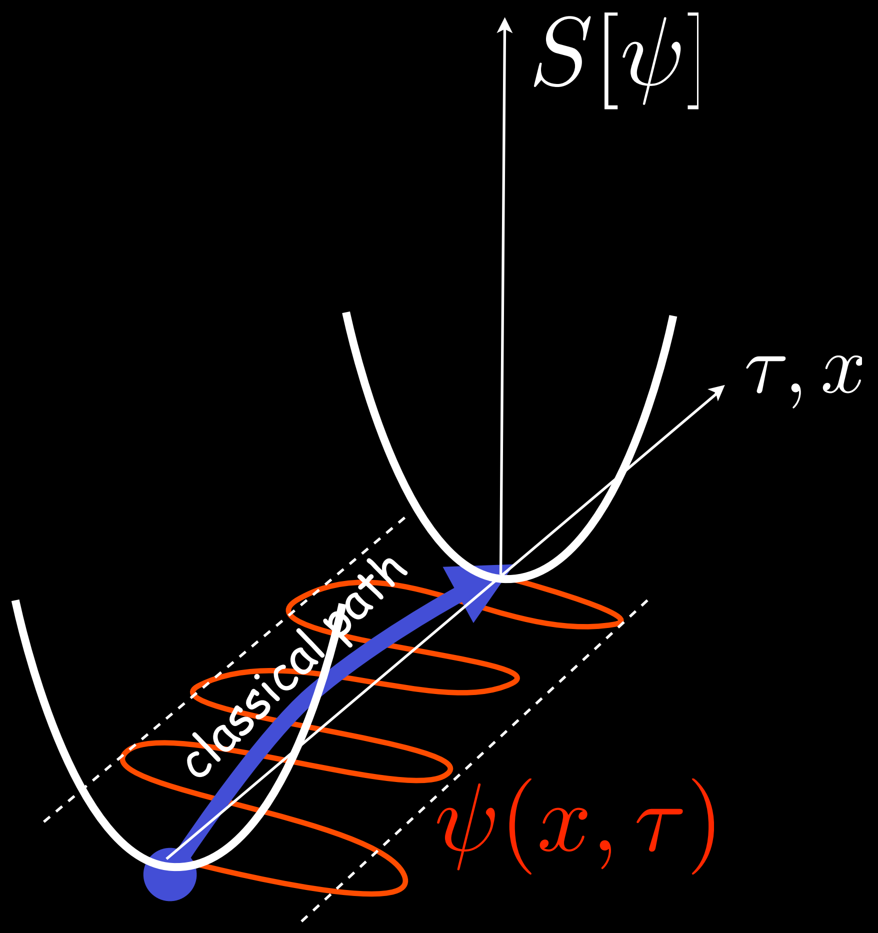

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Large N Approach.

Read and Newns '83.

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

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

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Constraint n_f = Q=qN

all terms extensive in N

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

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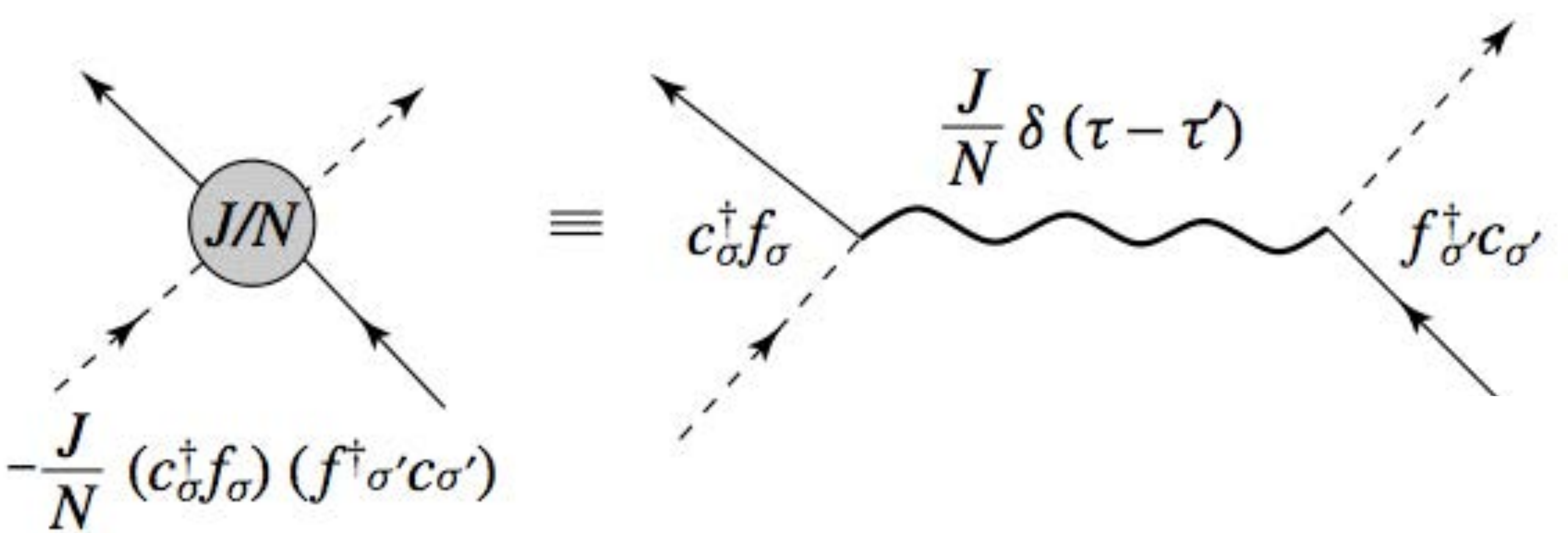
Constraint $n_f = Q = qN$

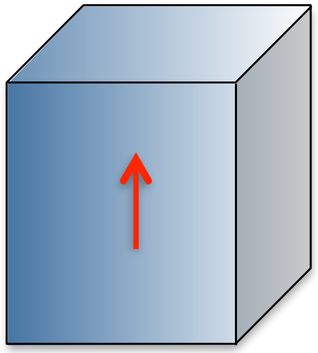
all terms extensive in N

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

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



Coherence and composite fermions



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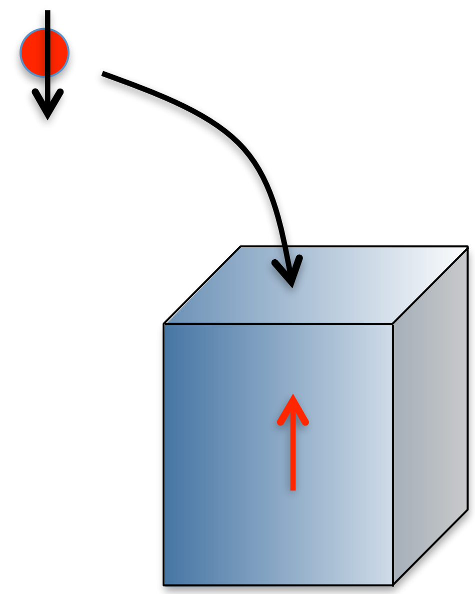

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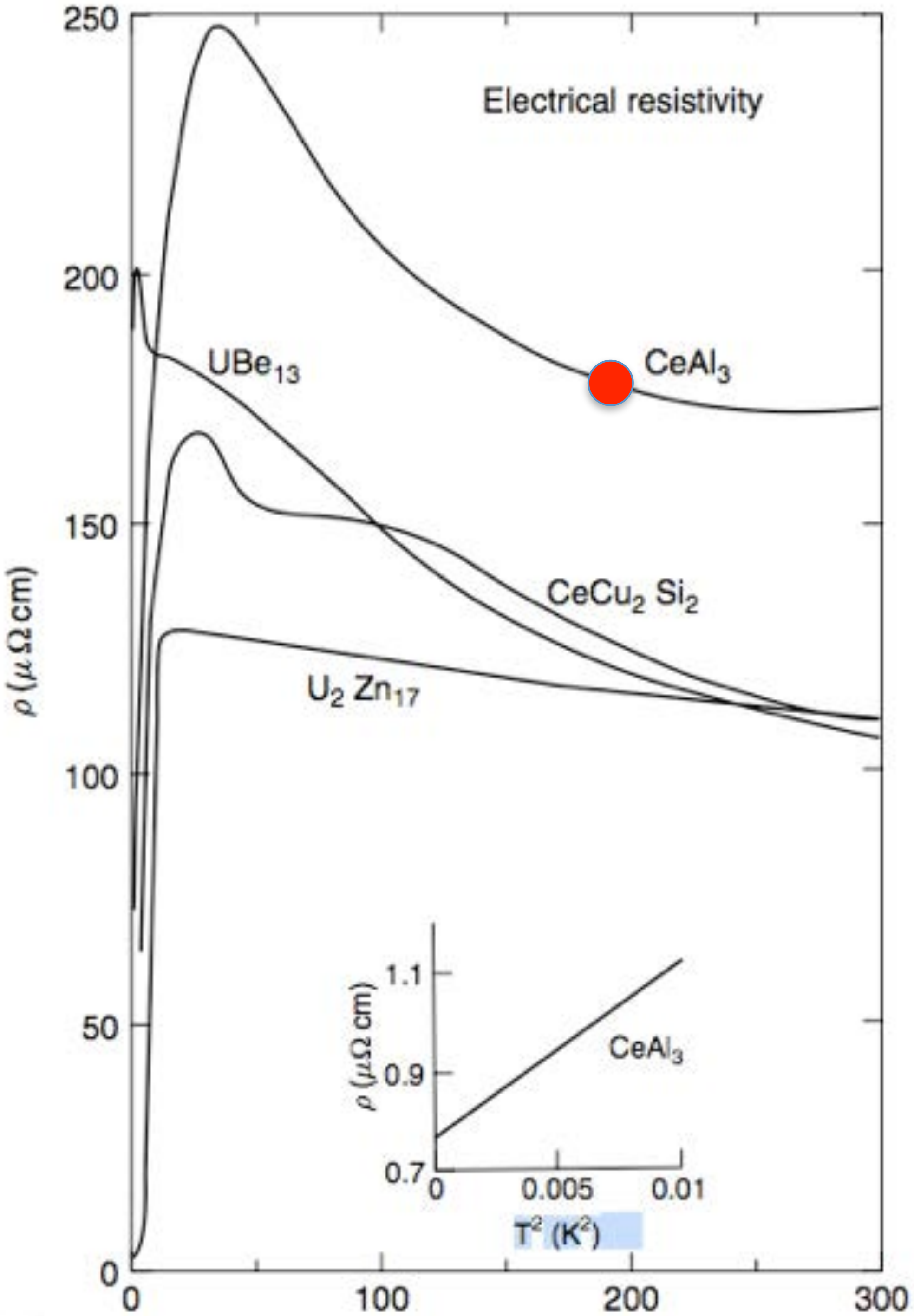

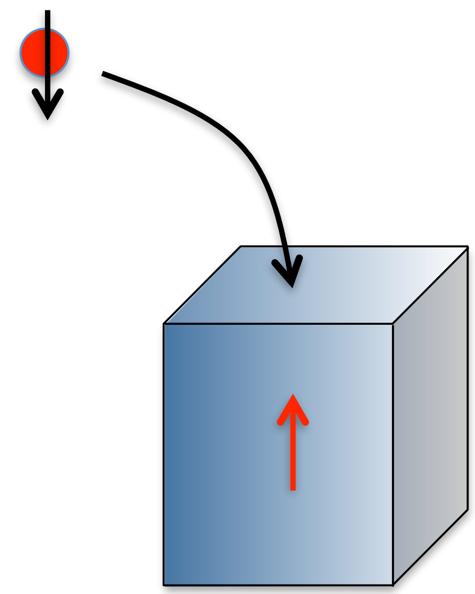

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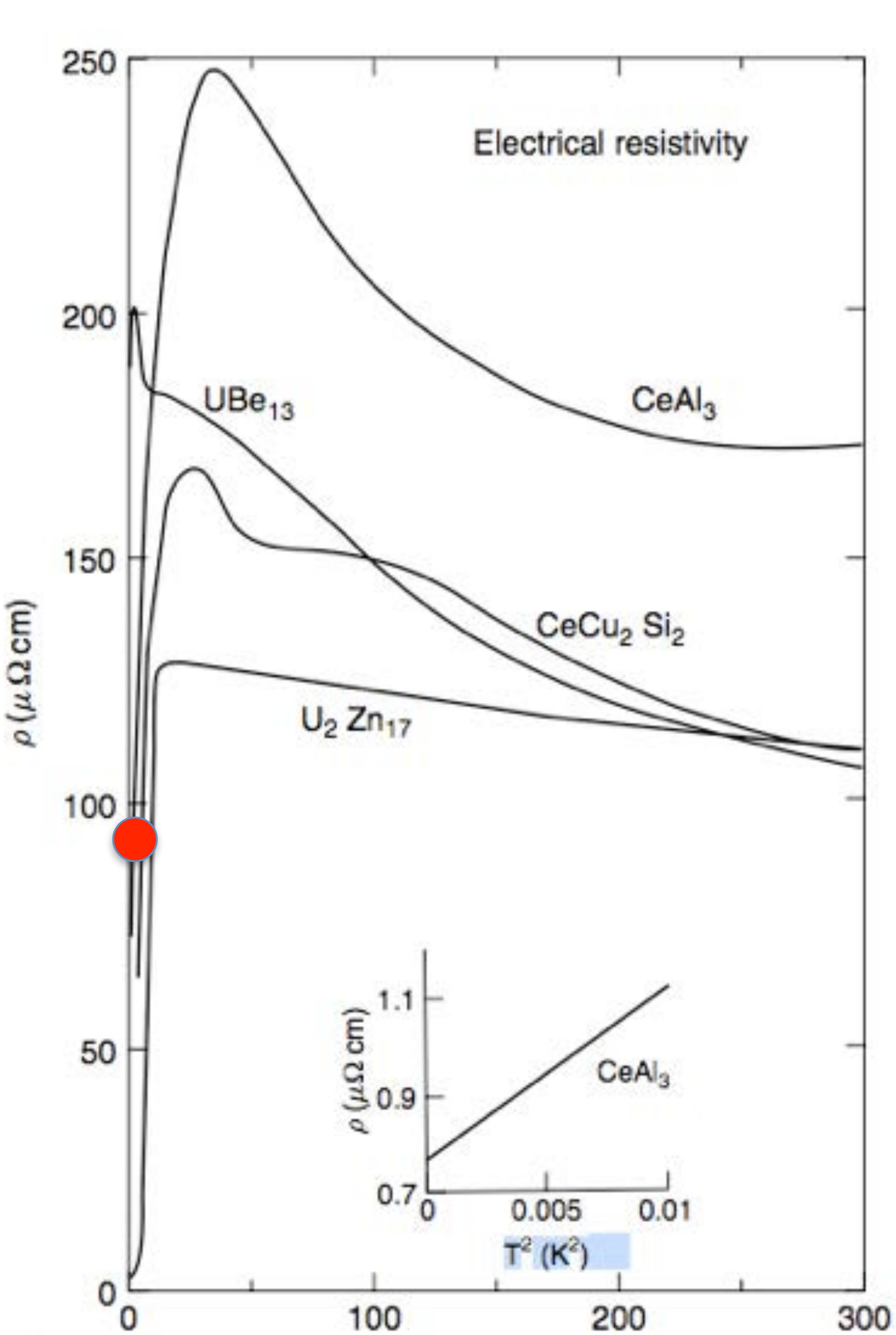

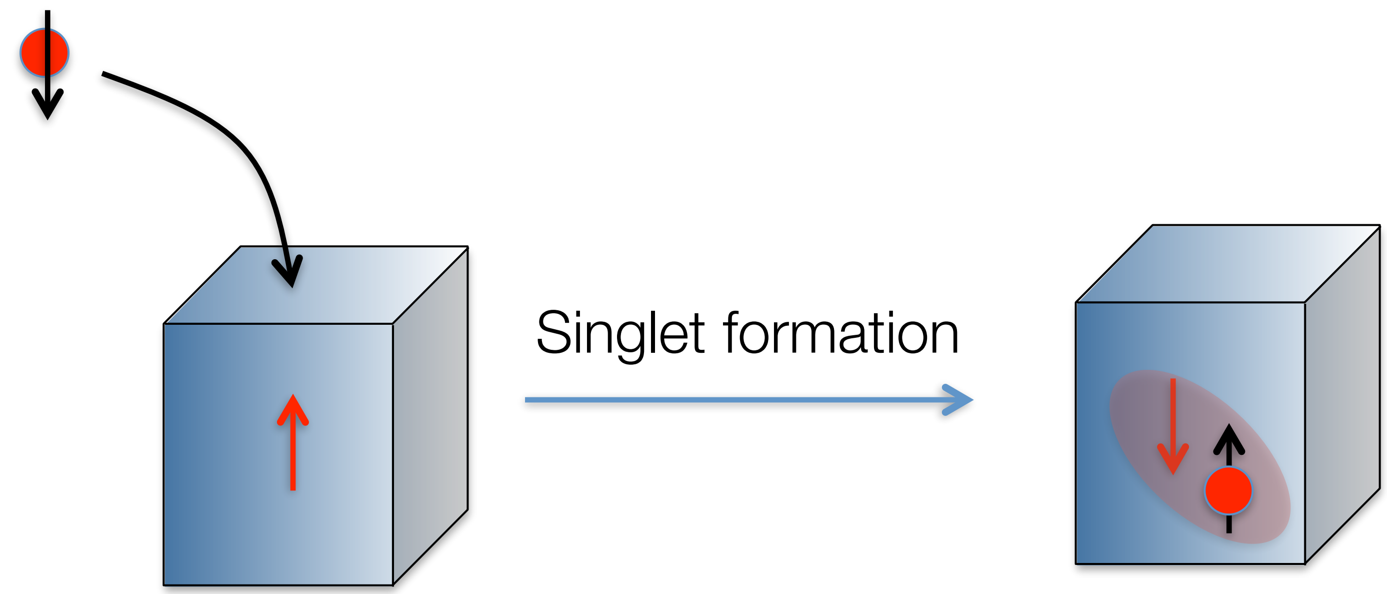

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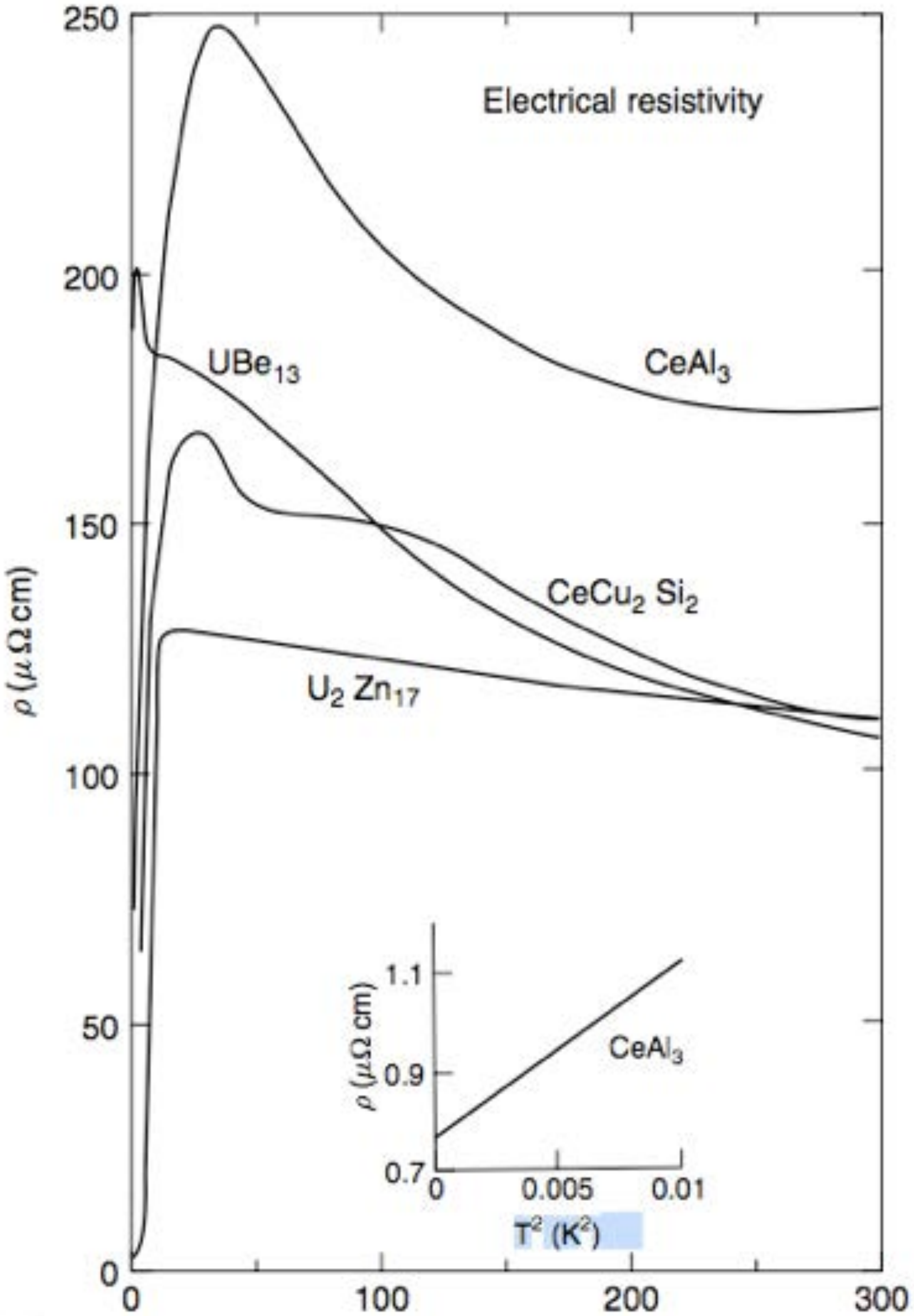
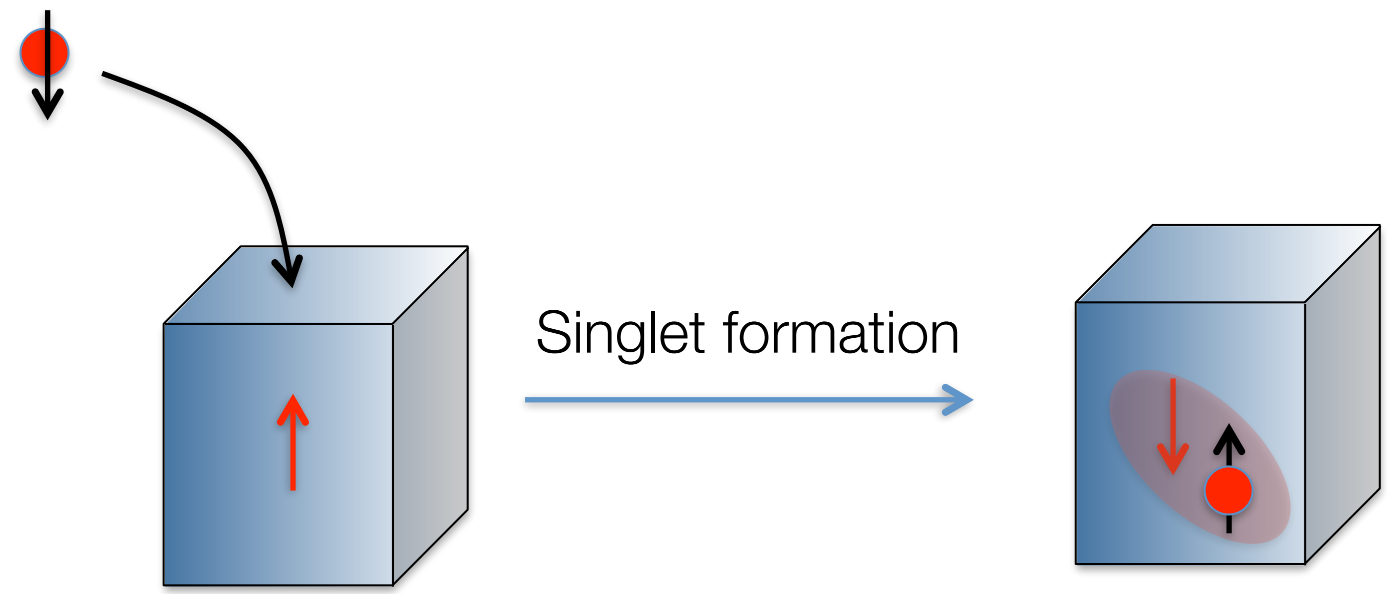
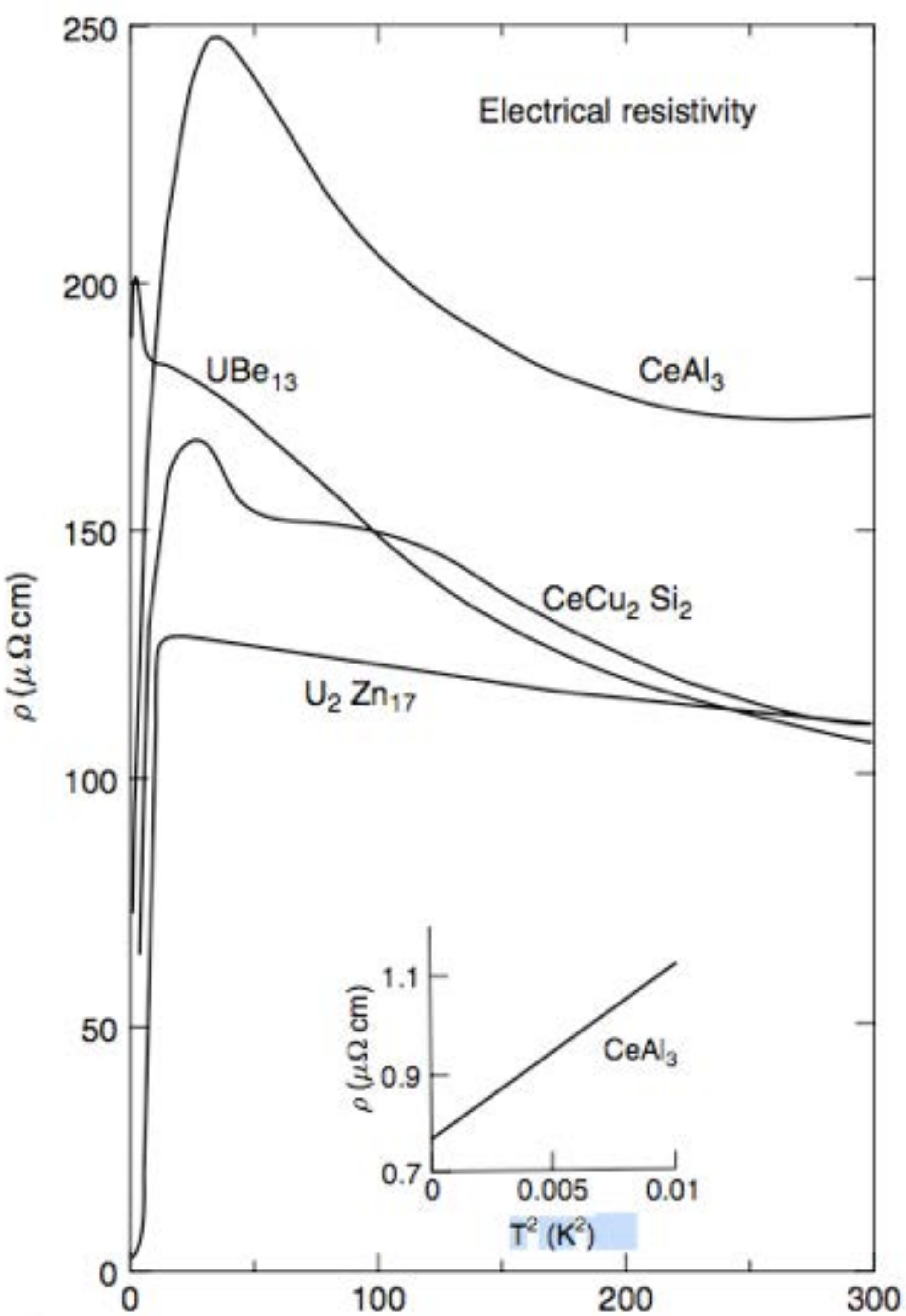
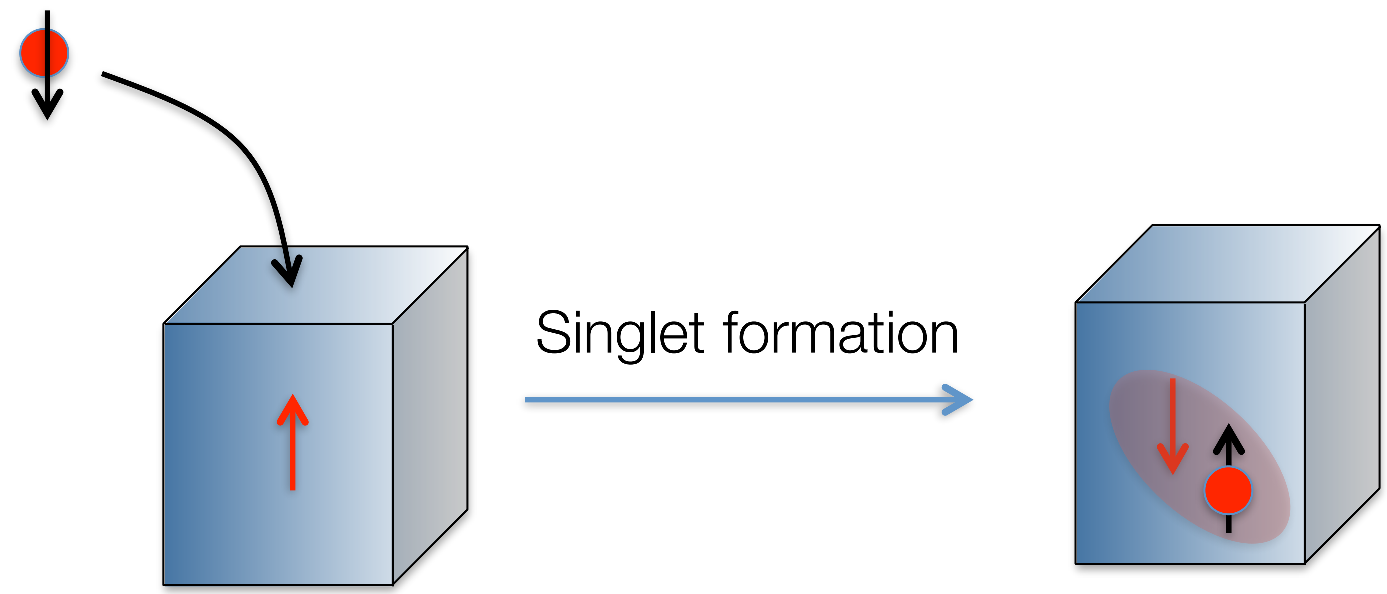




Heavy electron = (electron x spinflip)

Coherence and composite fermions





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  Spin x conduction = composite fermion

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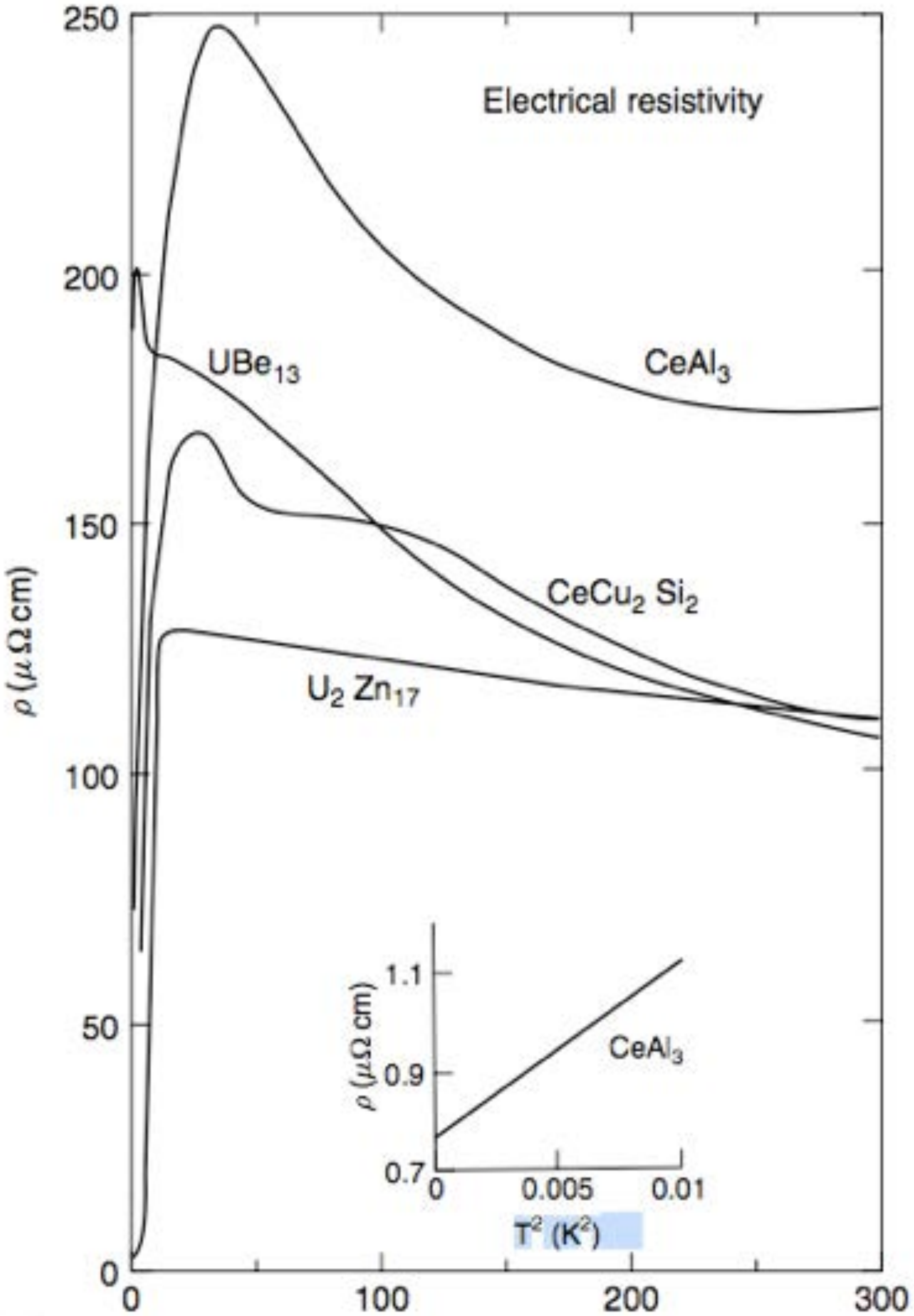

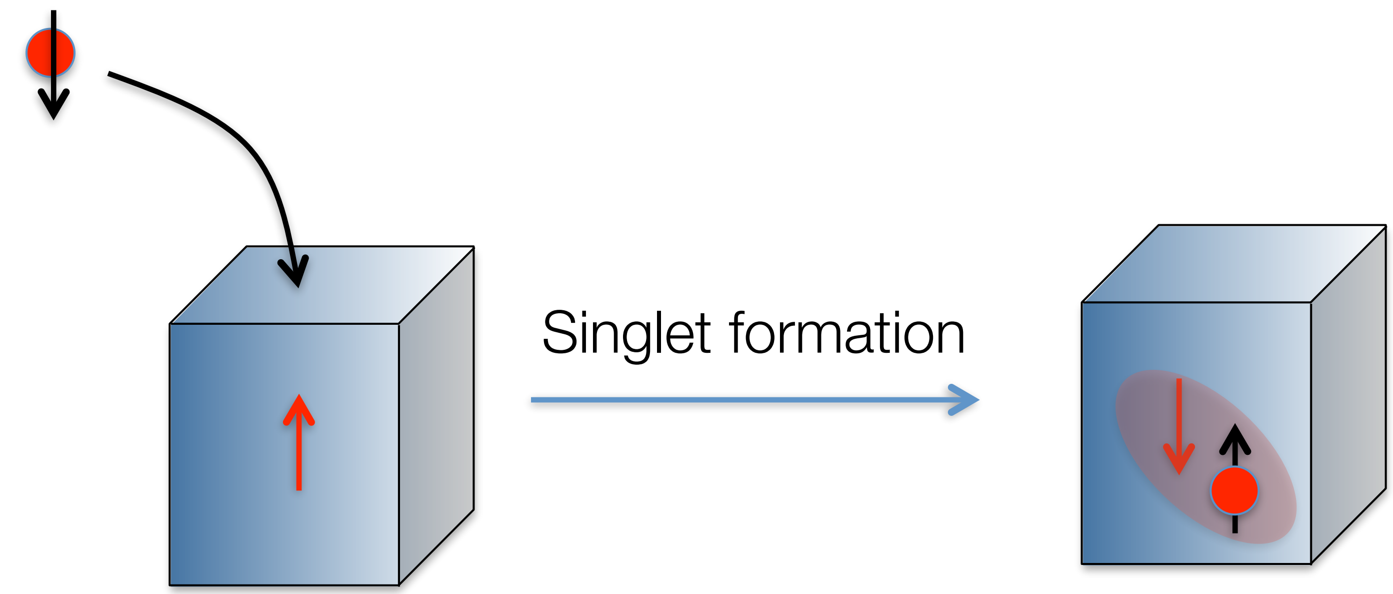

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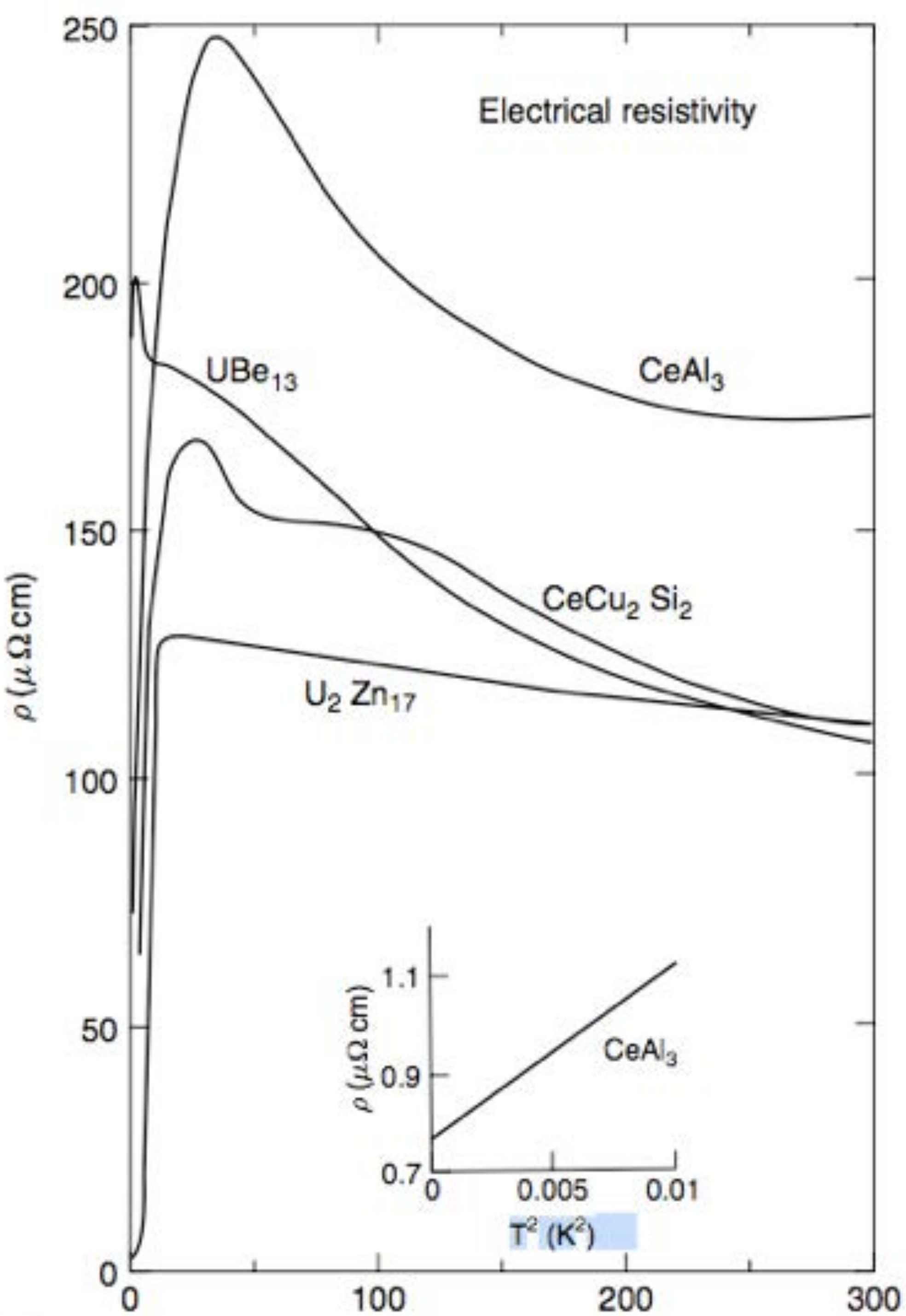
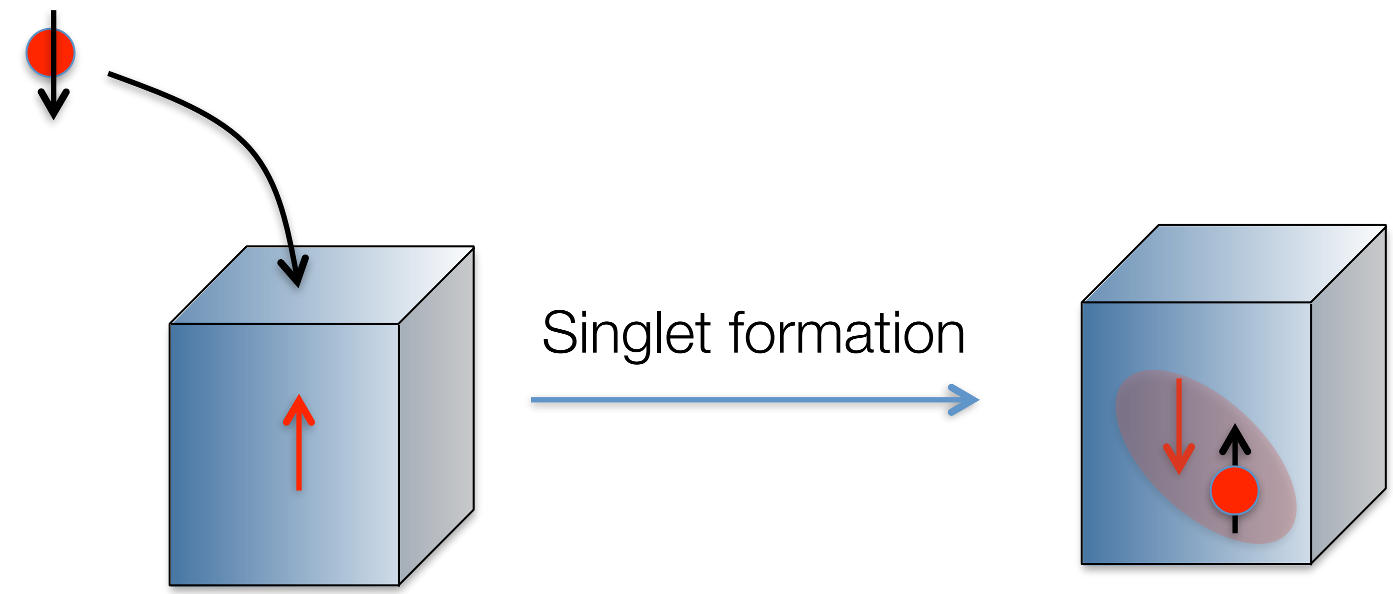
$$\frac{J}{N} {c^\dagger}_\beta S_{\alpha\beta} c_\alpha \longrightarrow \bar{V}\left({c^\dagger}_\alpha f_\alpha\right) + \left({f^\dagger}_\alpha c_\alpha\right) V + N\frac{\bar{V}V}{J},$$

Coherence and composite fermions





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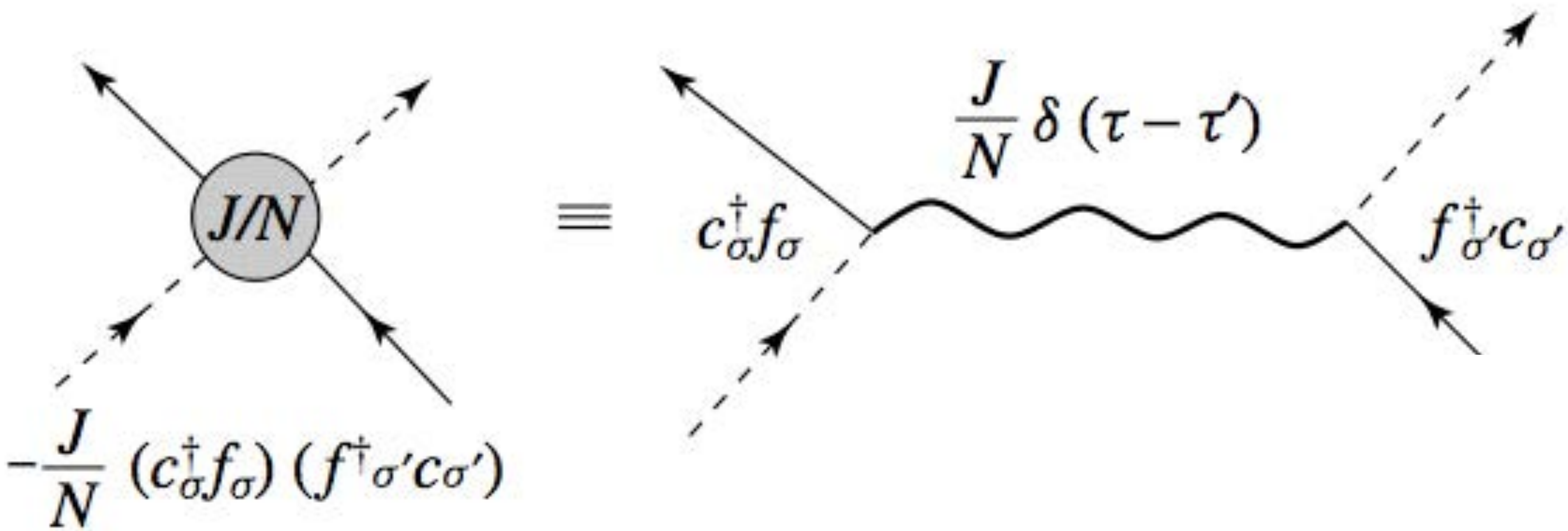
$$\frac{J}{N}c^{\dagger}_{j\alpha}S_{\alpha\beta} \equiv \bar{V}f^{\dagger}_{j\beta}$$

Composite Fermion

Large N Approach

Read and Newns '83.



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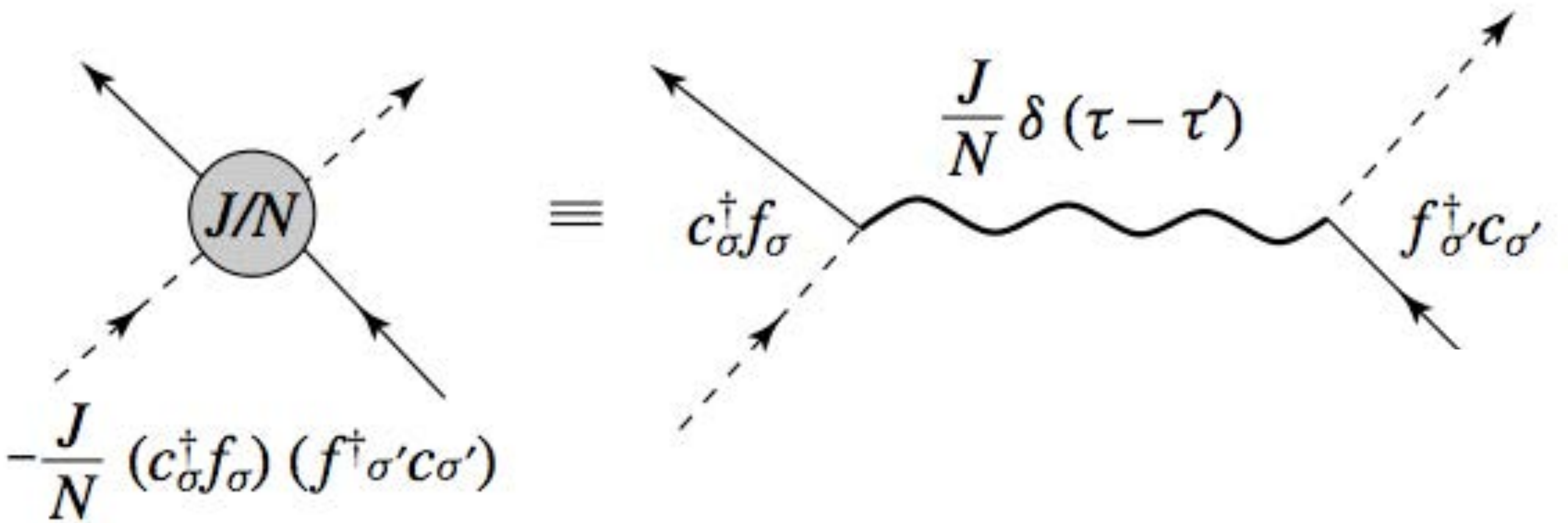

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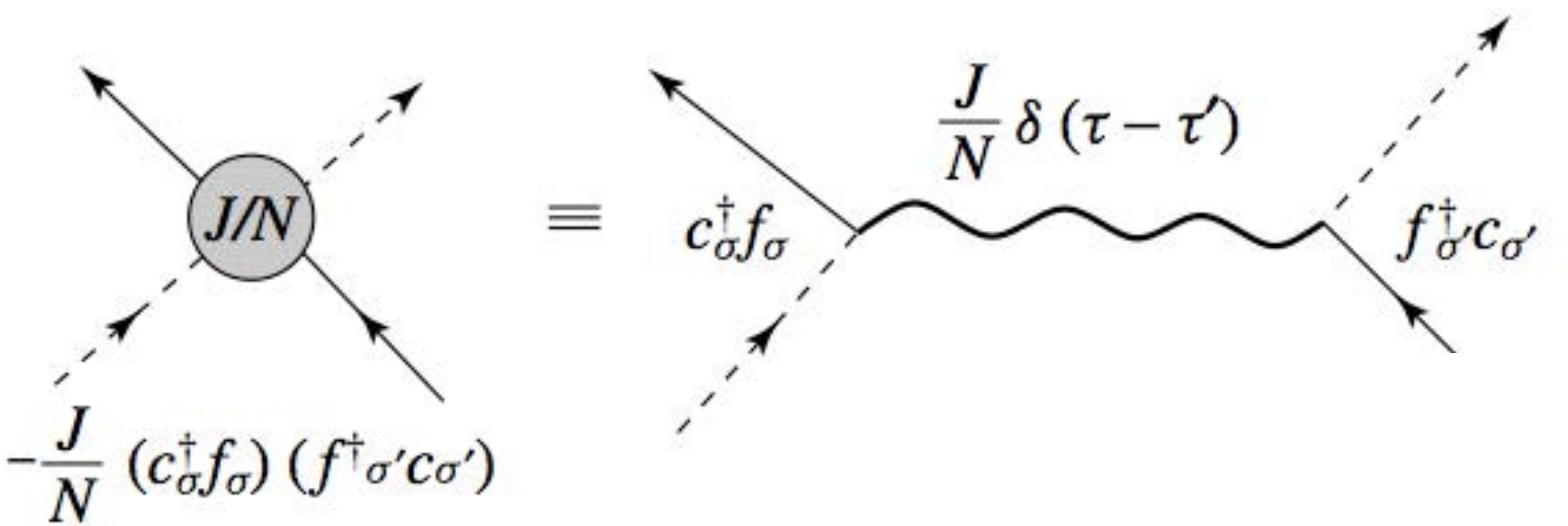
U(1) constraint: note n_f =Q =(qN)



Large N Approach

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

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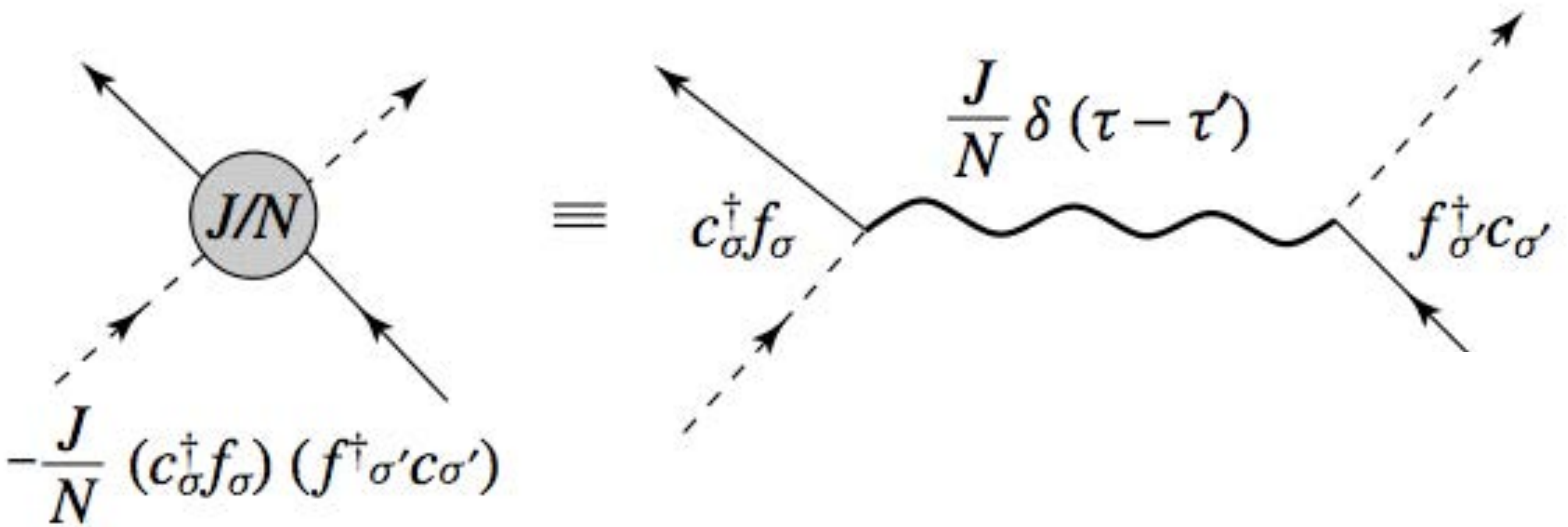

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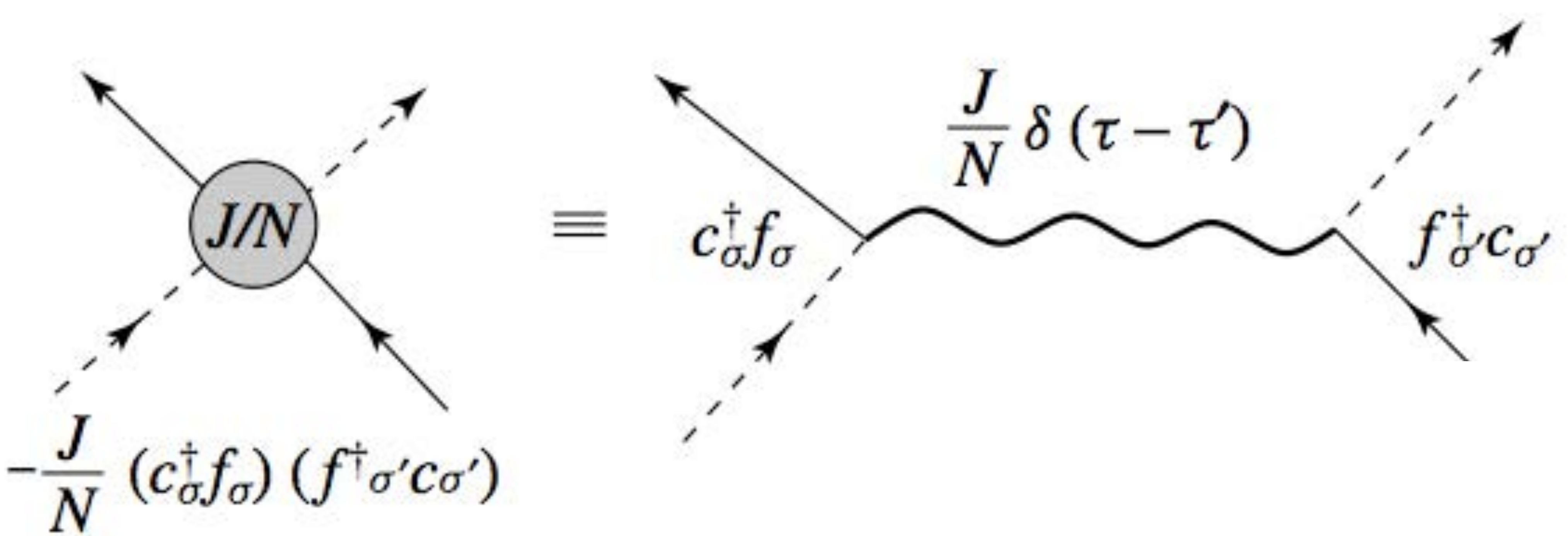

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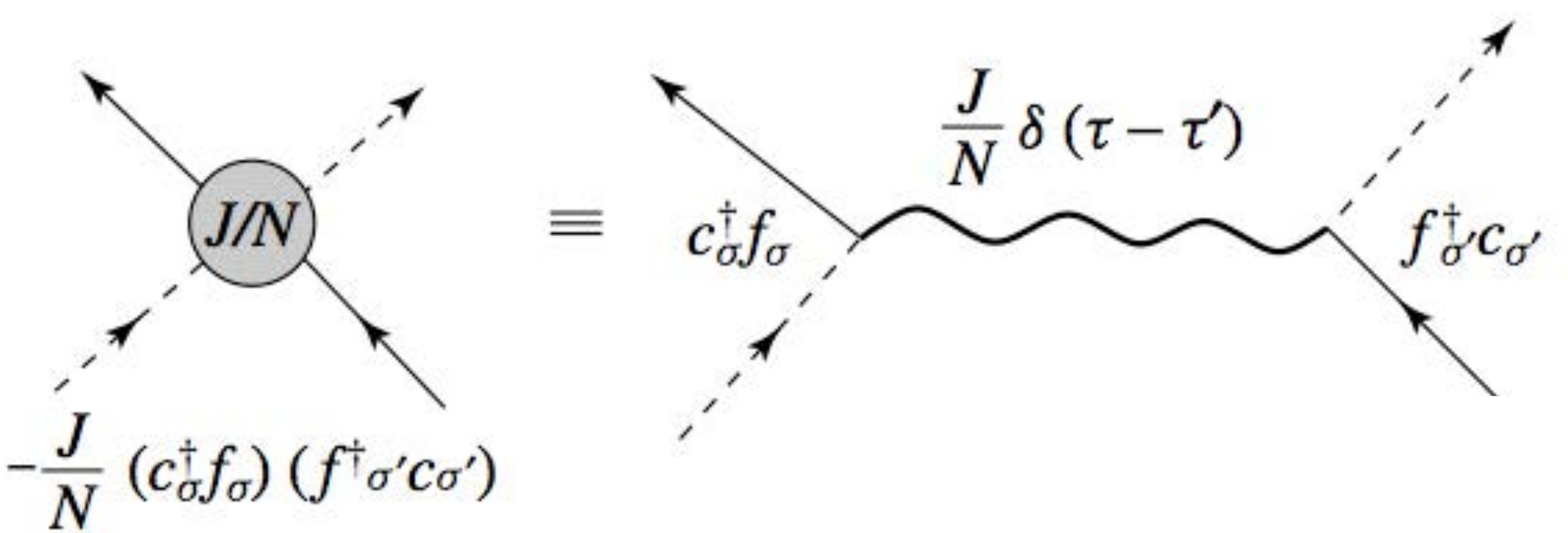

Large N Approach.

Read and Newns '83.

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

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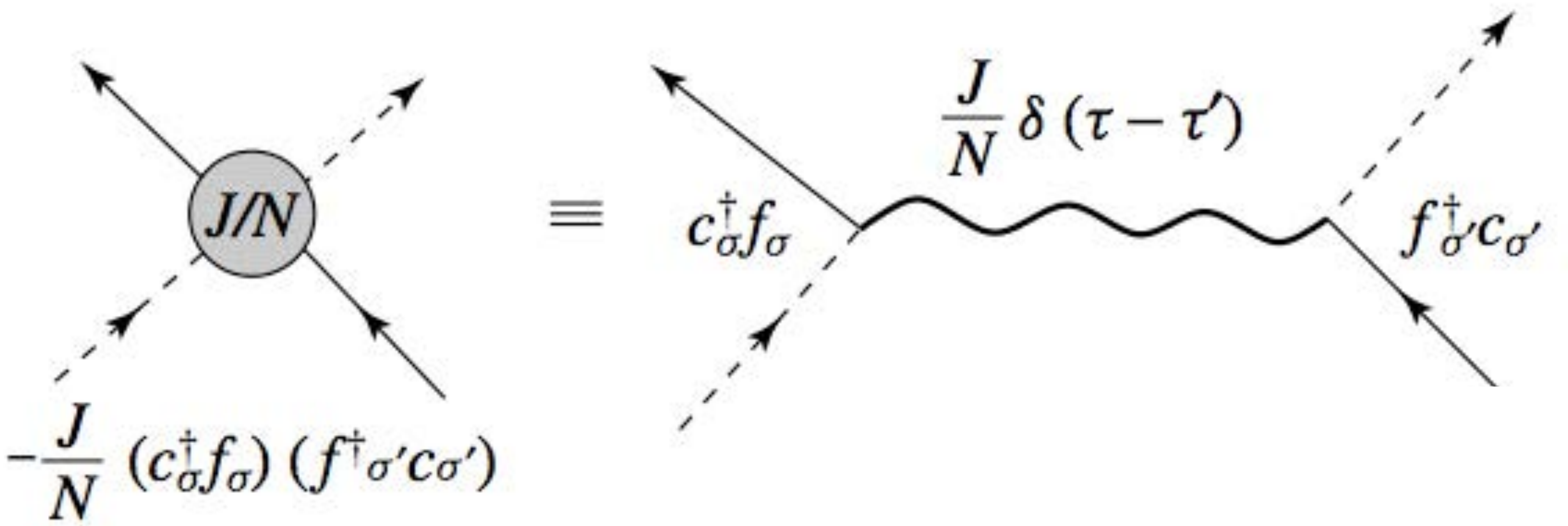

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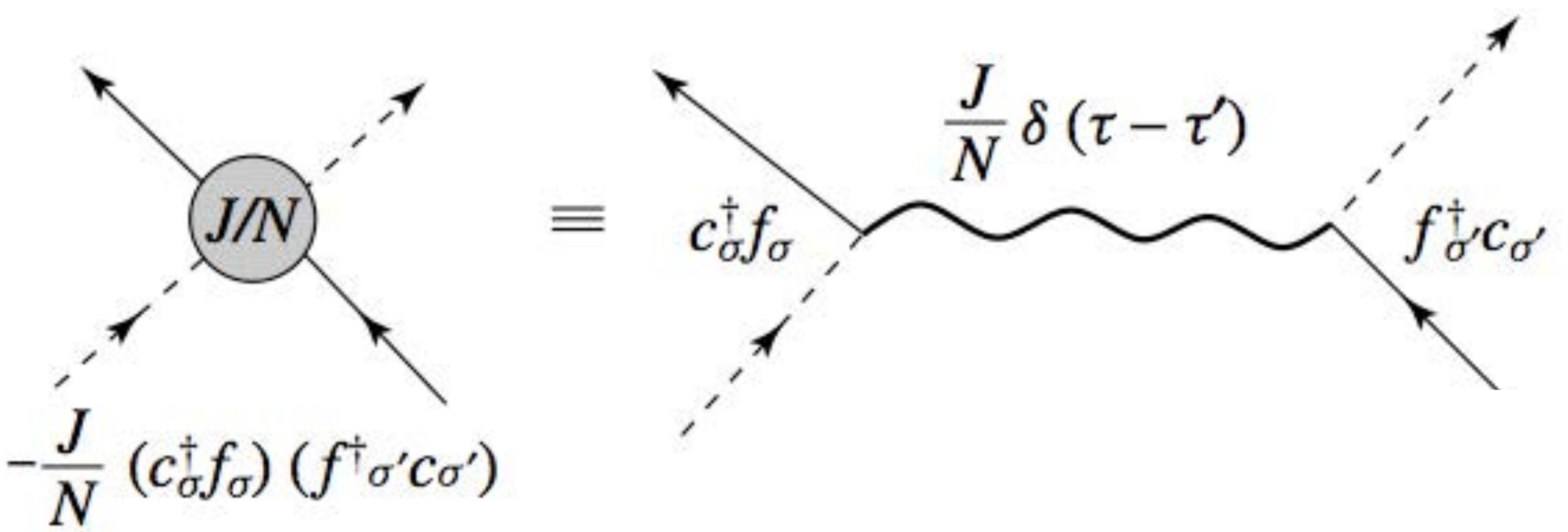

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$V_j = V$
at each site

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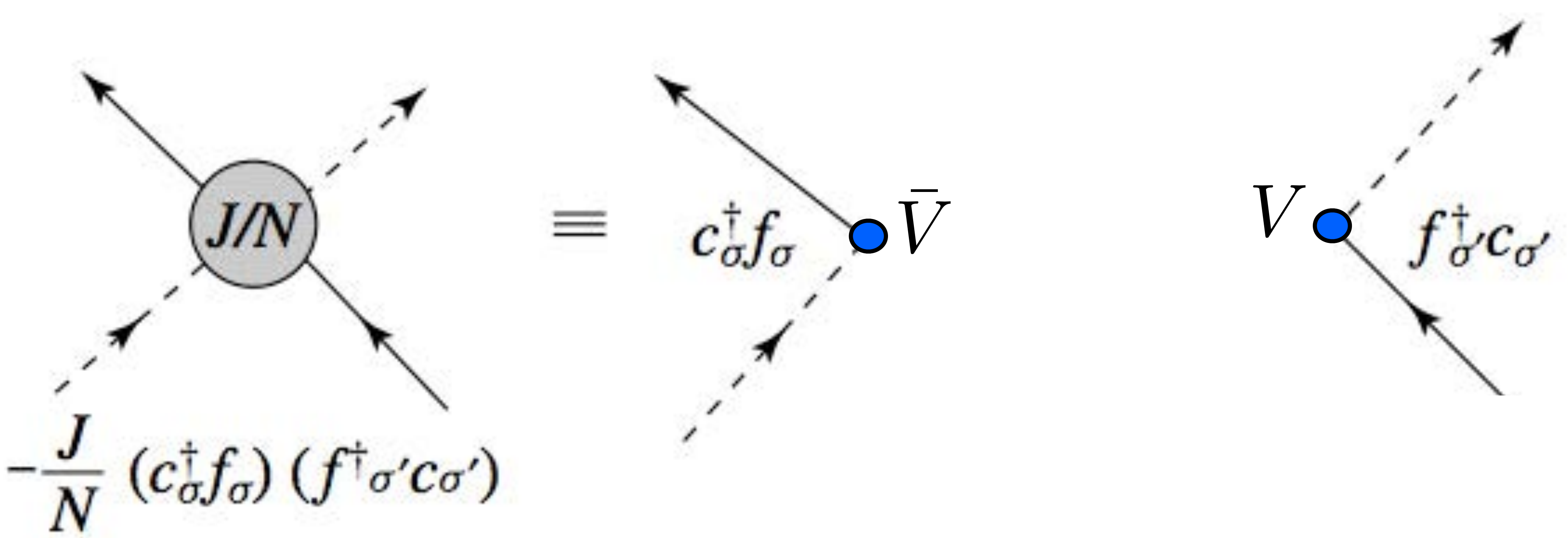

Detailed calcn.

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

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.

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

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

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

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

Detailed calcn.

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

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

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

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

"Gutzwiller" wavefunction

Detailed calcn.

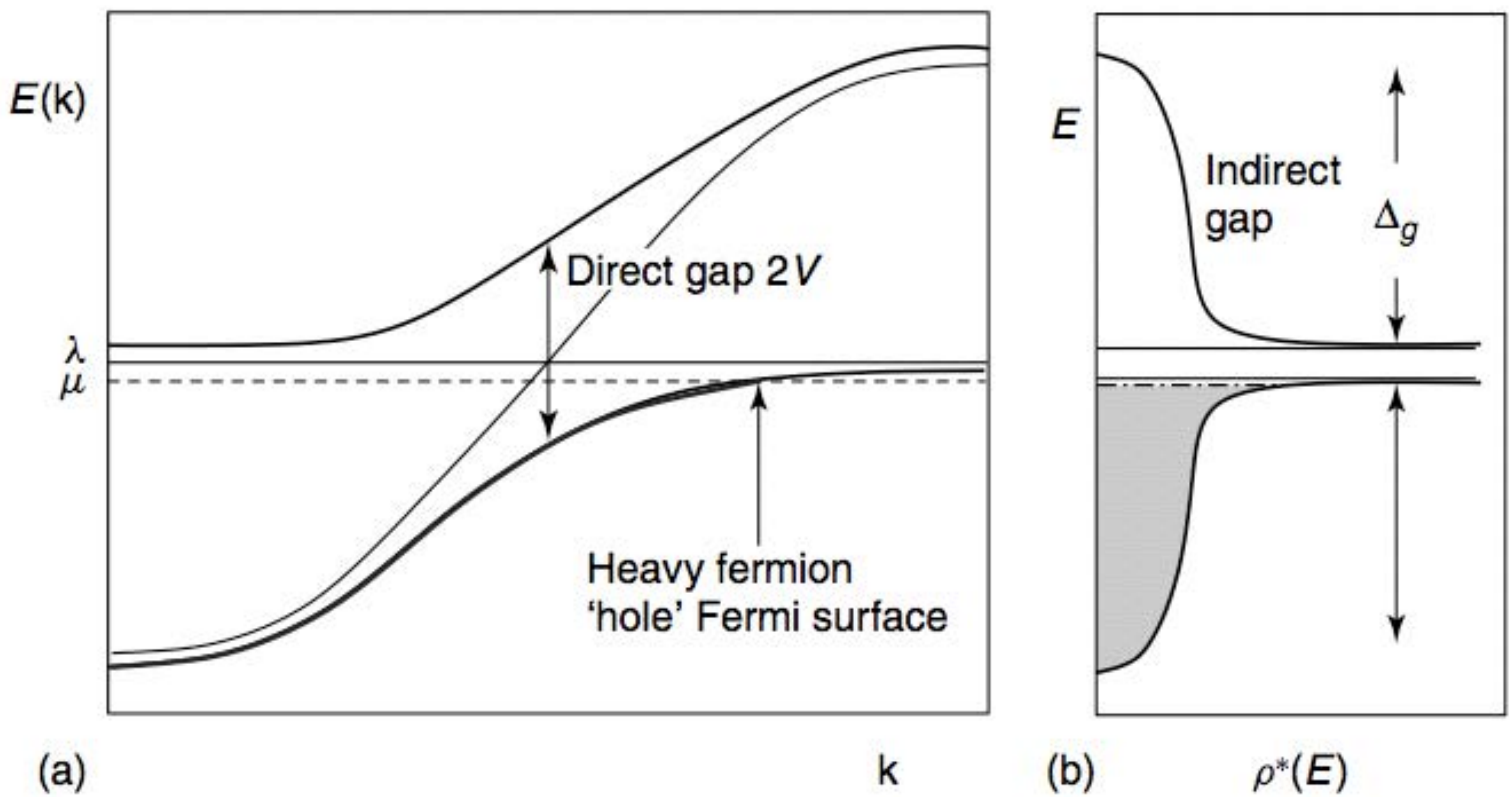
$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$

$$|MF\rangle = \prod_{|\mathbf{k}|<k_{F}\sigma} b^{\dagger}{}_{\mathbf{k}\sigma}|0\rangle = \prod_{|\mathbf{k}|<k_{F}\sigma} (-v_{\mathbf{k}} c_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma})|0\rangle.$$

$$\begin{aligned} a^{\dagger}{}_{\mathbf{k}\sigma} &= u_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + v_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma} \\ b^{\dagger}{}_{\mathbf{k}\sigma} &= -v_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma} \end{aligned} \qquad \left\{ \begin{array}{c} u_{\mathbf{k}} \\ v_{\mathbf{k}} \end{array} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_{\mathbf{k}} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_{\mathbf{k}}-\lambda}{2}\right)^2 + |V|^2}}\right]^{\frac{1}{2}}.$$

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

"Gutzwiller" wavefunction



Detailed calcn.

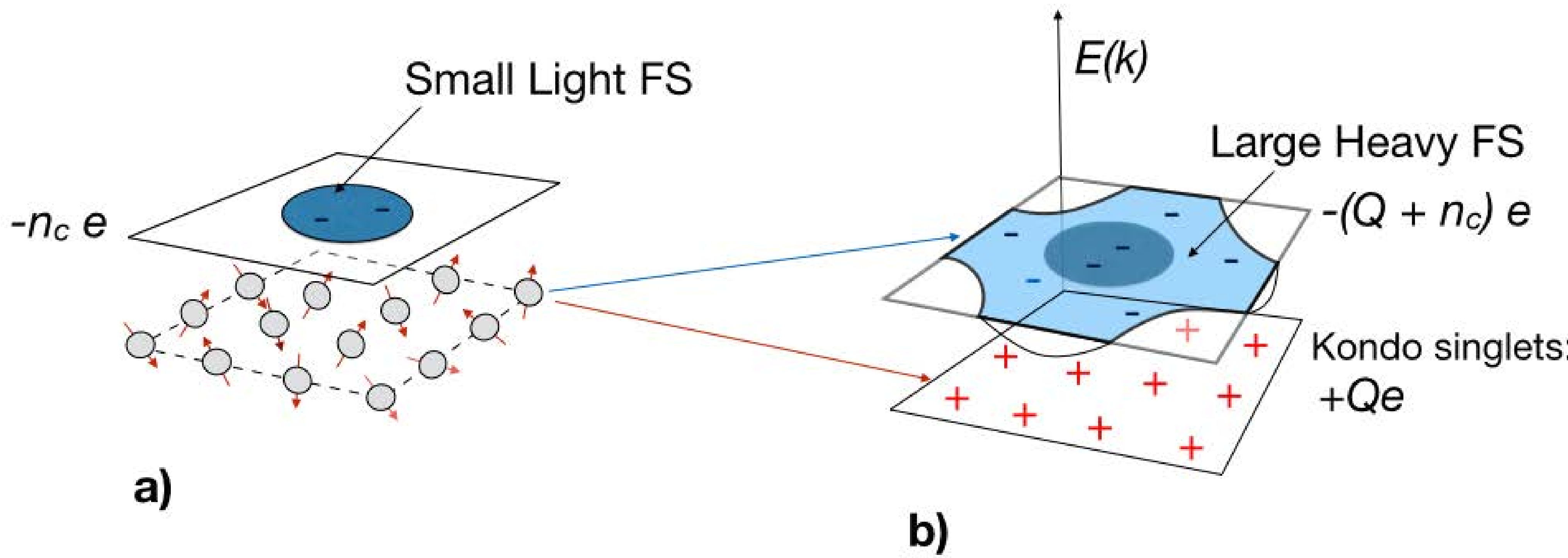
$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$

$$|MF\rangle = \prod_{|\mathbf{k}|<k_{F\sigma}} b^{\dagger}{}_{\mathbf{k}\sigma}|0\rangle = \prod_{|\mathbf{k}|<k_{F\sigma}} (-v_{\mathbf{k}}c_{\mathbf{k}\sigma} + u_{\mathbf{k}}f^{\dagger}{}_{\mathbf{k}\sigma})|0\rangle.$$

$$\begin{aligned} a^{\dagger}{}_{\mathbf{k}\sigma} &= u_{\mathbf{k}}c^{\dagger}{}_{\mathbf{k}\sigma} + v_{\mathbf{k}}f^{\dagger}{}_{\mathbf{k}\sigma} \\ b^{\dagger}{}_{\mathbf{k}\sigma} &= -v_{\mathbf{k}}c^{\dagger}{}_{\mathbf{k}\sigma} + u_{\mathbf{k}}f^{\dagger}{}_{\mathbf{k}\sigma} \end{aligned} \quad \left\{ \begin{matrix} u_{\mathbf{k}} \\ v_{\mathbf{k}} \end{matrix} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_{\mathbf{k}} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_{\mathbf{k}}-\lambda}{2}\right)^2 + |V|^2}}\right]^{\frac{1}{2}}$$

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

"Gutzwiller" wavefunction



Detailed calcn.

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

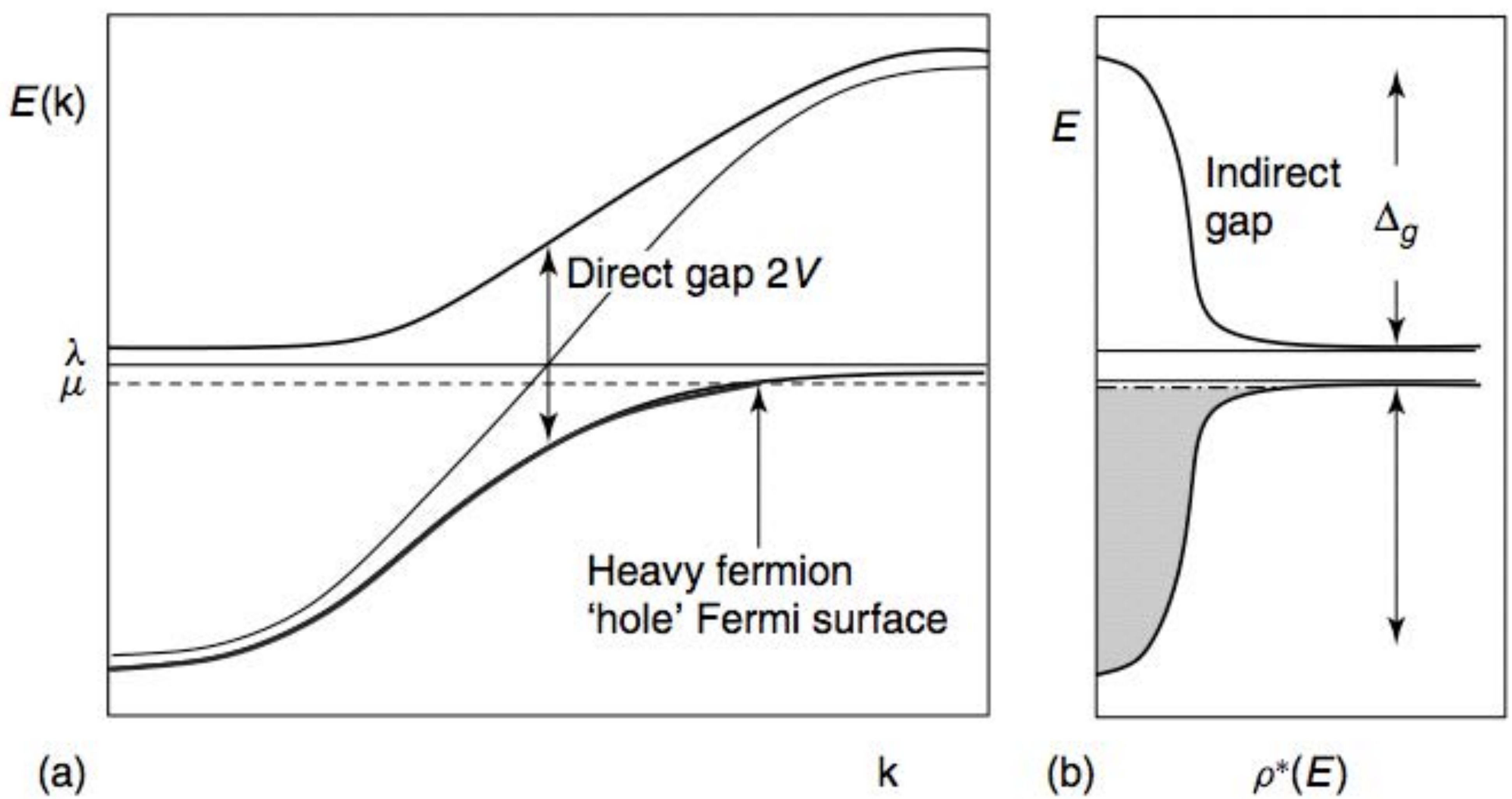
$$|MF\rangle = \prod_{|\mathbf{k}|<k_{F\sigma}} b^{\dagger}{}_{\mathbf{k}\sigma}|0\rangle = \prod_{|\mathbf{k}|<k_{F\sigma}} (-v_{\mathbf{k}} c_{\mathbf{k}\sigma} + u_{\mathbf{k}} f^{\dagger}{}_{\mathbf{k}\sigma})|0\rangle.$$

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

"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.

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

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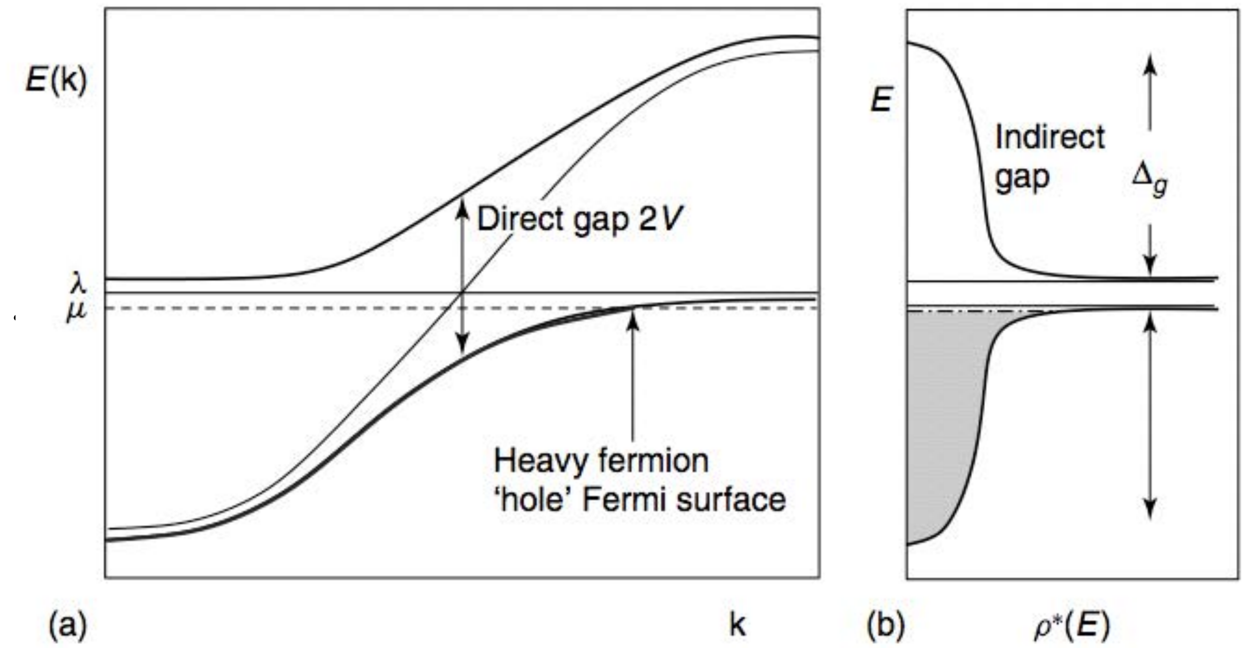
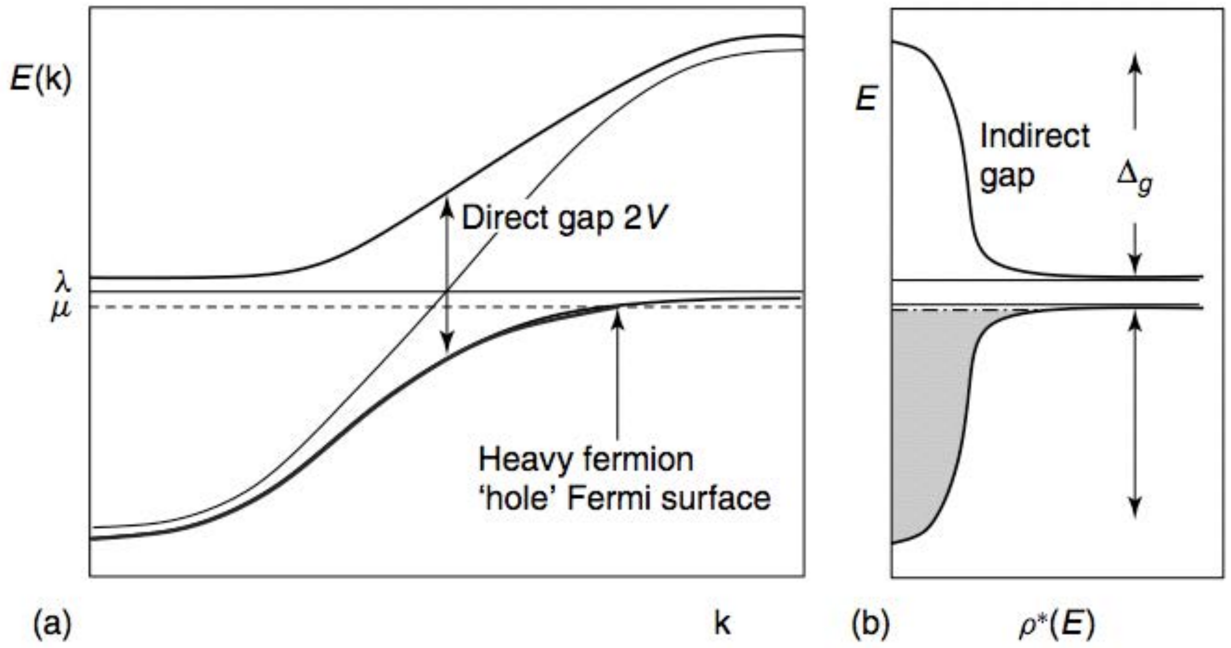
$$\left\{ \begin{array}{c} u_{\mathbf{k}} \\ v_{\mathbf{k}} \end{array} \right\} = \left[\frac{1}{2} \pm \frac{(\epsilon_{\mathbf{k}} - \lambda)/2}{2\sqrt{\left(\frac{\epsilon_{\mathbf{k}}-\lambda}{2}\right)^2 + |V|^2}}\right]^{\frac{1}{2}}.$$



Detailed calcn.

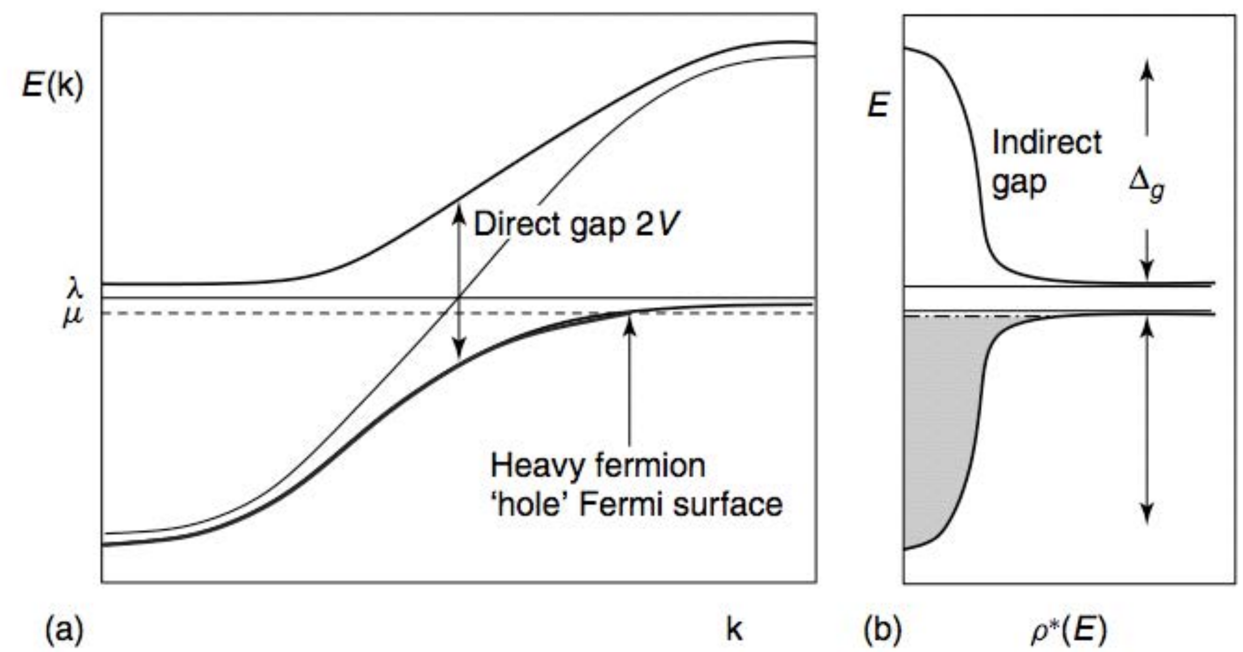
$$E_{\mathbf{k}\pm} = \frac{\epsilon_{\mathbf{k}} + \lambda}{2} \pm \left[\left(\frac{\epsilon_{\mathbf{k}} - \lambda}{2}\right)^2 + |V|^2\right]^{\frac{1}{2}},$$



Detailed calcn.

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

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

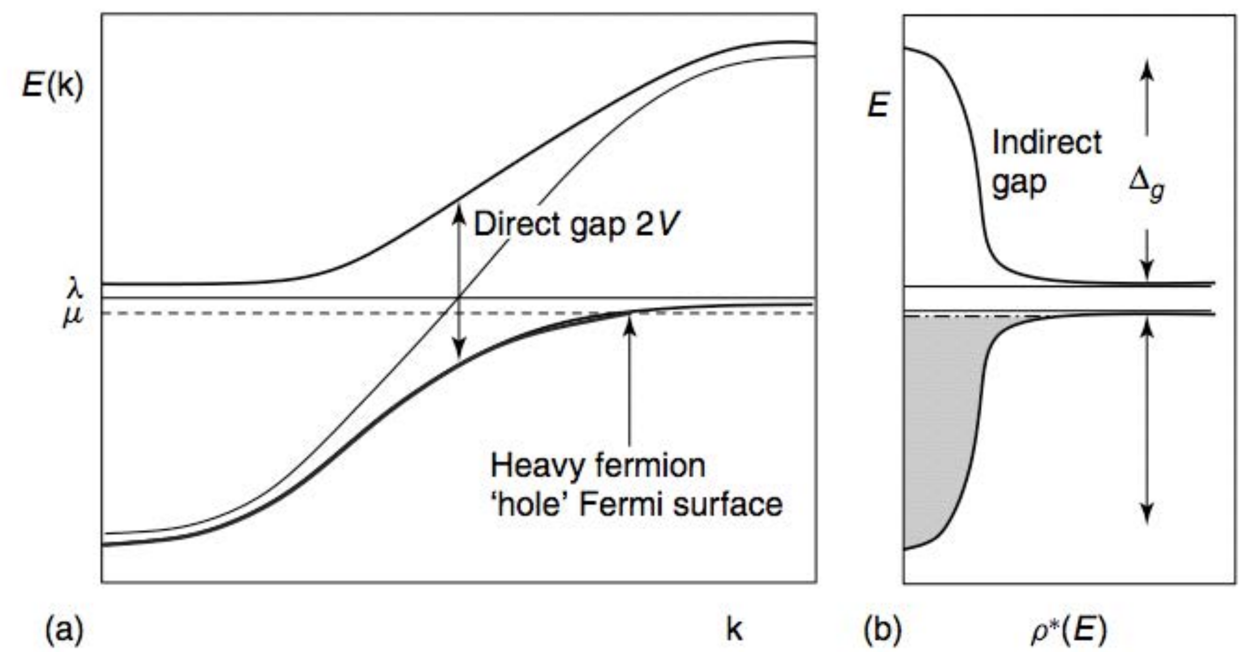


Detailed calcn.

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

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

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



Detailed calcn.

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

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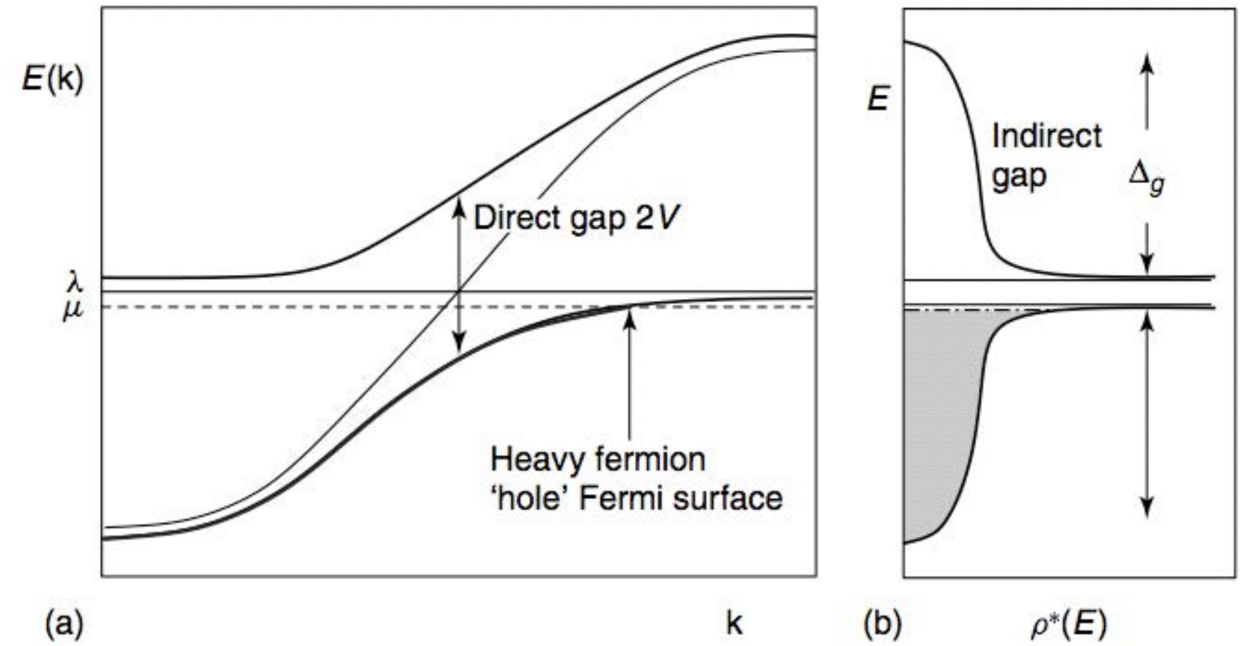
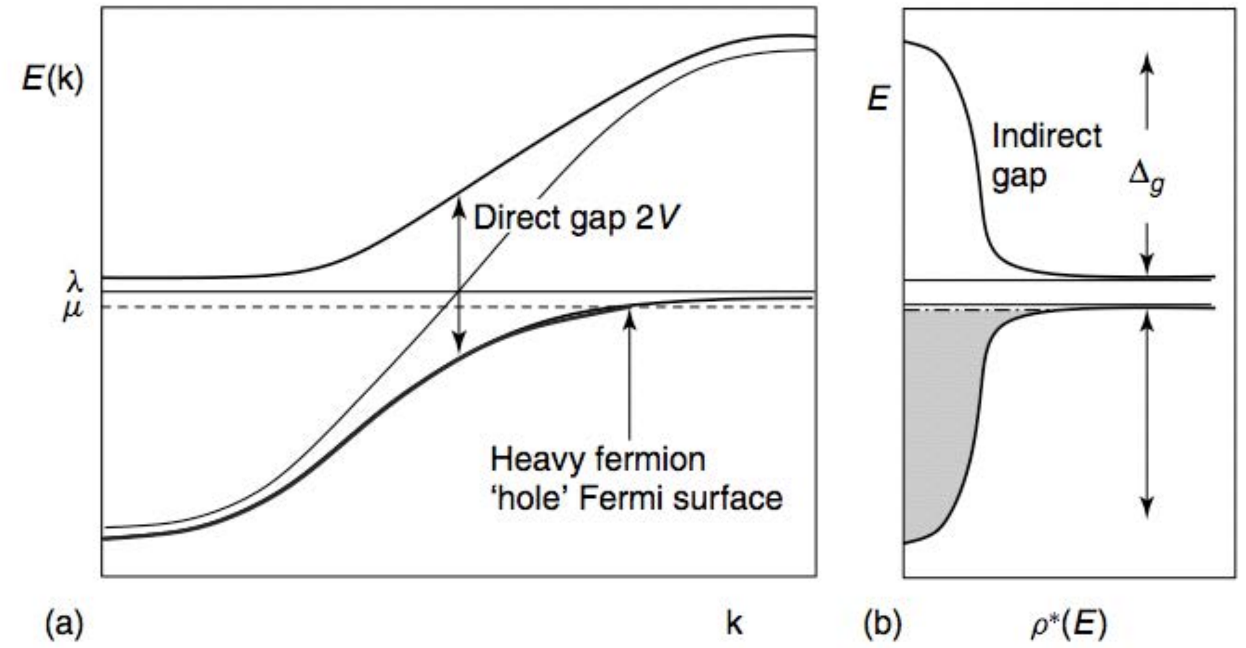
$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE \rho^*(E) E + \left(\frac{V^2}{J} - \lambda q\right)$$

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



Detailed calcn.

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



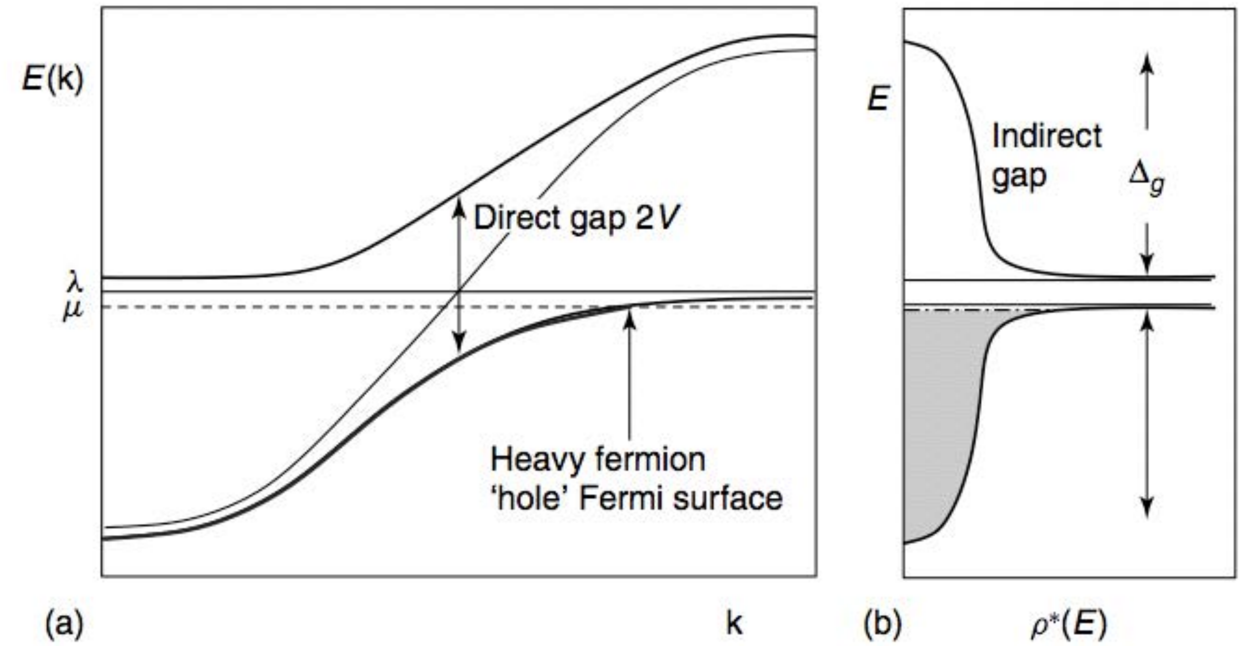
$$\frac{F}{N} = -T \sum_{\mathbf{k},\pm} \ln\left[1 + e^{-\beta E_{\mathbf{k}\pm}}\right] + \mathcal{N}_s \left(\frac{V^2}{J} - \lambda q \right).$$

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

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

Detailed calcn.

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



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

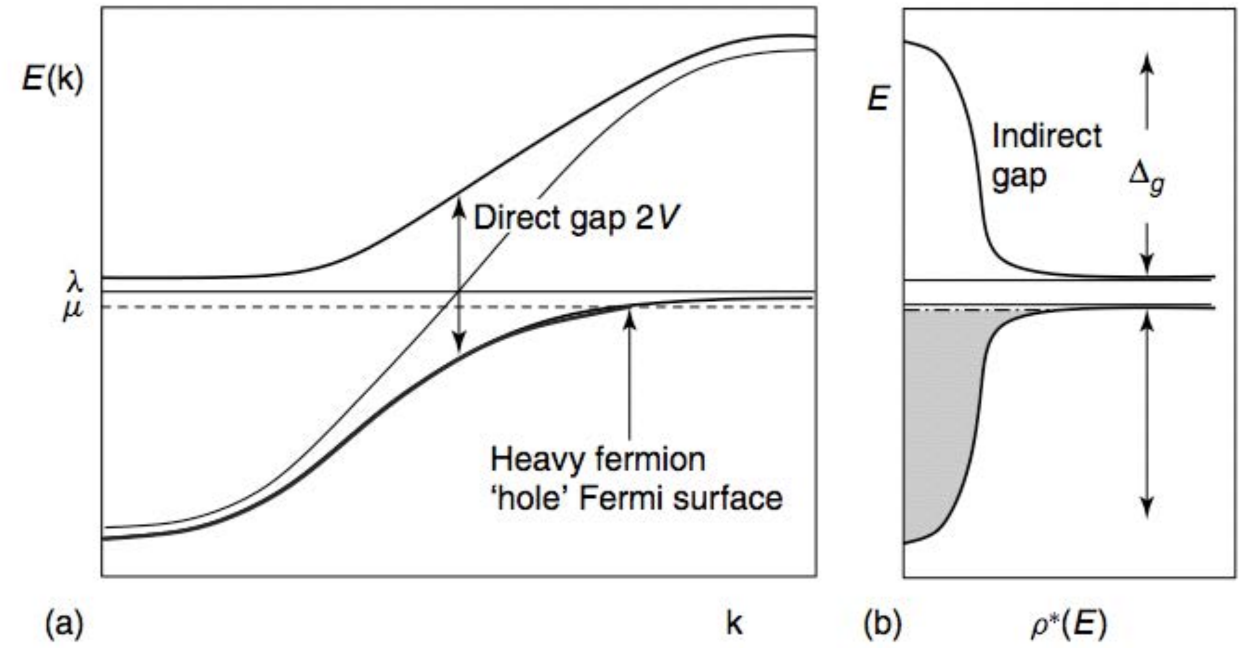
$$\frac{E_o}{N\mathcal{N}_s} = \int_{-\infty}^{0} dE \rho^*(E) E + \left(\frac{V^2}{J} - \lambda q\right)$$

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

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

Detailed calcn.

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



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

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

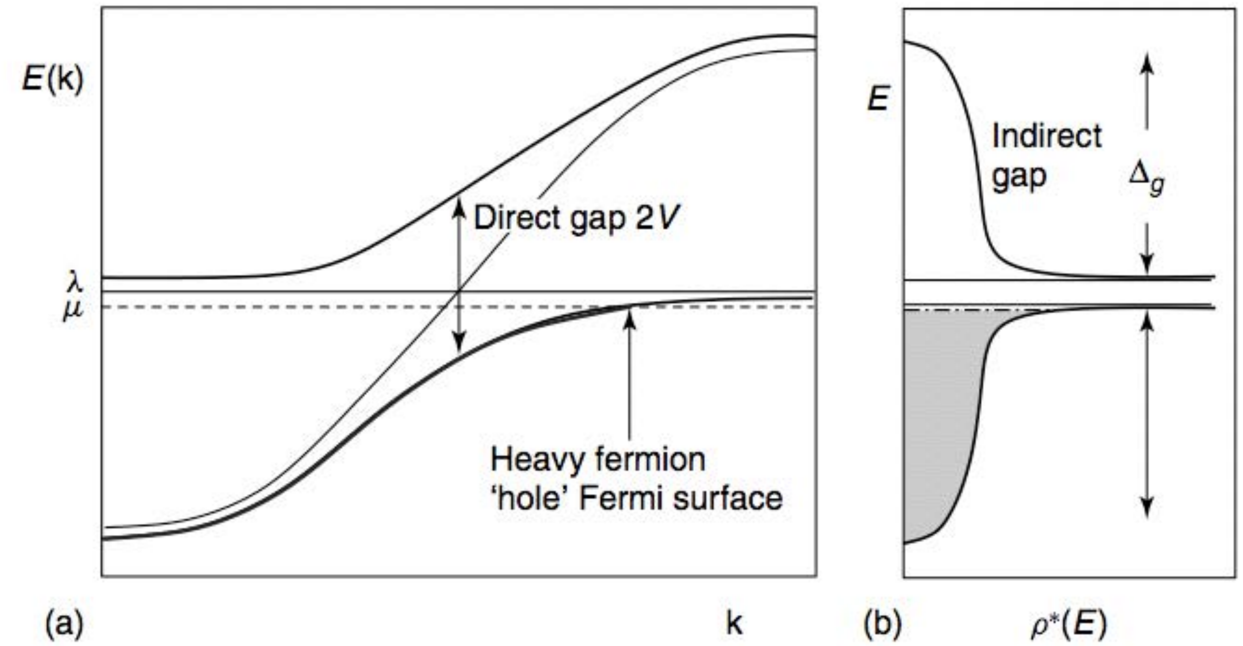
$$E = \epsilon + \frac{V^2}{E - \lambda} \qquad \rho^*(E) = \rho\frac{d\epsilon}{dE} = \rho\left(1 + \frac{V^2}{(E-\lambda)^2}\right)$$

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

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

Detailed calcn.

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



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

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

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

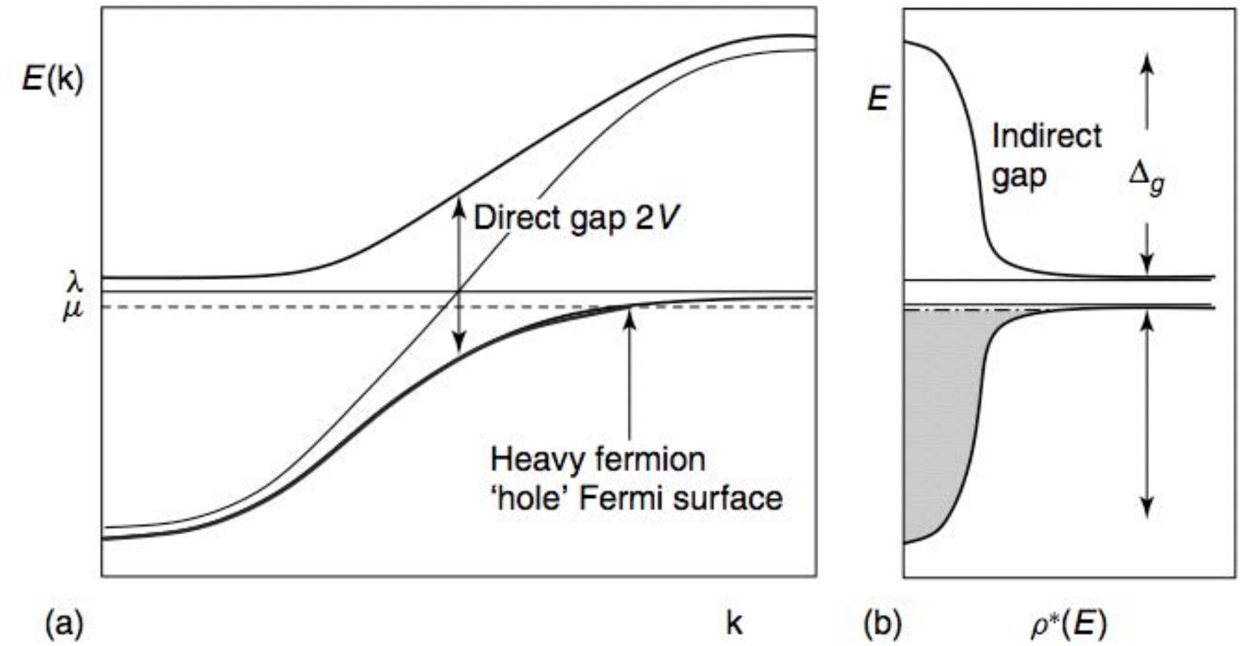
$$\frac{E_o}{N\mathcal{N}_s} = \rho \int_{-D-V^2/D}^{0} dE E \left(1 + \frac{V^2}{(E - \lambda)^2}\right) + \left(\frac{V^2}{J} - \lambda q\right)$$

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

Detailed calcn.

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

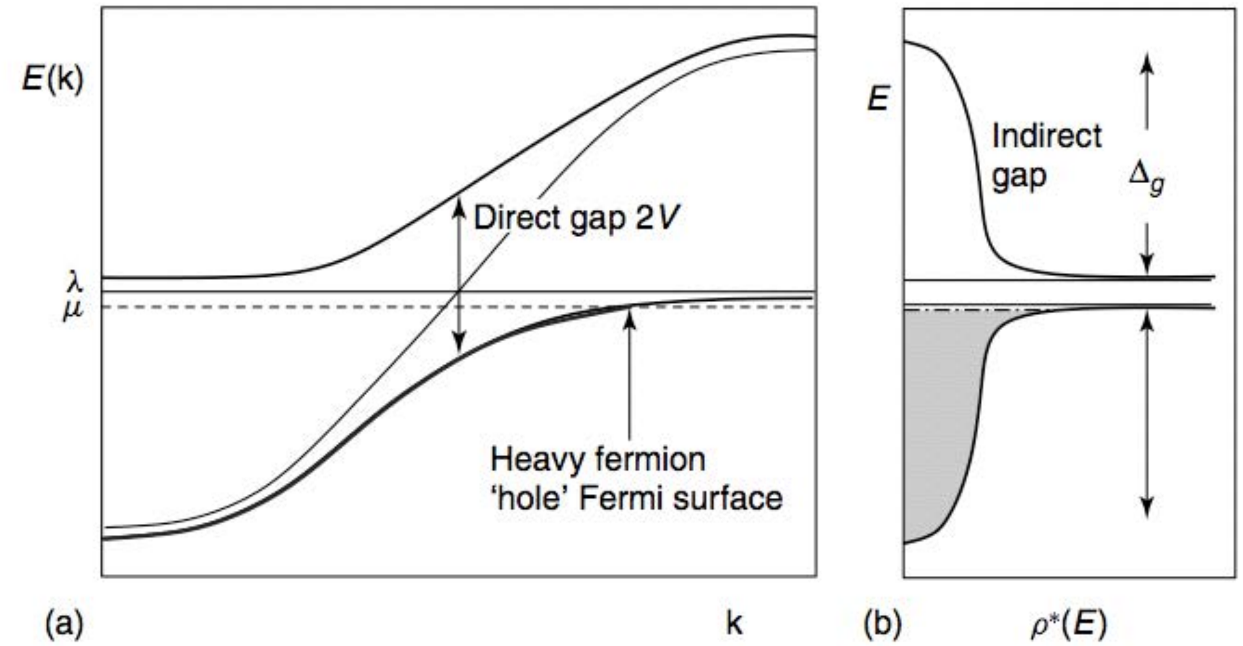
$$= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{V^2}{J} - \lambda q\right)$$



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.

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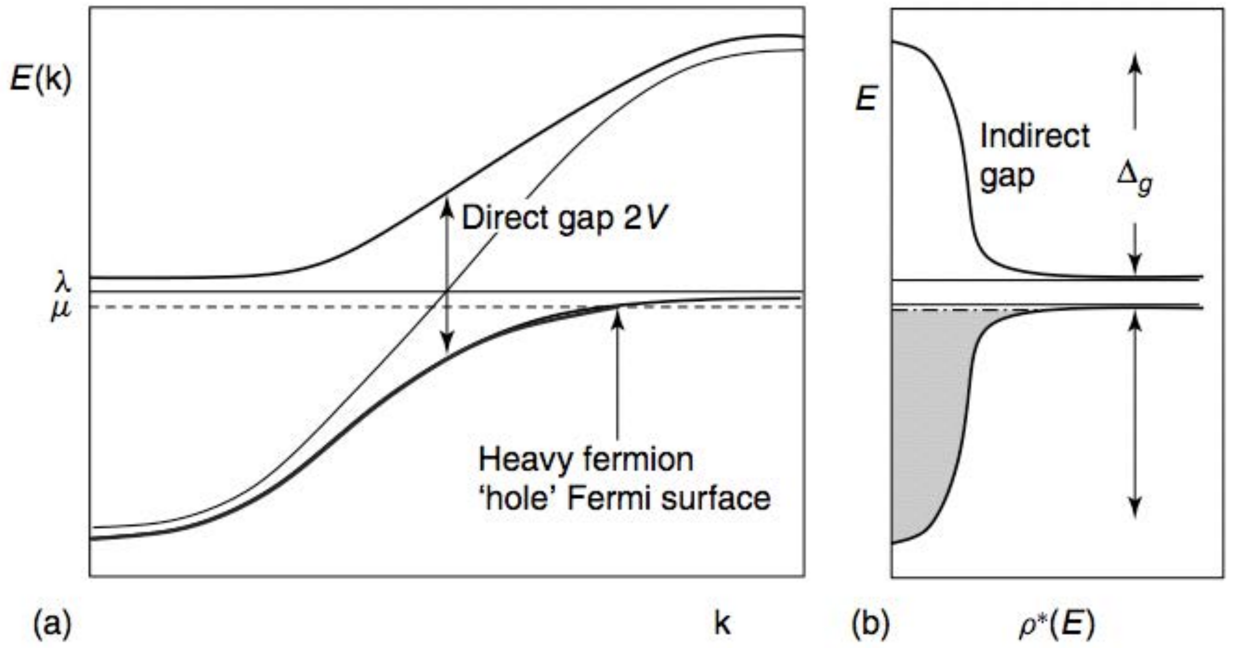
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{D}\right) + \left(\frac{\Delta}{\pi\rho J} - \lambda q\right) \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{De^{-\frac{1}{J\rho}}}\right) - \lambda q \\
&= -\frac{D^2\rho}{2} + \frac{\Delta}{\pi}\ln\left(\frac{\lambda}{T_K}\right)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



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

Detailed calcn.

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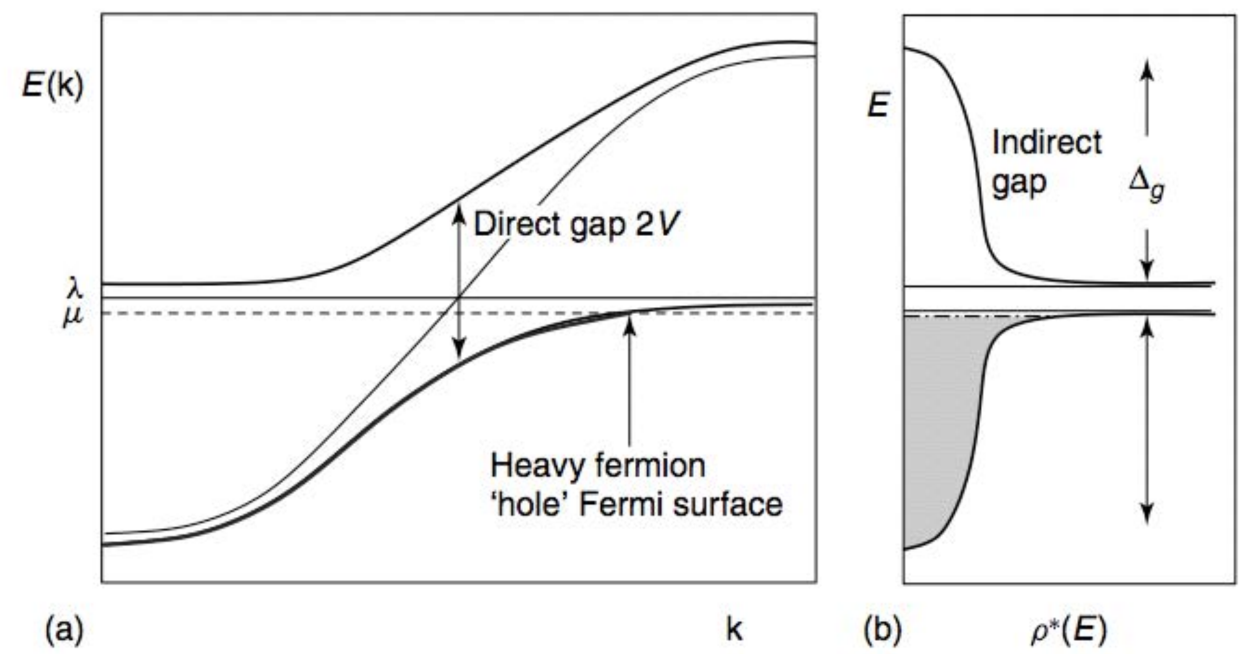

$$T_K = De^{-\frac{1}{J\rho}}$$

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

Detailed calcn.

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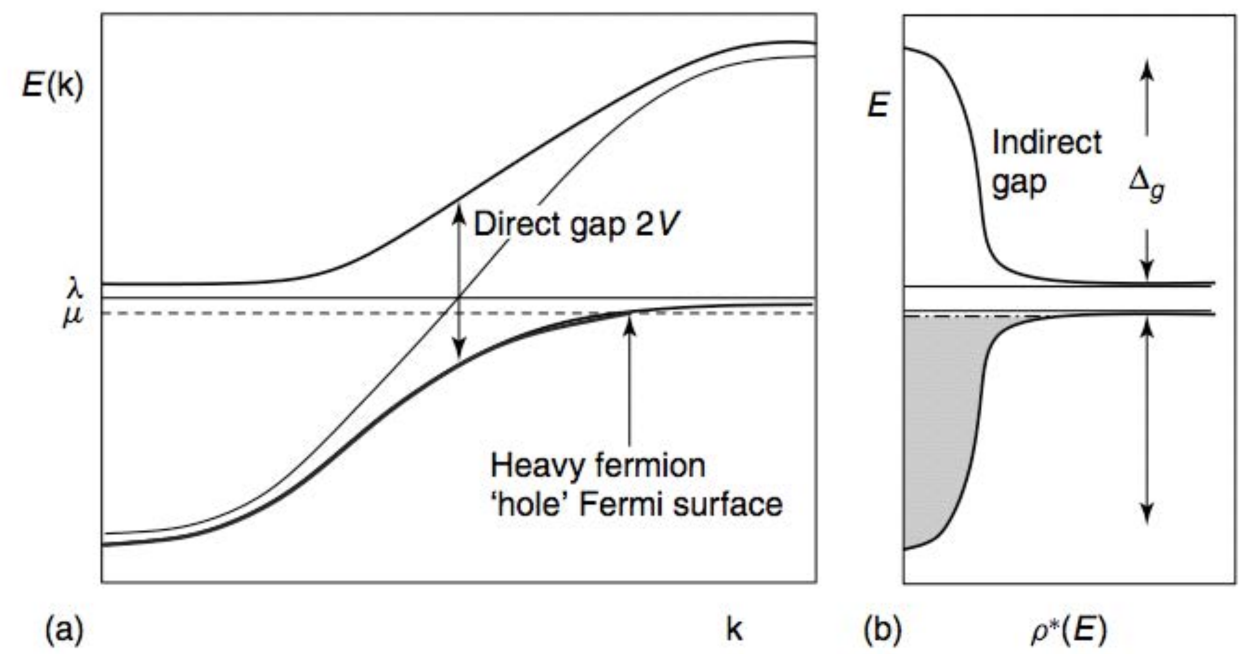

$$T_K = De^{-\frac{1}{J\rho}}$$

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

Detailed calcn.

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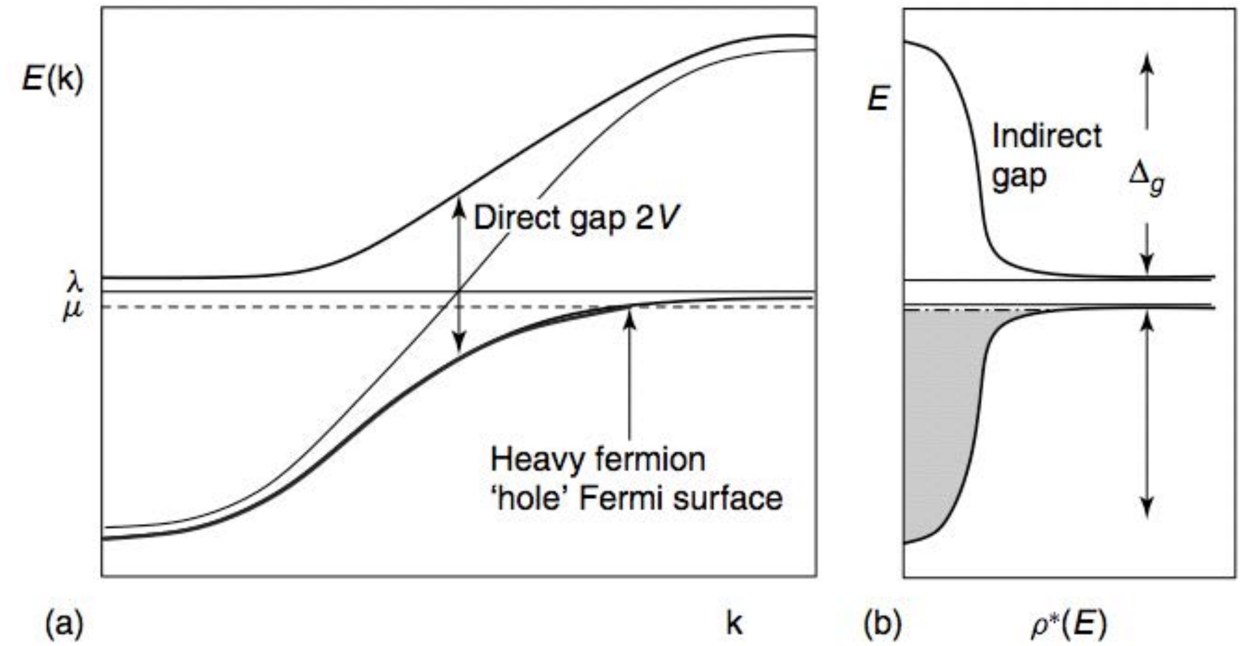

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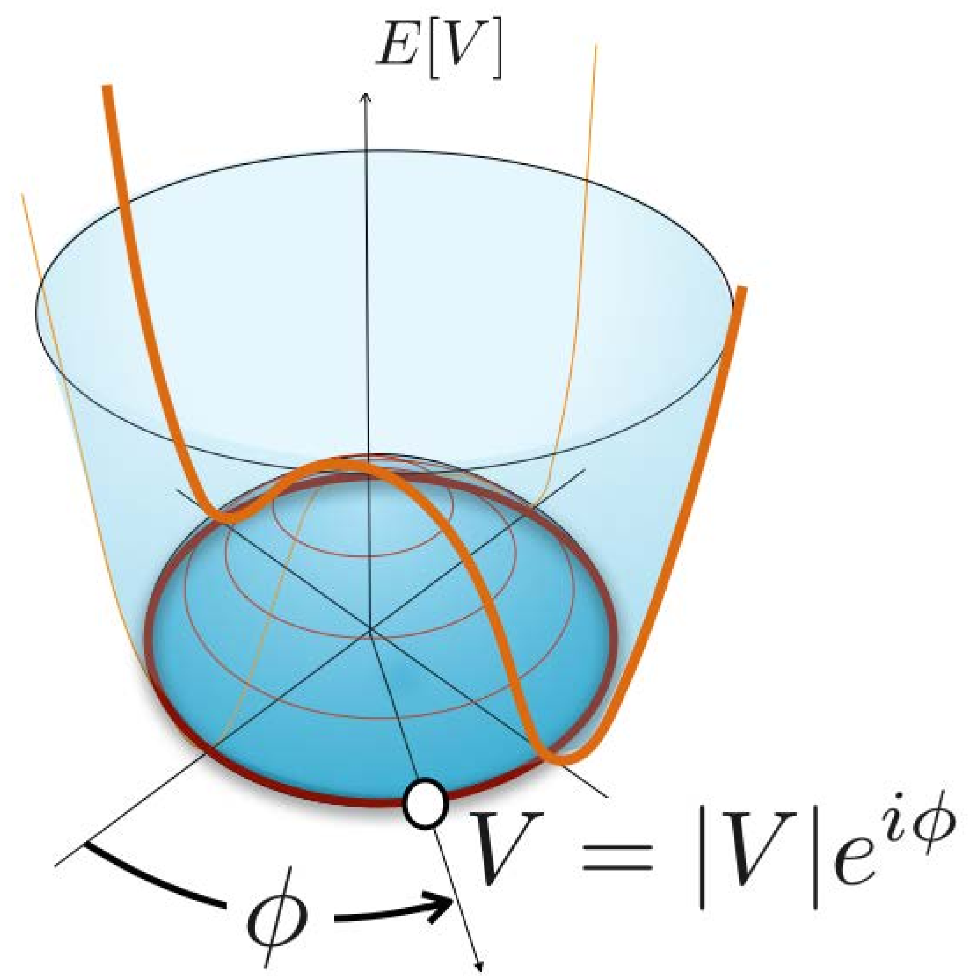

Detailed calcn.

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

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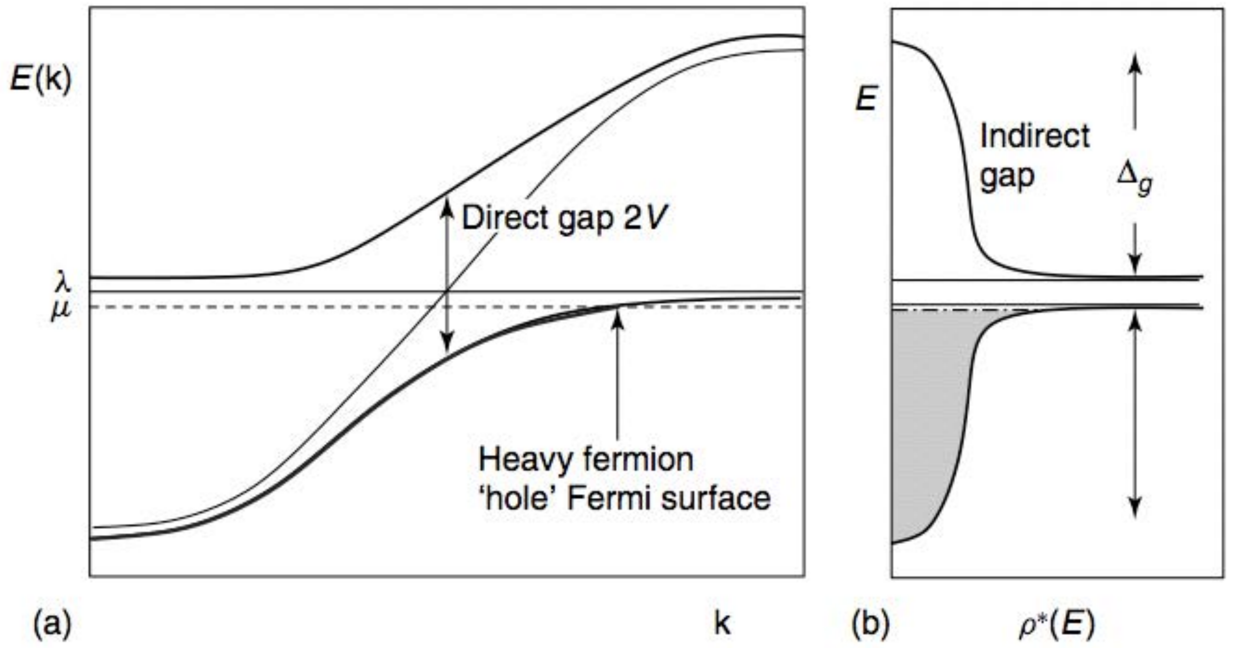

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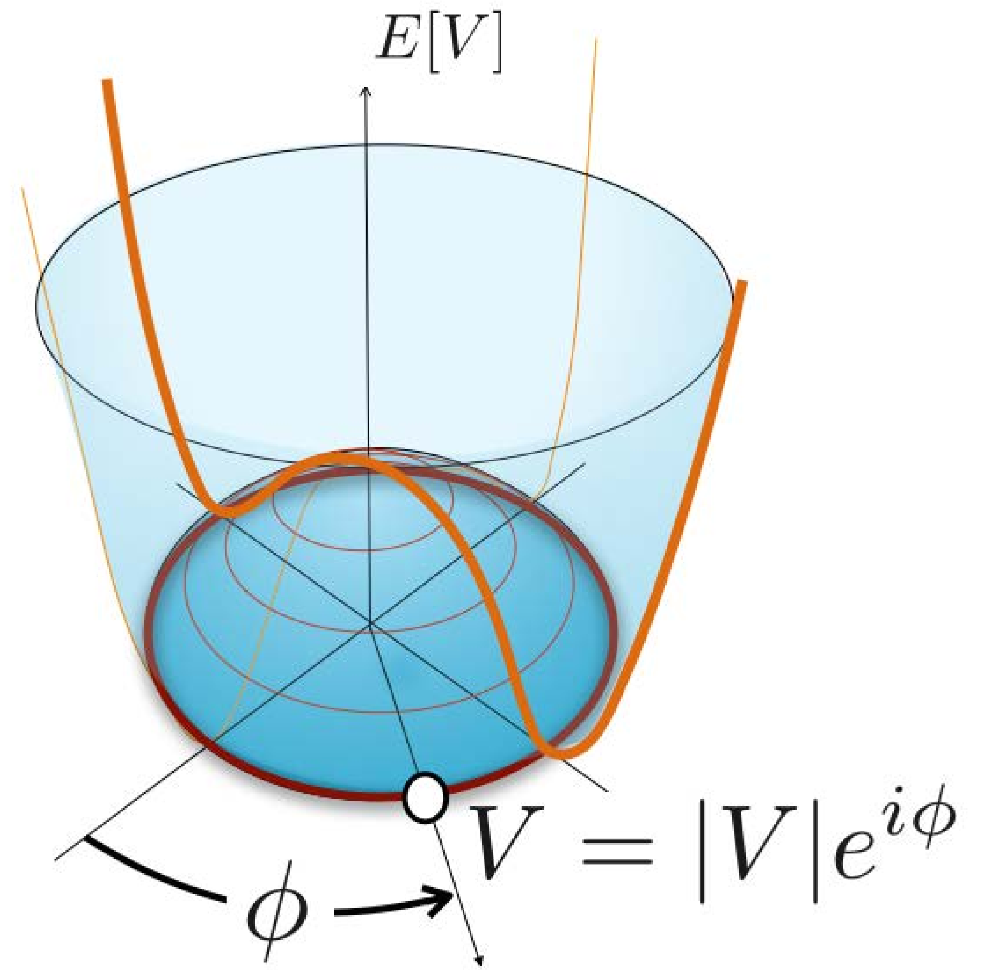
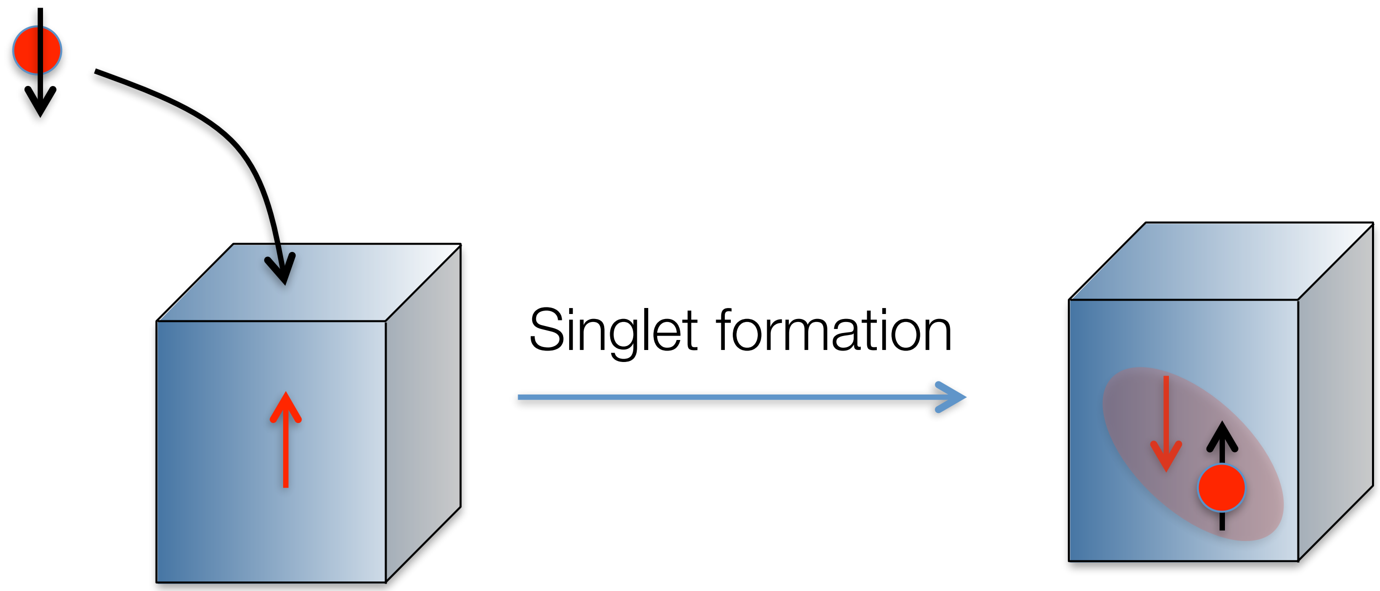
$$\frac{\partial E_0}{\partial \Delta} = 0 \qquad 0 = \frac{1}{\pi}\ln\left(\frac{\Delta e^2}{\pi q T_K}\right)$$

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



Composite nature of the Heavy Fermion.

Coherence and composite fermions (again)



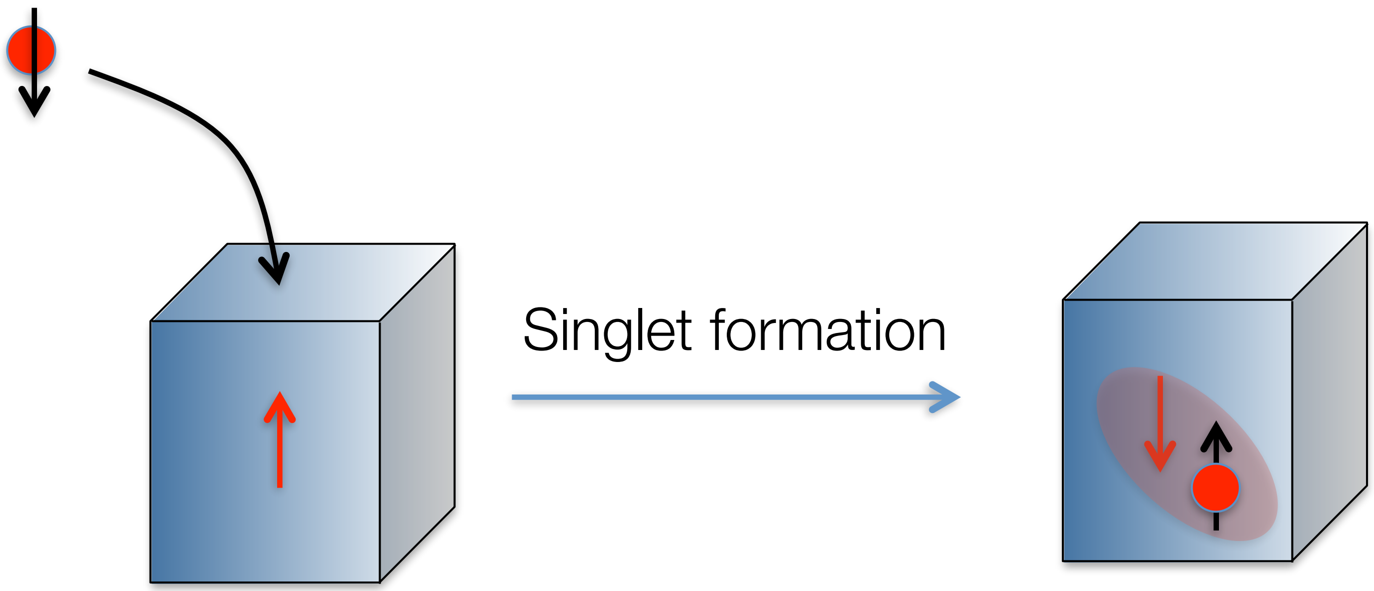
- The large N approach to the Kondo lattice.

Spin x conduction = composite fermion

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

Composite Fermion

Coherence and composite fermions (again)



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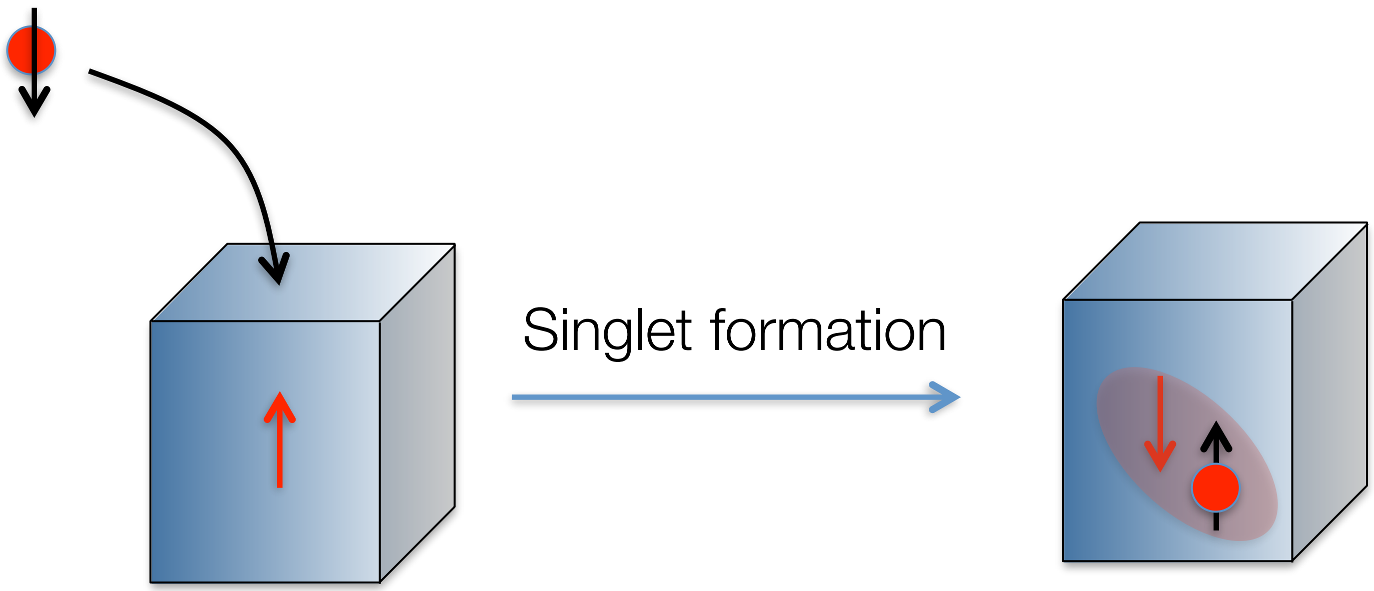
Composite Fermion

$$\frac{1}{N}\sum_{\beta} \overline{c_{\beta}(\tau) S}_{\beta\alpha}(\tau') = g(\tau-\tau')\hat{f}_{\alpha}(\tau').$$

Coherence and composite fermions (again)



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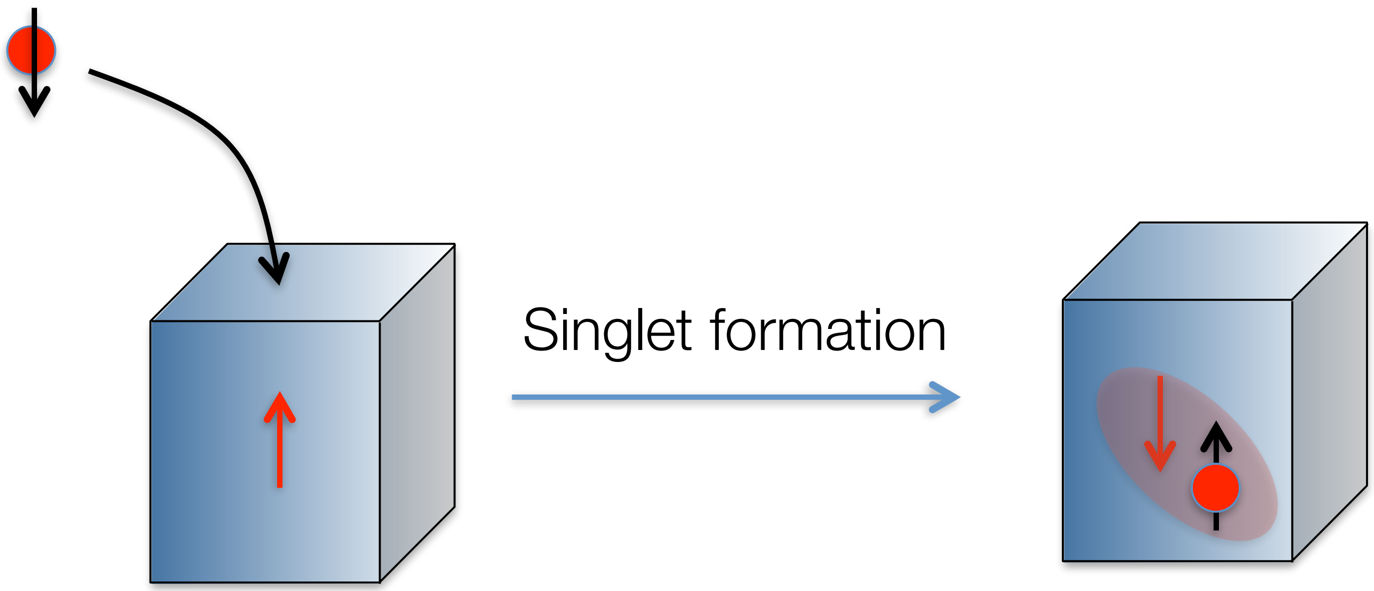
$$\begin{aligned}\frac{1}{N}\sum_{\beta} c_{\beta}(\tau) S_{\beta\alpha}(\tau') &= \frac{1}{N}\sum_{\beta} c_{\beta}(\tau) f^{\dagger}{}_{\beta}(\tau') f_{\alpha}(\tau') \\ &= \frac{1}{N}\sum_{\beta} \langle T c_{\beta}(\tau) f^{\dagger}{}_{\beta}(\tau')\rangle f_{\alpha}(\tau') \\ &= -G_{cf}(\tau-\tau') f_{\alpha}(\tau').\end{aligned}$$

Coherence and composite fermions (again)



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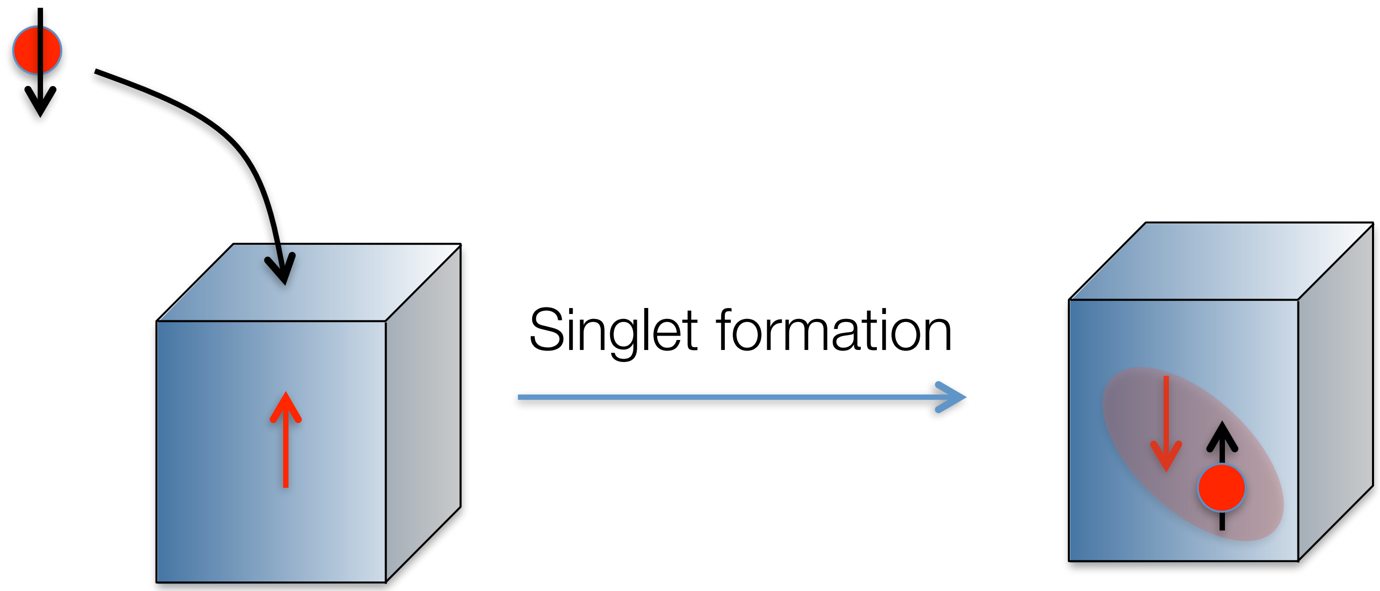
Coherence and composite fermions (again)



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$$g(\tau) \sim \begin{cases} \rho V \ln\left(\frac{T_K \tau}{\hbar}\right) & (\hbar/D << \tau << \hbar/T_K) \\ \frac{1}{\tau} & (\tau >> \hbar/T_K) \end{cases}$$

$$g(\tau-\tau') = \langle T c_{\beta}(\tau) f^{\dagger}{}_{\beta}(\tau')\rangle = -G_{cf}(\tau-\tau')$$

Bound-state built from electrons spanning decades of energy out to the Band-Width.

Physics of Heavy Fermion Superconductivity Lecture II:

1. The large N approach to the Kondo lattice.

2. Heavy Fermion Metals.

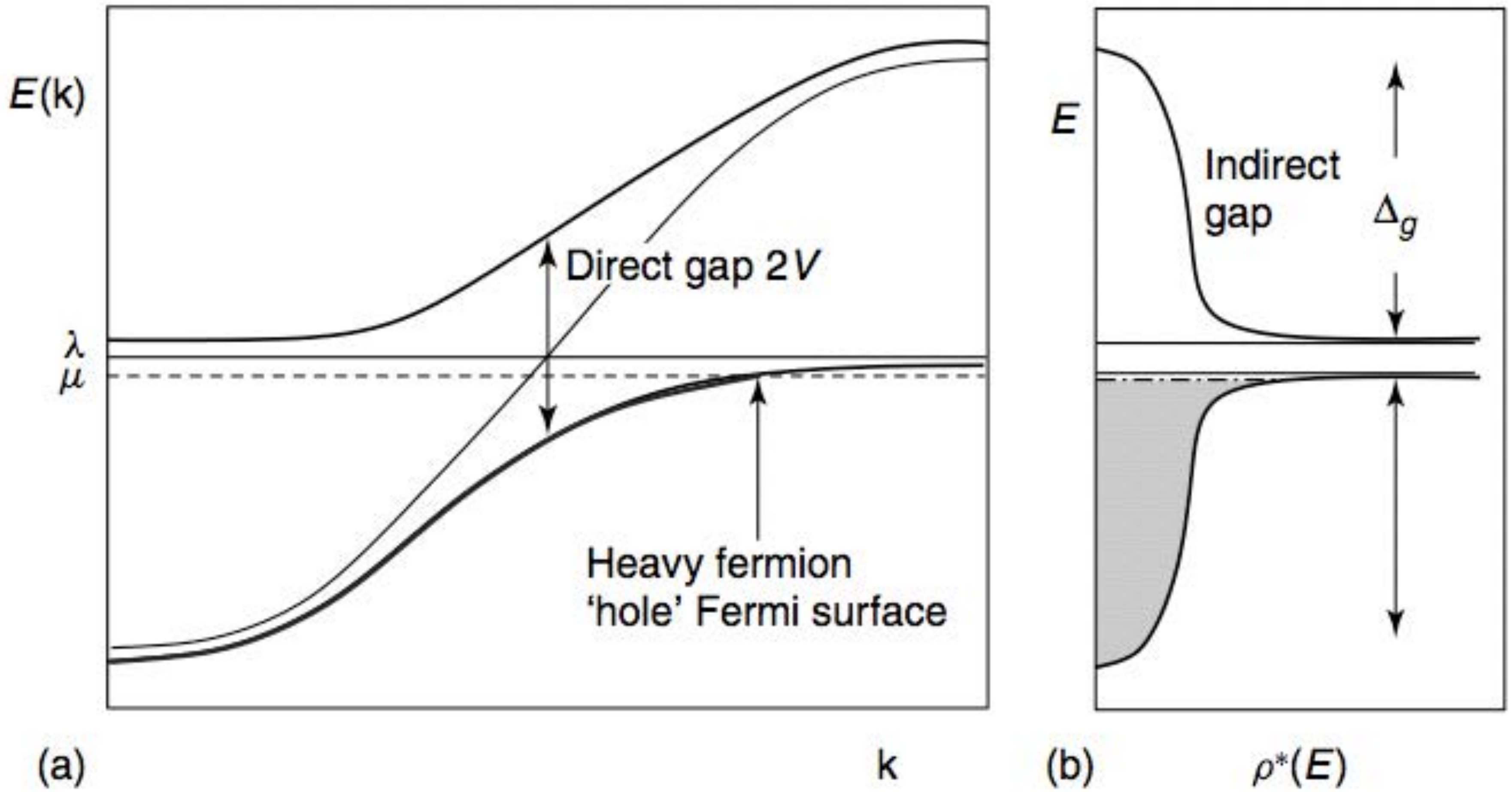
3. Optical Conductivity of Heavy Fermion Metals

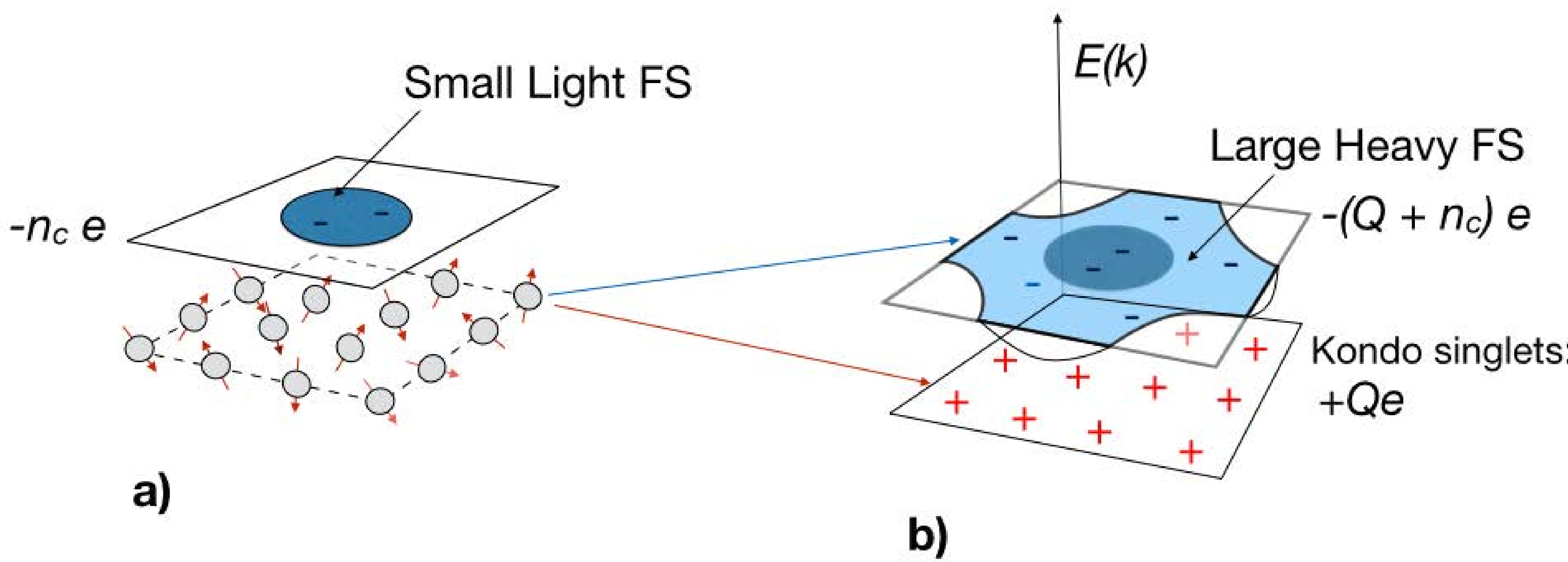
4. Kondo Insulators

Rutgers
Center for Materials Theory

Large N Approach.

Read and Newns '83.





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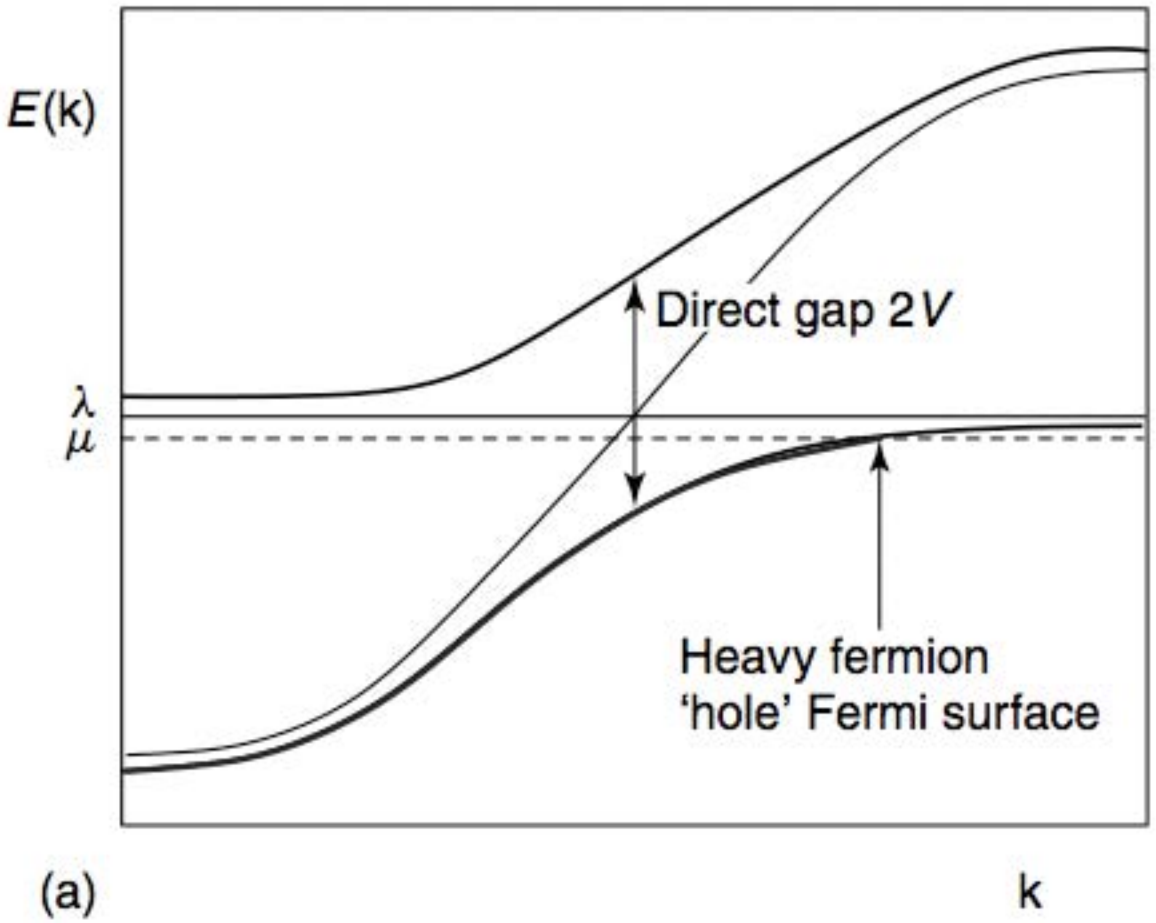
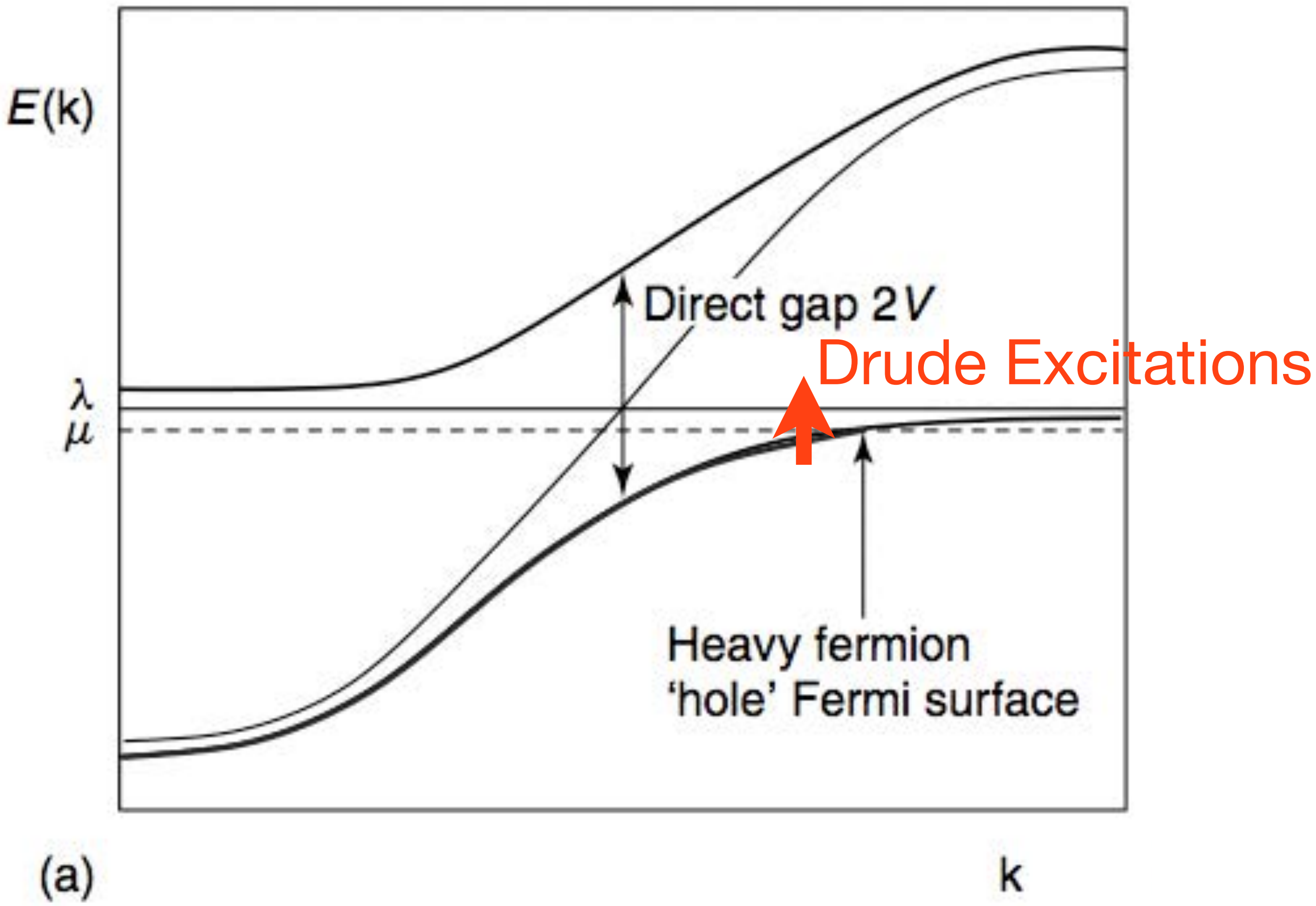
Optical Conductivity.



Optical Conductivity.



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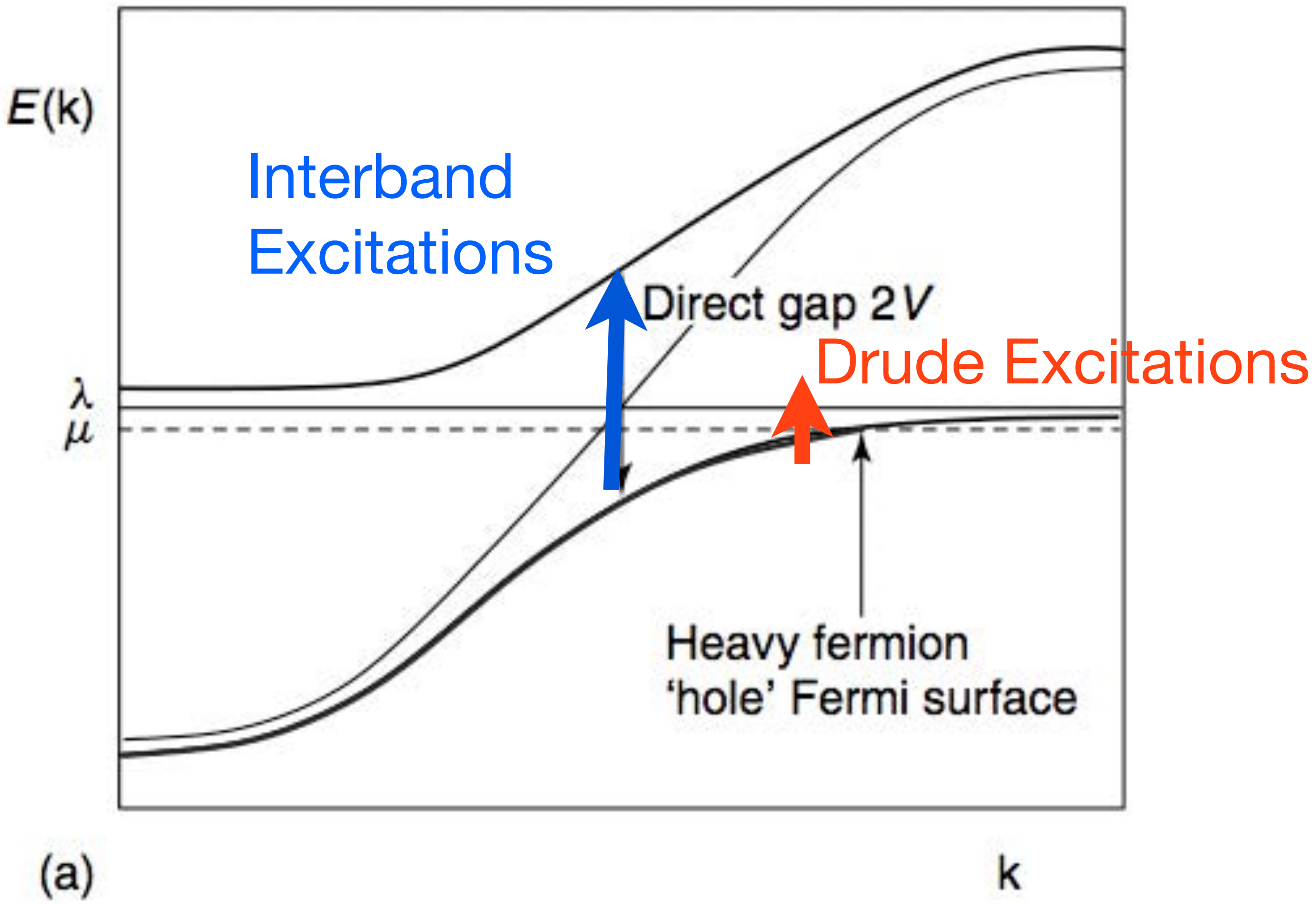

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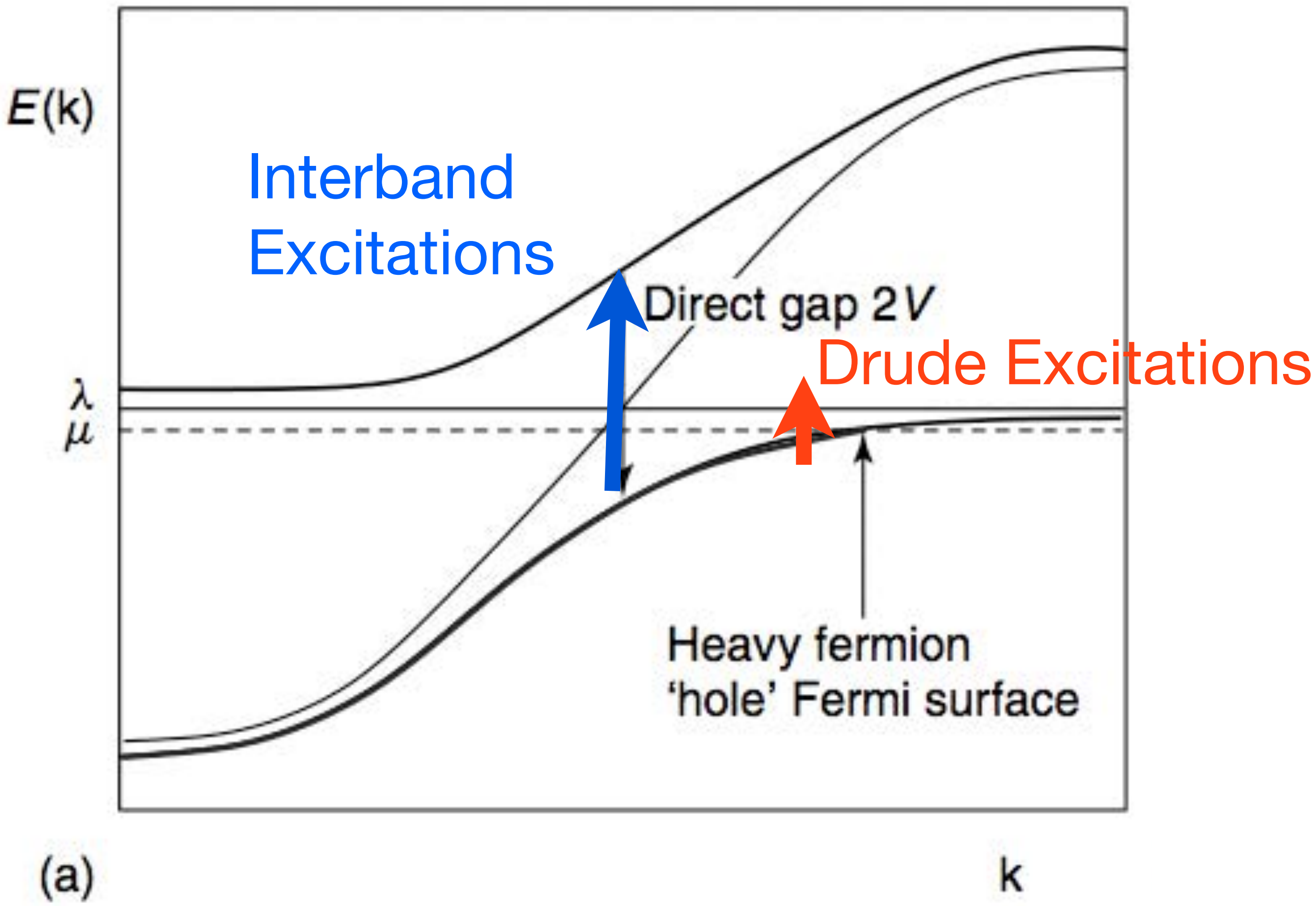
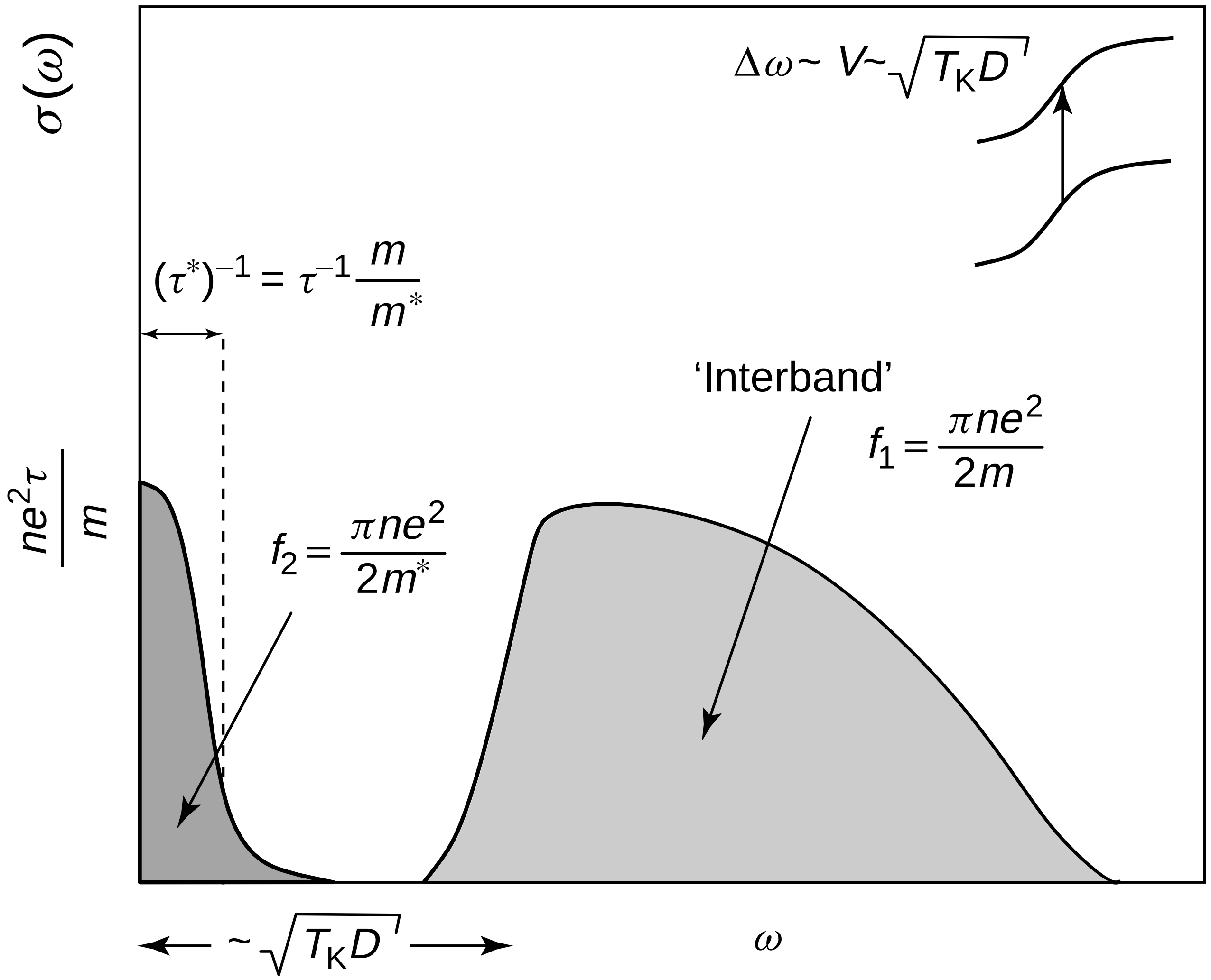


Millis and Lee, 1987



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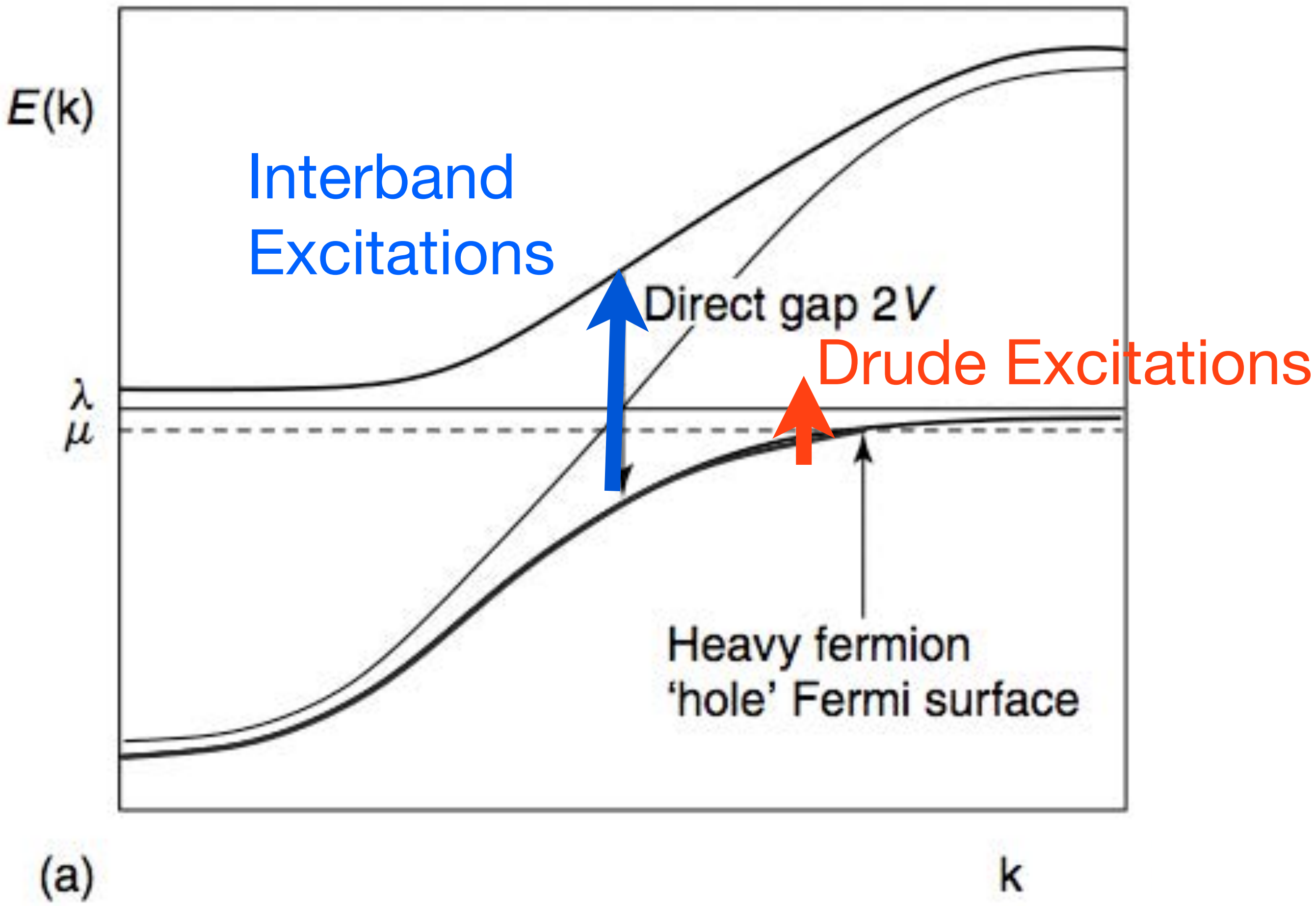

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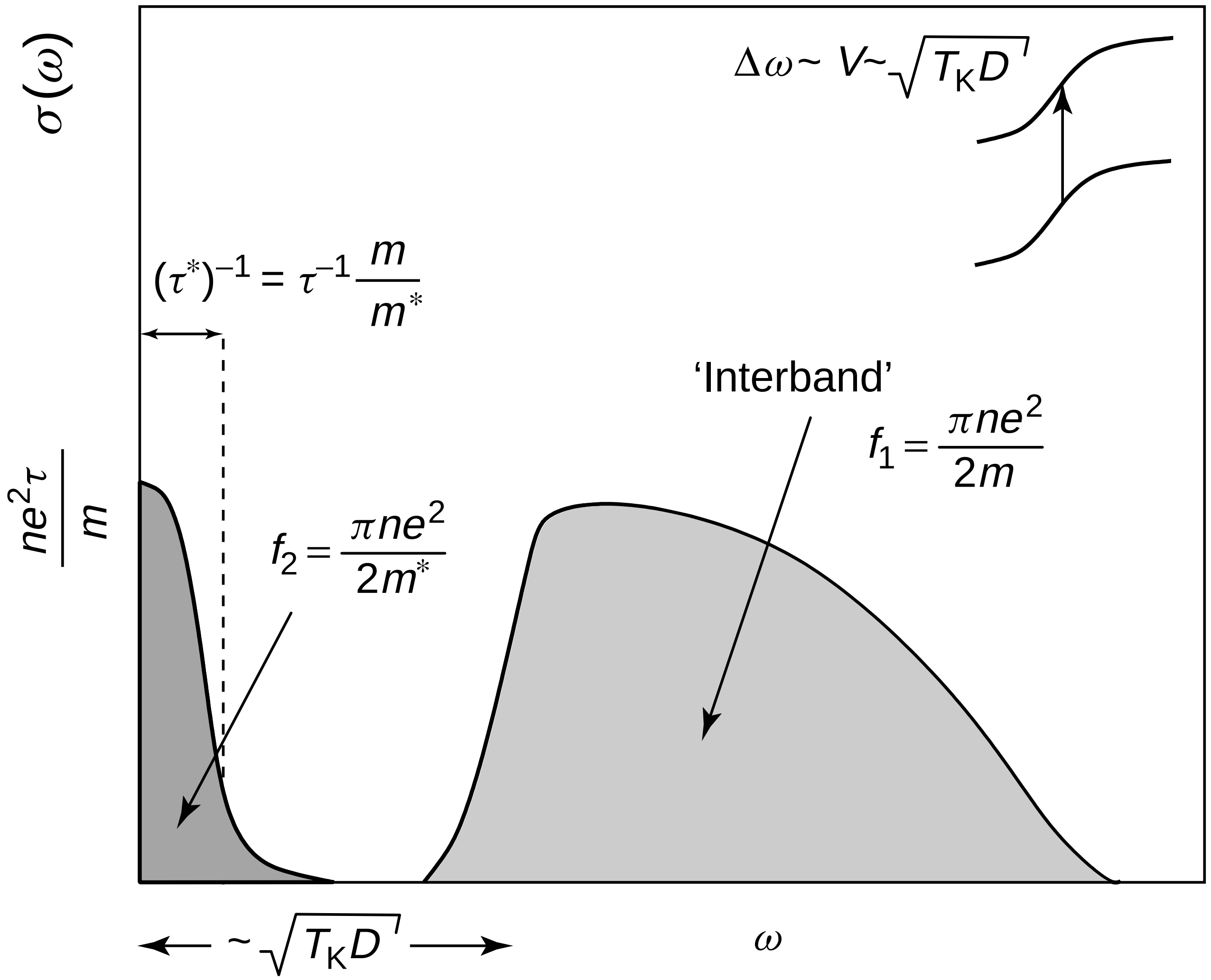
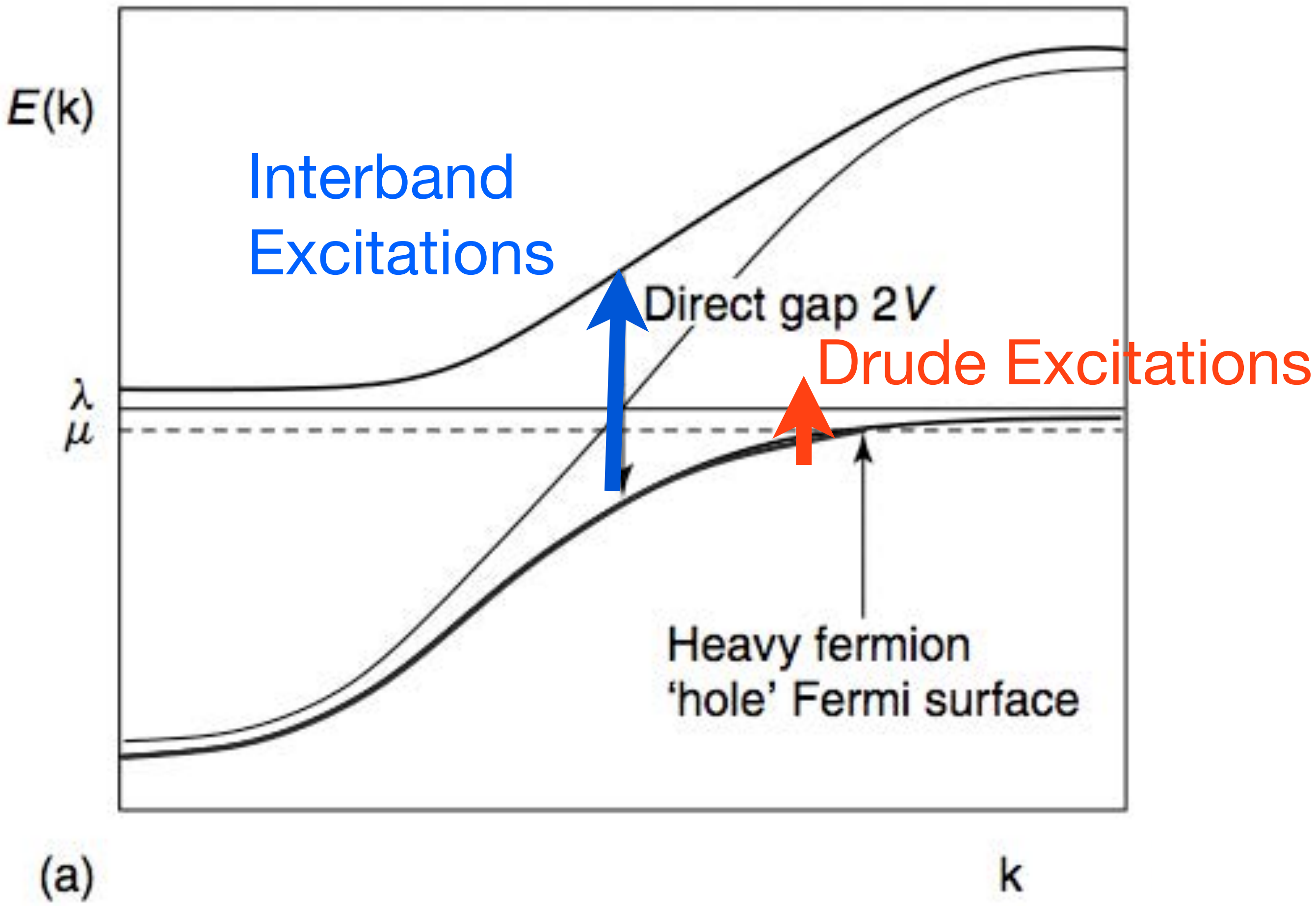


$$V^2/D \sim T_K \Rightarrow V \sim \sqrt{T_K D}$$

Optical Conductivity.



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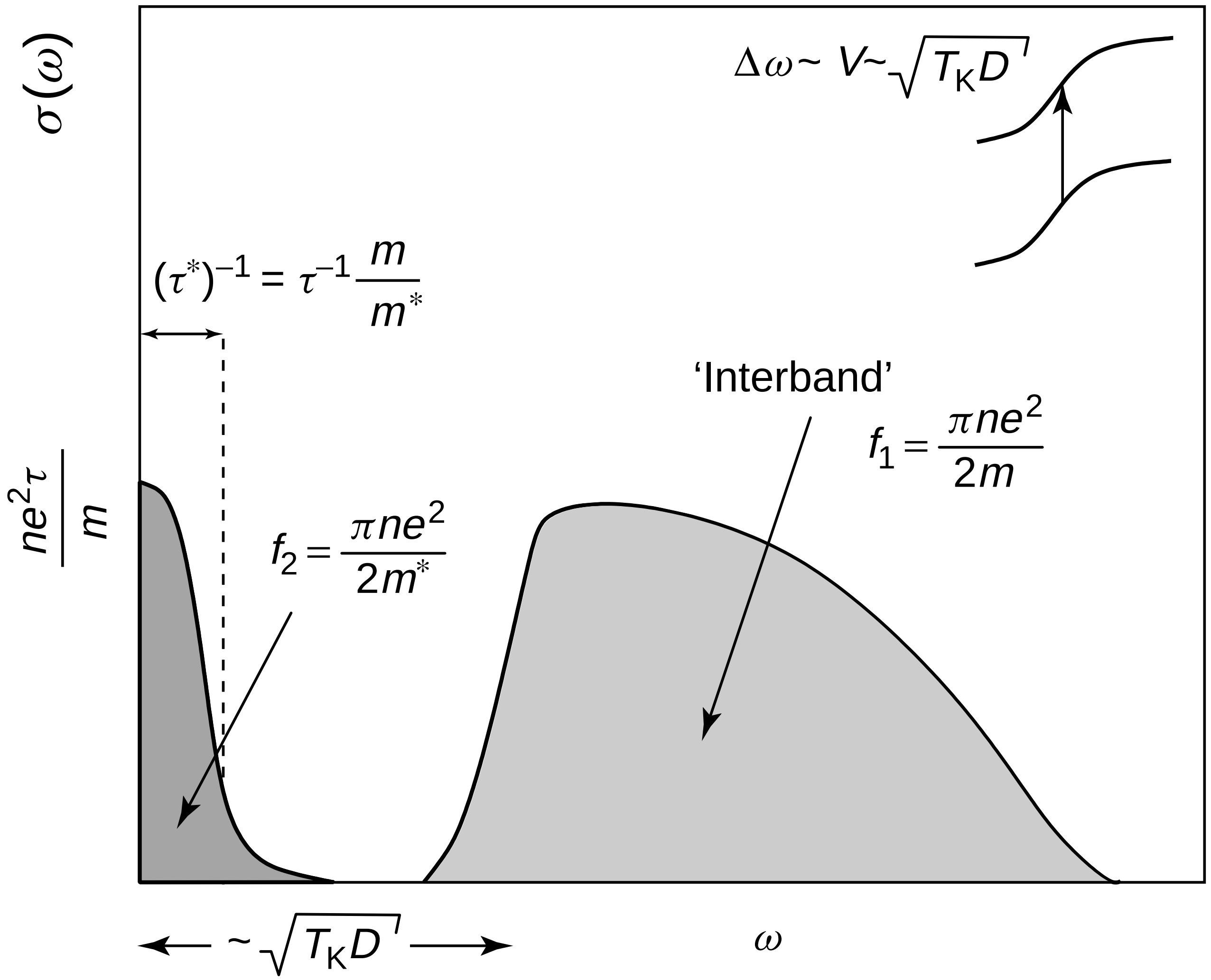
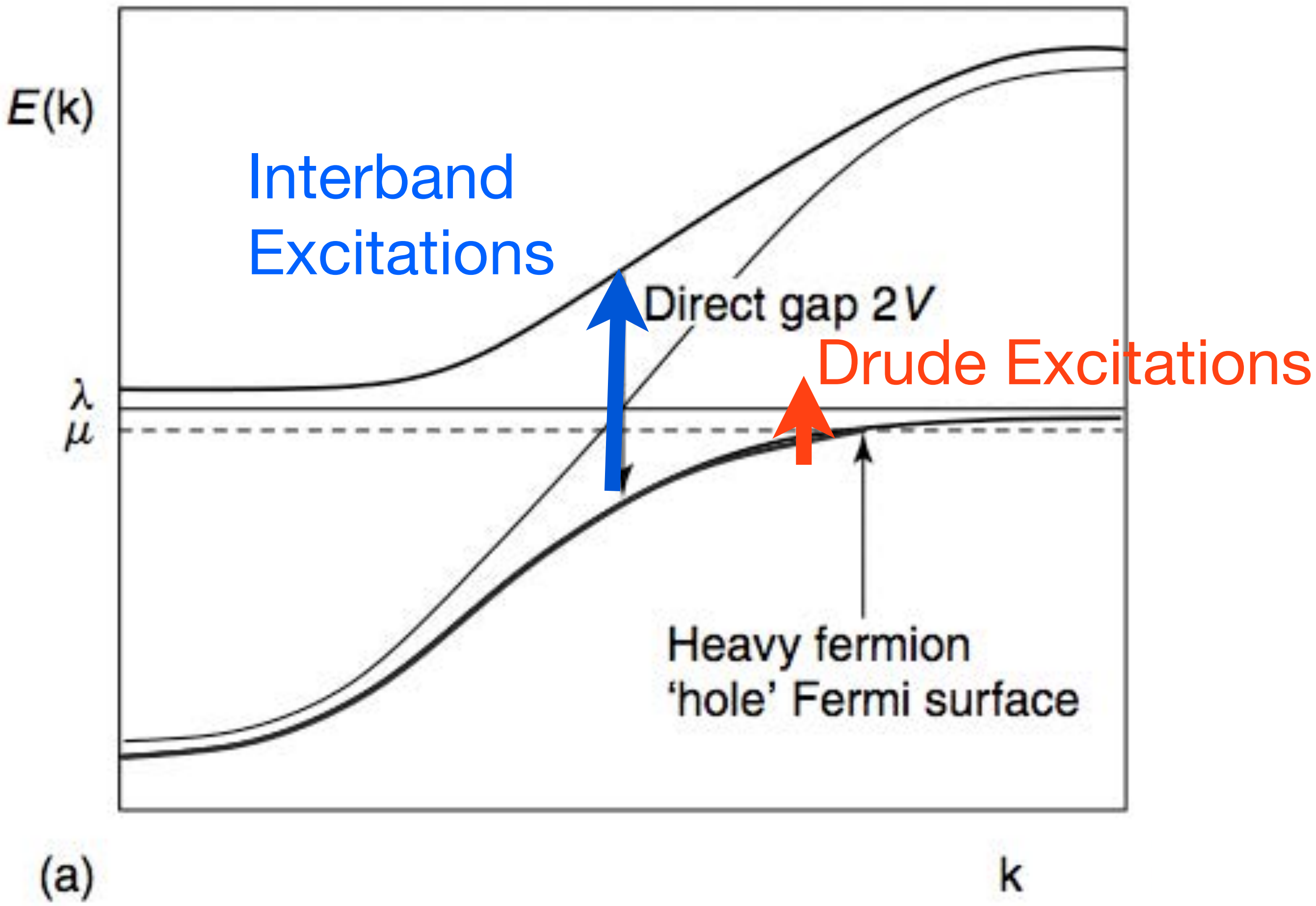


$$V^2/D \sim T_K \Rightarrow V \sim \sqrt{T_K D}$$

$$\int_0^\infty \frac{d\omega}{\pi} \sigma(\omega) = f_1 = \frac{\pi}{2}\left(\frac{n_c e^2}{m}\right)$$

Optical Conductivity.



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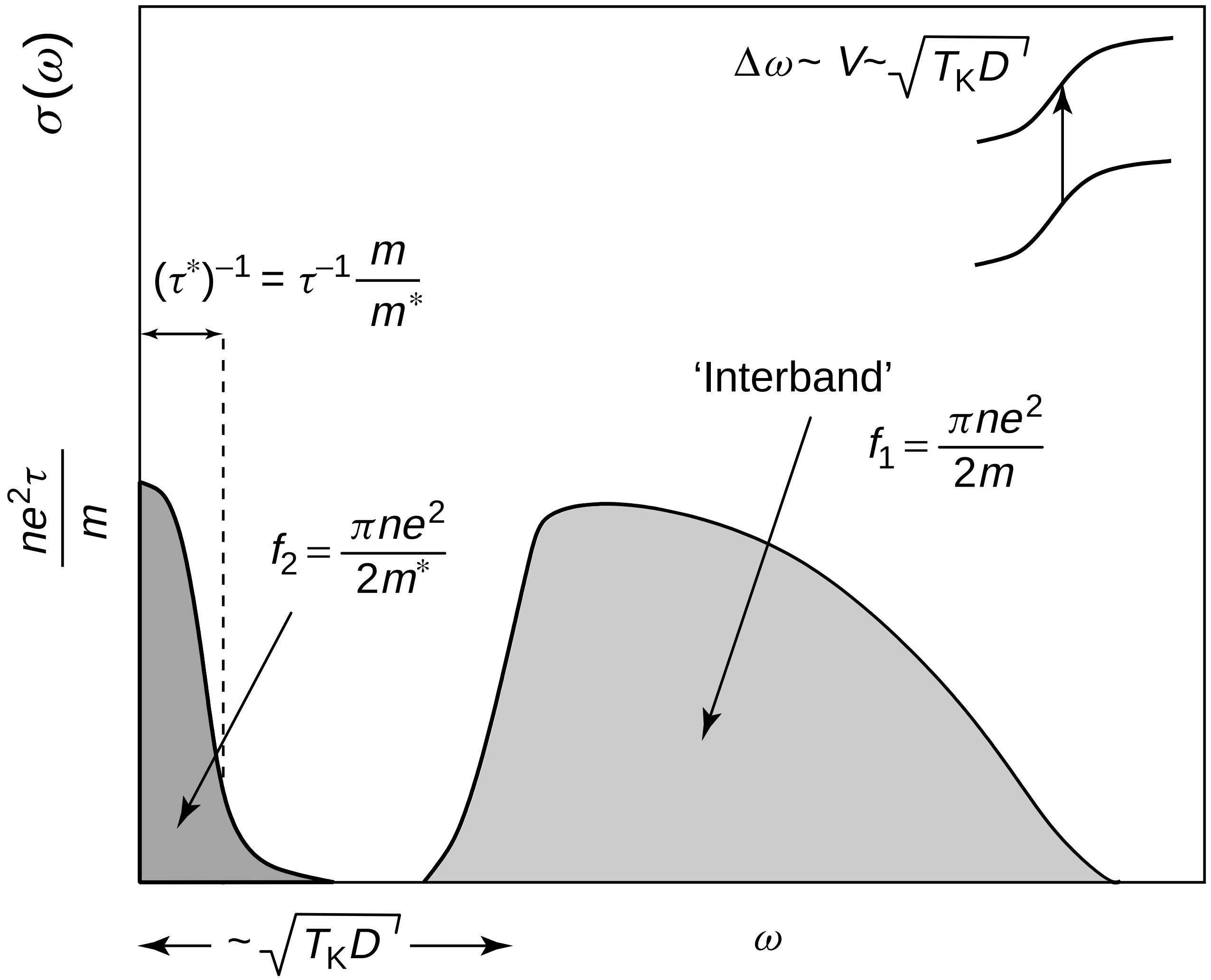

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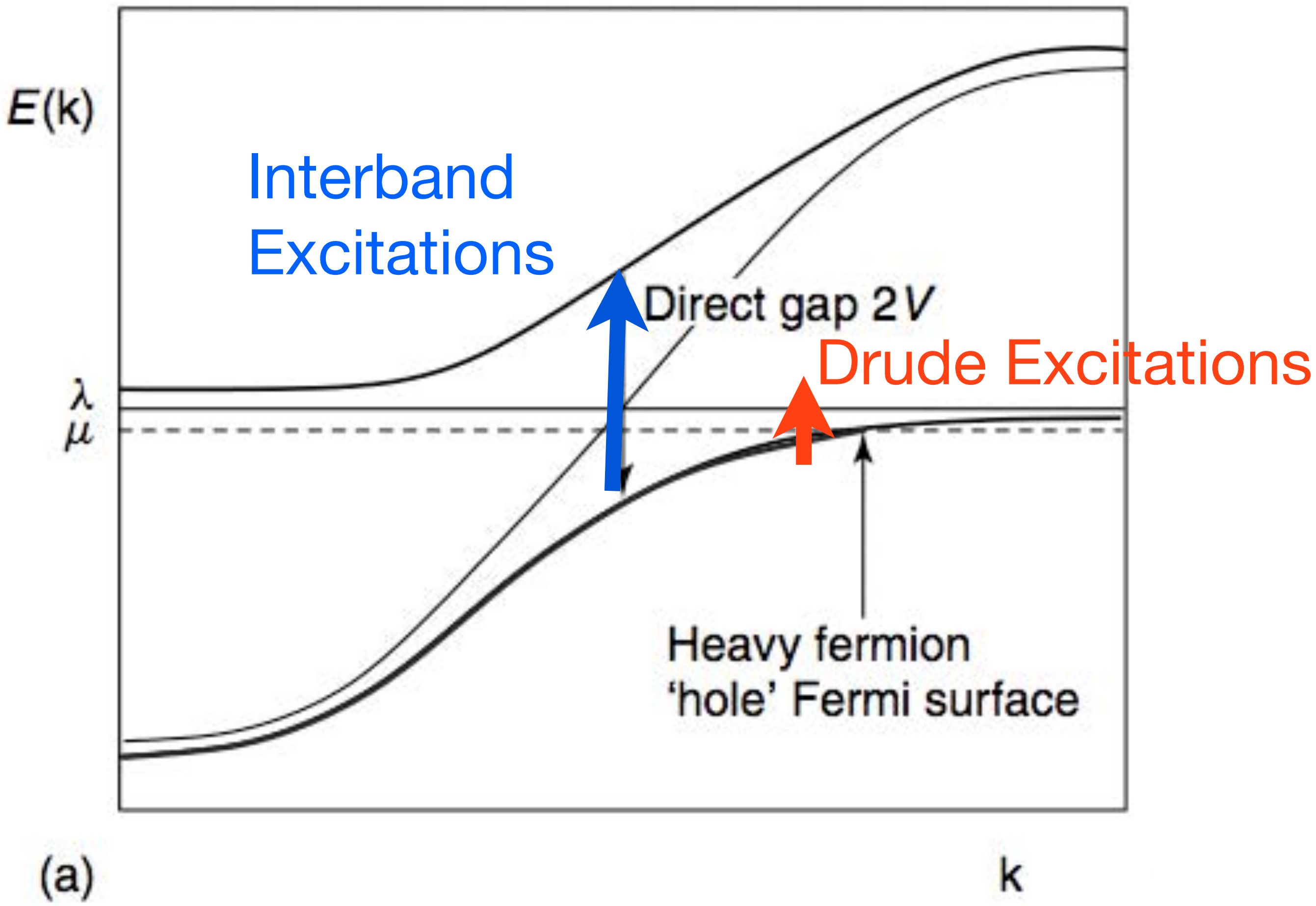
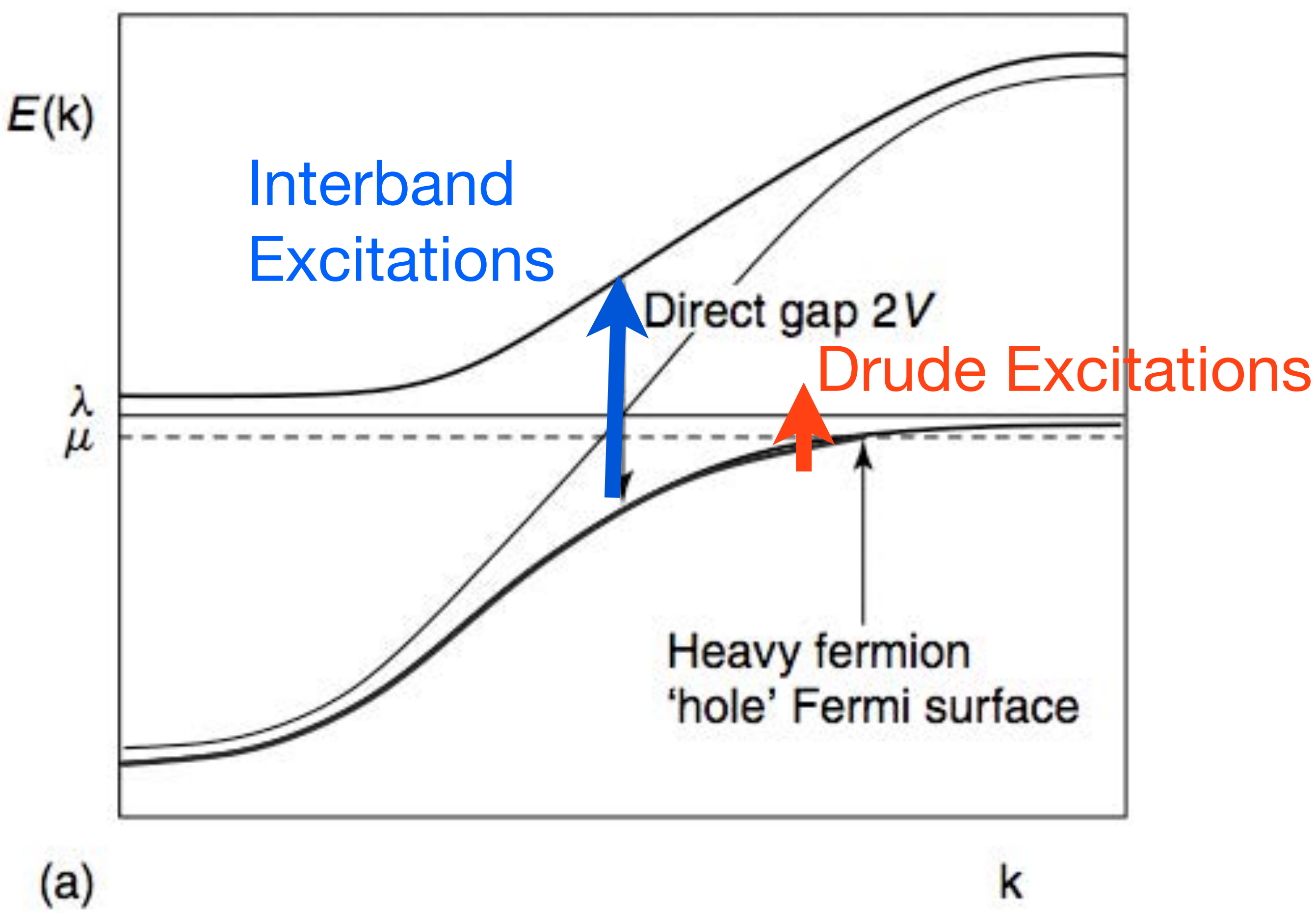
$$\int_0^{\sim V} \mathrm{d}\omega\sigma(\omega) = f_2 = \frac{\pi}{2}\frac{n_{\mathrm{HF}}e^2}{m^*},$$

Optical Conductivity: Details

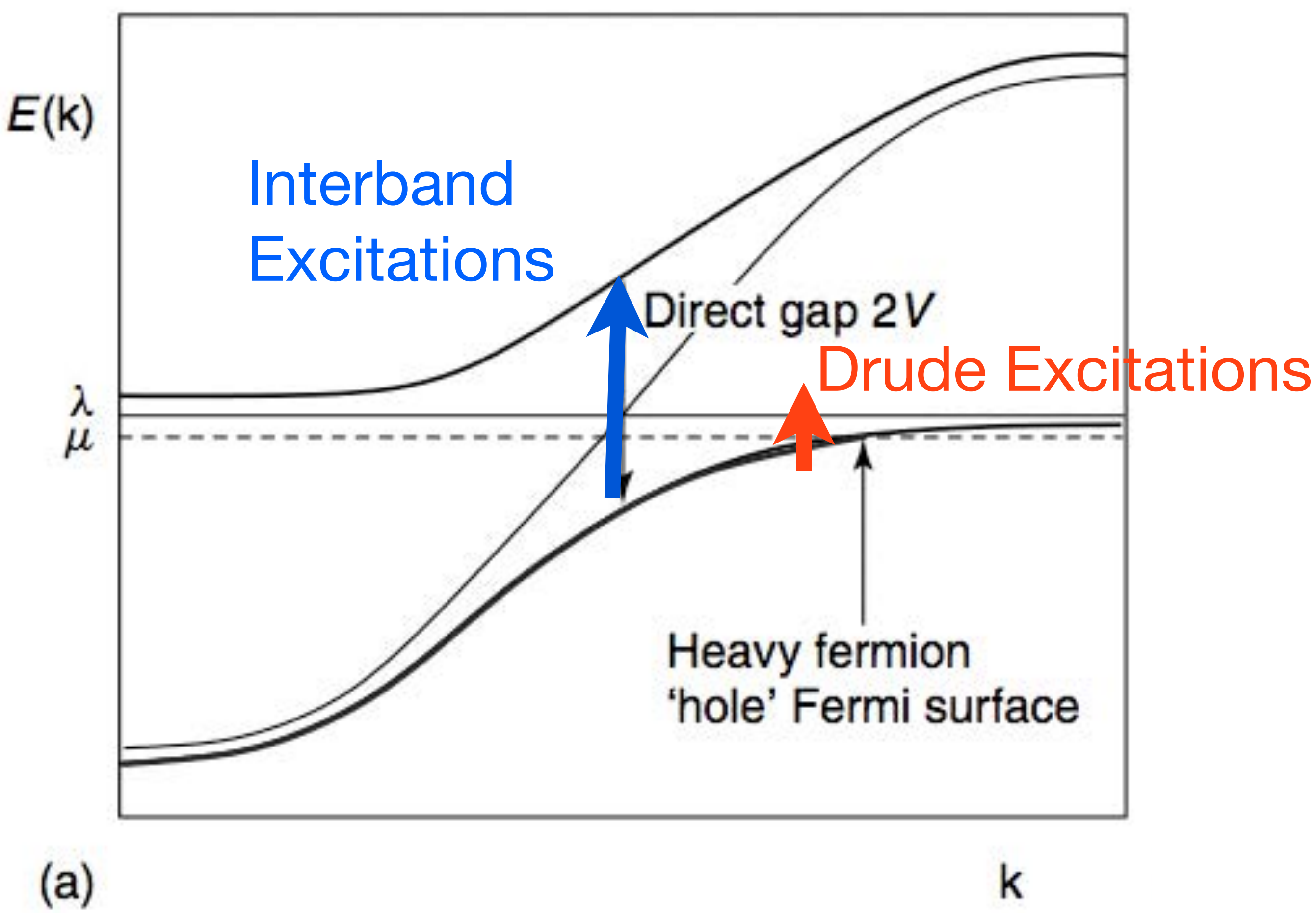


Optical Conductivity: Details



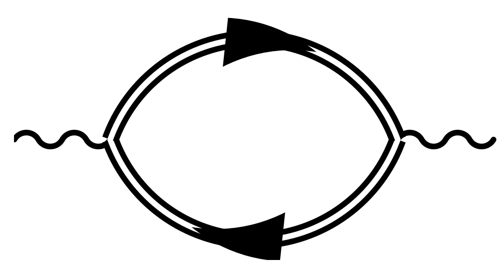
$$\vec{j} = e \sum_{\mathbf{k}\sigma} \vec{\nabla}_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$

Optical Conductivity: Details



$$\vec{j} = e \sum_{\mathbf{k}\sigma} \vec{\nabla}_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$

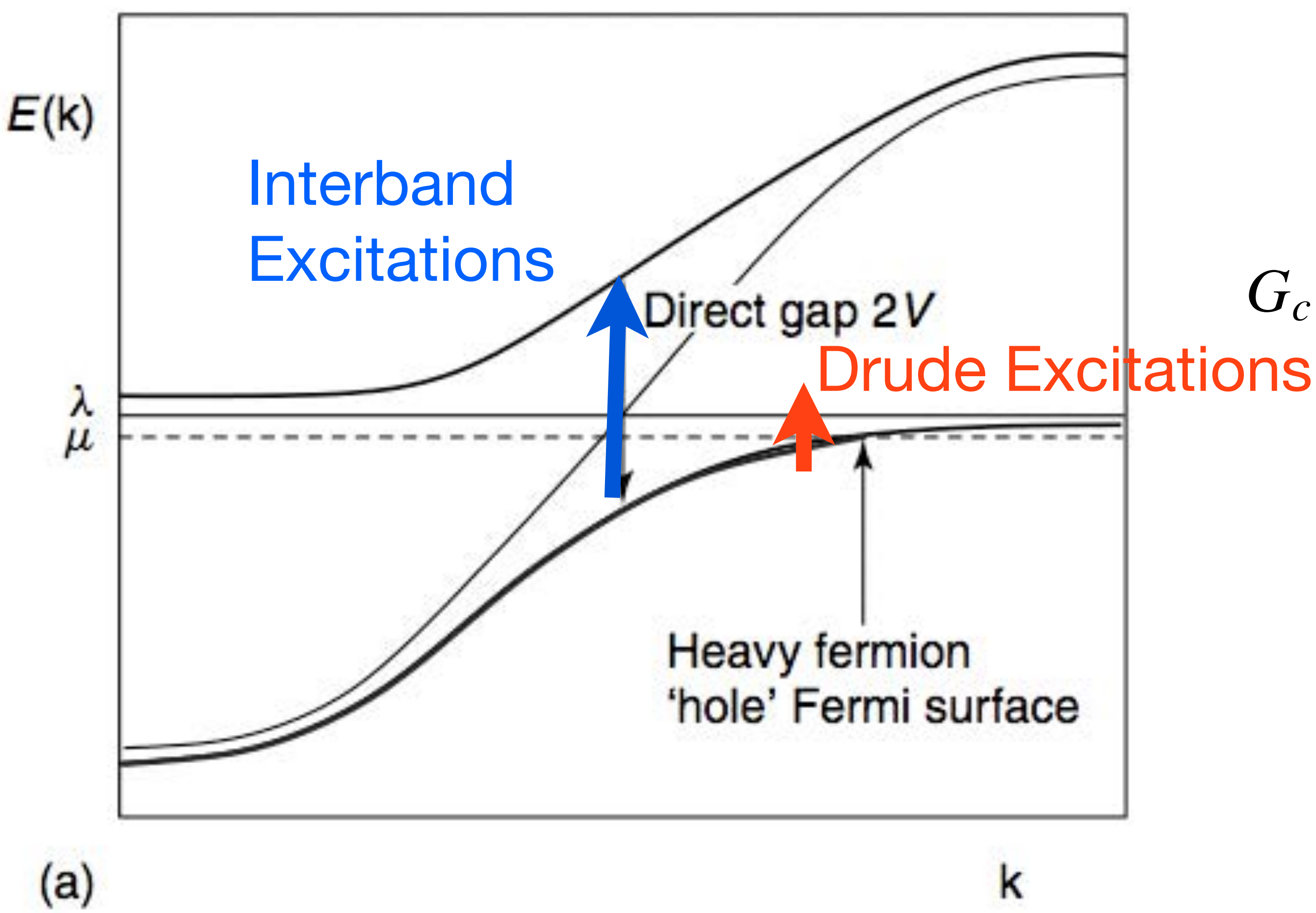
$$\sigma(i\nu_n)\delta_{ab} = -\frac{e^2}{\nu_n}\Big[\, a$$



$$b \,\Big]_0^{i\nu_n}$$

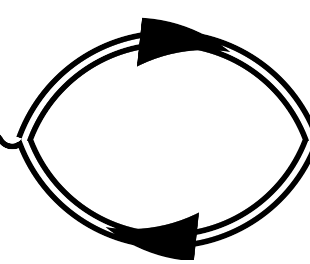
$$= -\frac{e^2}{\nu_n}\left[T \sum_{\kappa=(\mathbf{k}, i\omega_r)} \Big(\nabla_a \epsilon_{\mathbf{k}} \nabla_b \epsilon_{\mathbf{k}} G_c(\mathbf{k}, i\omega_r + i\nu_n) G_c(\mathbf{k}, i\omega_r) \Big) - (i\nu_n \to 0) \right].$$

Optical Conductivity: Details



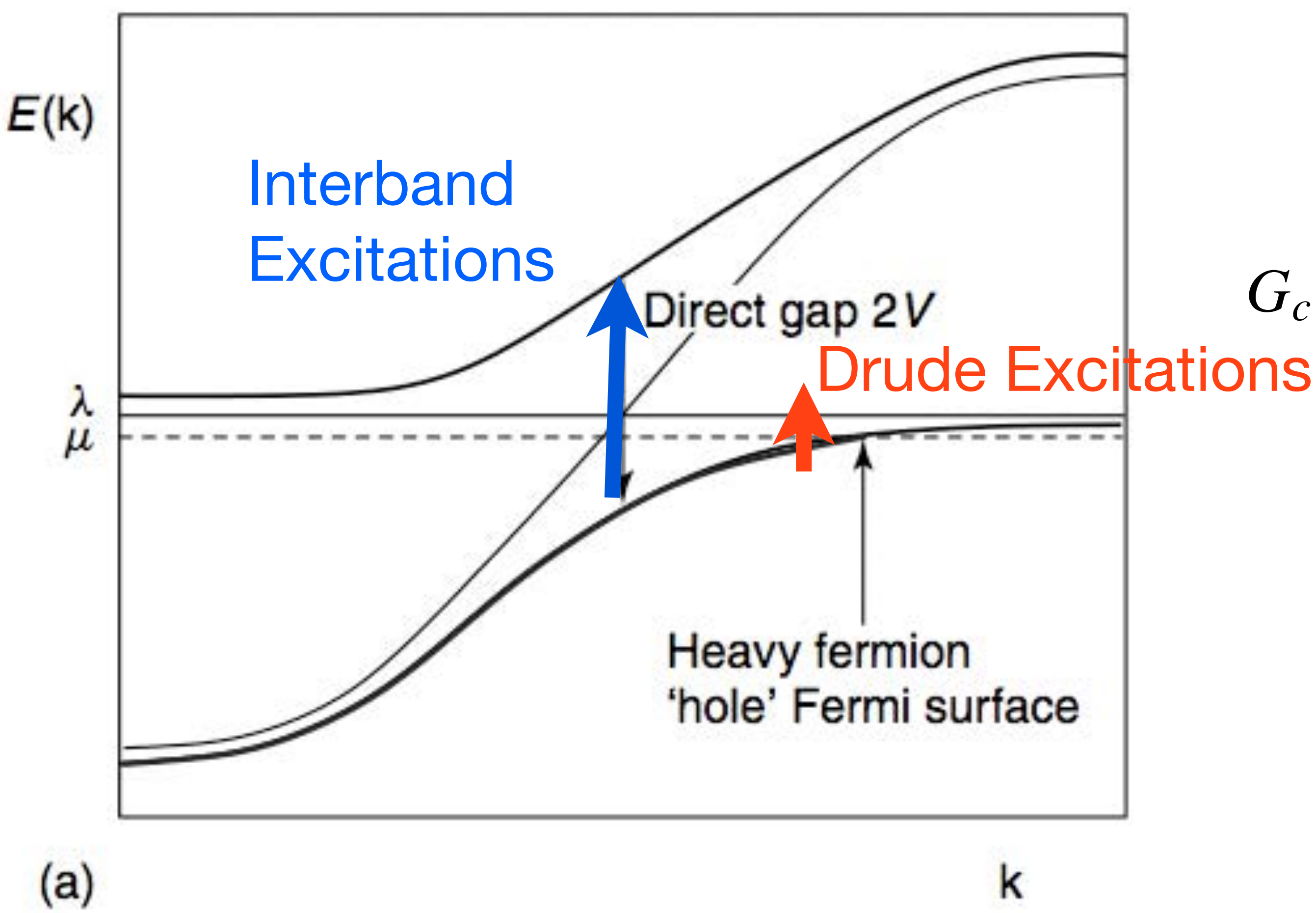
$$\vec{j} = e \sum_{\mathbf{k}\sigma} \vec{\nabla}_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$

$$G_c(\mathbf{k}, i\omega_n) = \frac{1}{i\tilde{\omega}_n - \epsilon_{\mathbf{k}} - \Sigma_c(i\tilde{\omega}_n)}, \qquad \Sigma_c(z) = \frac{V^2}{i\omega_n - \lambda}$$

$$\sigma(i\nu_n)\delta_{ab} = -\frac{e^2}{\nu_n}\Big[\, a \sim$$

$$\sim b \,\Big]_0^{i\nu_n}$$

$$= -\frac{e^2}{\nu_n}\left[T \sum_{\kappa=(\mathbf{k}, i\omega_r)} \left(\nabla_a \epsilon_{\mathbf{k}} \nabla_b \epsilon_{\mathbf{k}} G_c(\mathbf{k}, i\omega_r + i\nu_n) G_c(\mathbf{k}, i\omega_r) \right) - (i\nu_n \to 0) \right].$$

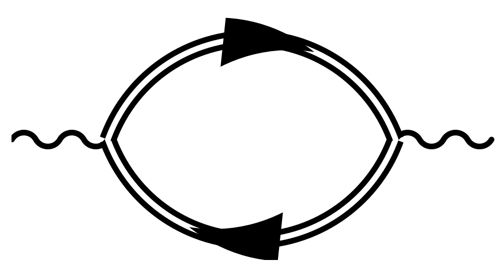
Optical Conductivity: Details



$$\vec{j} = e \sum_{\mathbf{k}\sigma} \vec{\nabla}_{\mathbf{k}} \epsilon_{\mathbf{k}} c^{\dagger}{}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$

$$G_c(\mathbf{k}, i\omega_n) = \frac{1}{i\tilde{\omega}_n - \epsilon_{\mathbf{k}} - \Sigma_c(i\tilde{\omega}_n)}, \qquad \Sigma_c(z) = \frac{V^2}{i\omega_n - \lambda}$$

$$i\tilde{\omega}_n = i\omega_n + i\mathrm{sgn}(\omega_n)\frac{\Gamma}{2}$$

$\sigma(i\nu_n)\delta_{ab} = -\dfrac{e^2}{\nu_n}\Big[\, a$  $b\,\Big]_0^{i\nu_n}$

$$= -\frac{e^2}{\nu_n}\left[T \sum_{\kappa=(\mathbf{k}, i\omega_r)} \Big(\nabla_a \epsilon_{\mathbf{k}} \nabla_b \epsilon_{\mathbf{k}} G_c(\mathbf{k}, i\omega_r + i\nu_n) G_c(\mathbf{k}, i\omega_r) \Big) - (i\nu_n \to 0) \right].$$

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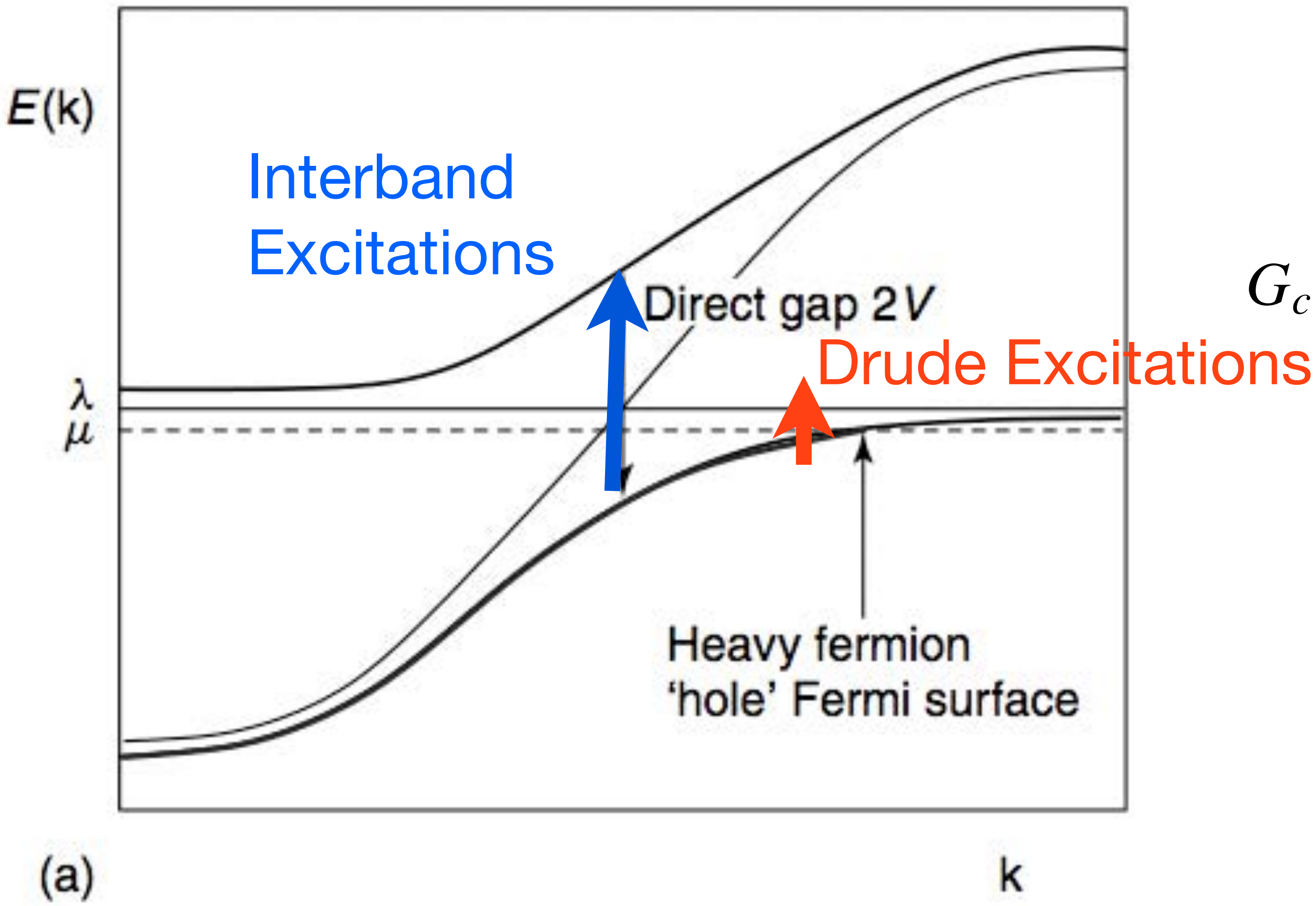

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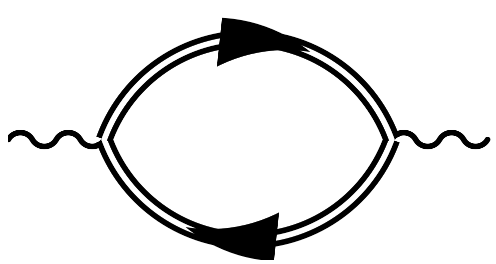

$$= -\frac{e^2}{\nu_n}\left[T \sum_{\kappa=(\mathbf{k}, i\omega_r)} \left(\nabla_a \epsilon_{\mathbf{k}} \nabla_b \epsilon_{\mathbf{k}} G_c(\mathbf{k}, i\omega_r + i\nu_n) G_c(\mathbf{k}, i\omega_r) \right) - (i\nu_n \to 0)\right].$$

$$\sigma(i\nu_n) = -\left(\frac{ne^2}{m}\right)\frac{1}{\nu_n}\left[T \sum_{i\omega_r} \int_{-\infty}^{\infty} \frac{d\epsilon}{(i\tilde{\omega}_r^+ - \epsilon - \Sigma_c(i\omega_r^+))(i\tilde{\omega}_r^- - \epsilon - \Sigma_c(i\omega_r^-))} - (i\nu_n \to 0)\right]$$

Optical Conductivity: Details

$$\sigma(i\nu_n) = \left(\frac{ne^2}{m}\right)\frac{1}{\nu_n}\left[2\pi i T \sum_{|\omega_r|<\nu_n/2} \frac{1}{i\nu_n + i\Gamma - (\Sigma^+ - \Sigma^-)}\right], \qquad (\nu_n > 0)$$

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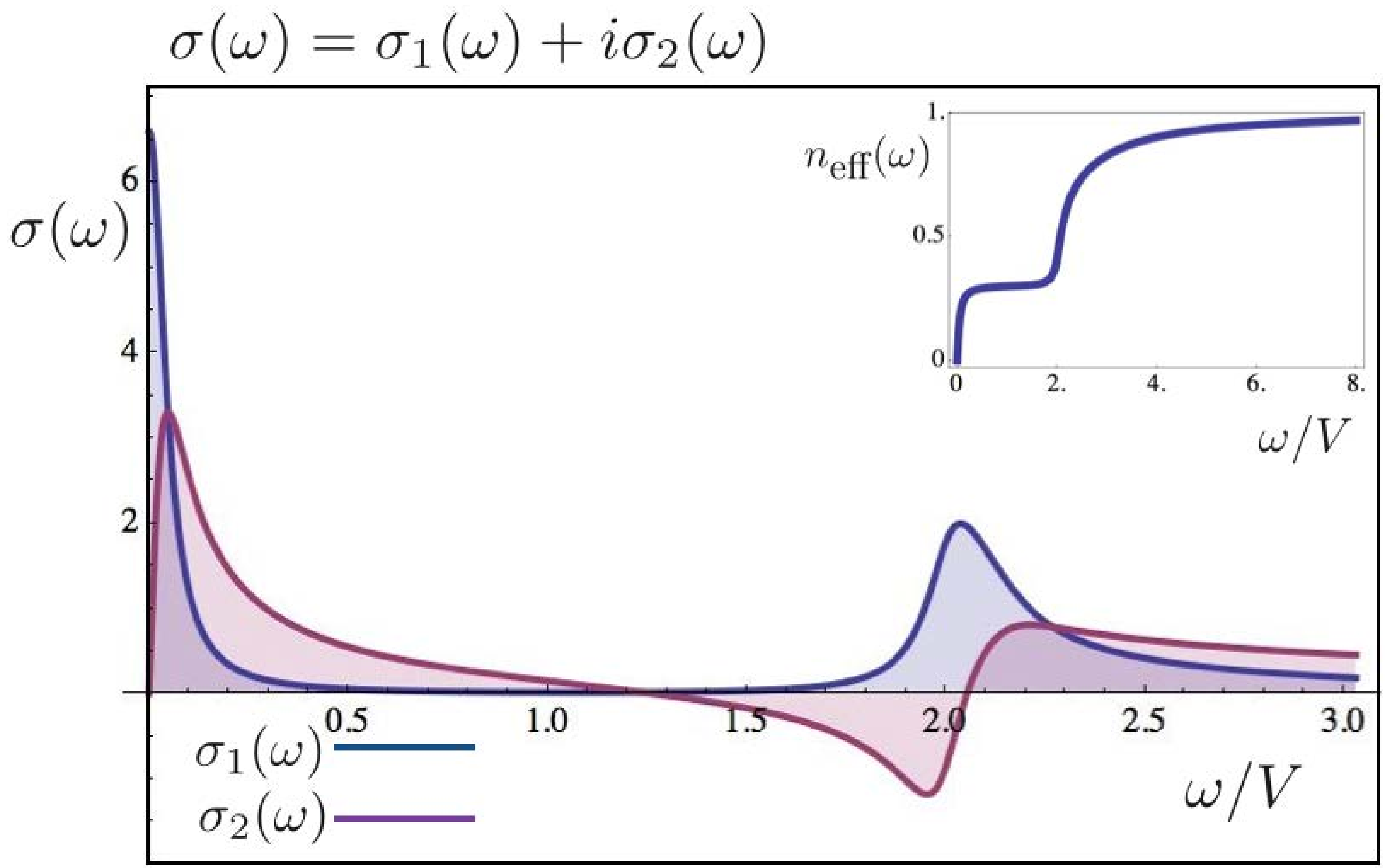
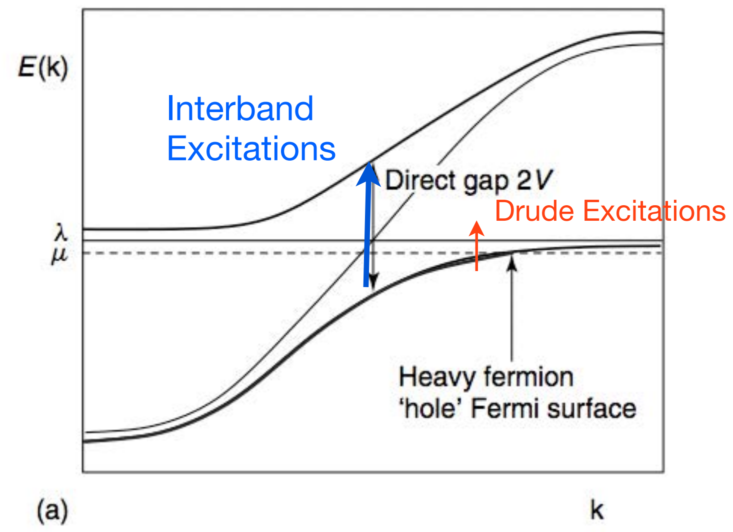
Optical Conductivity: Details





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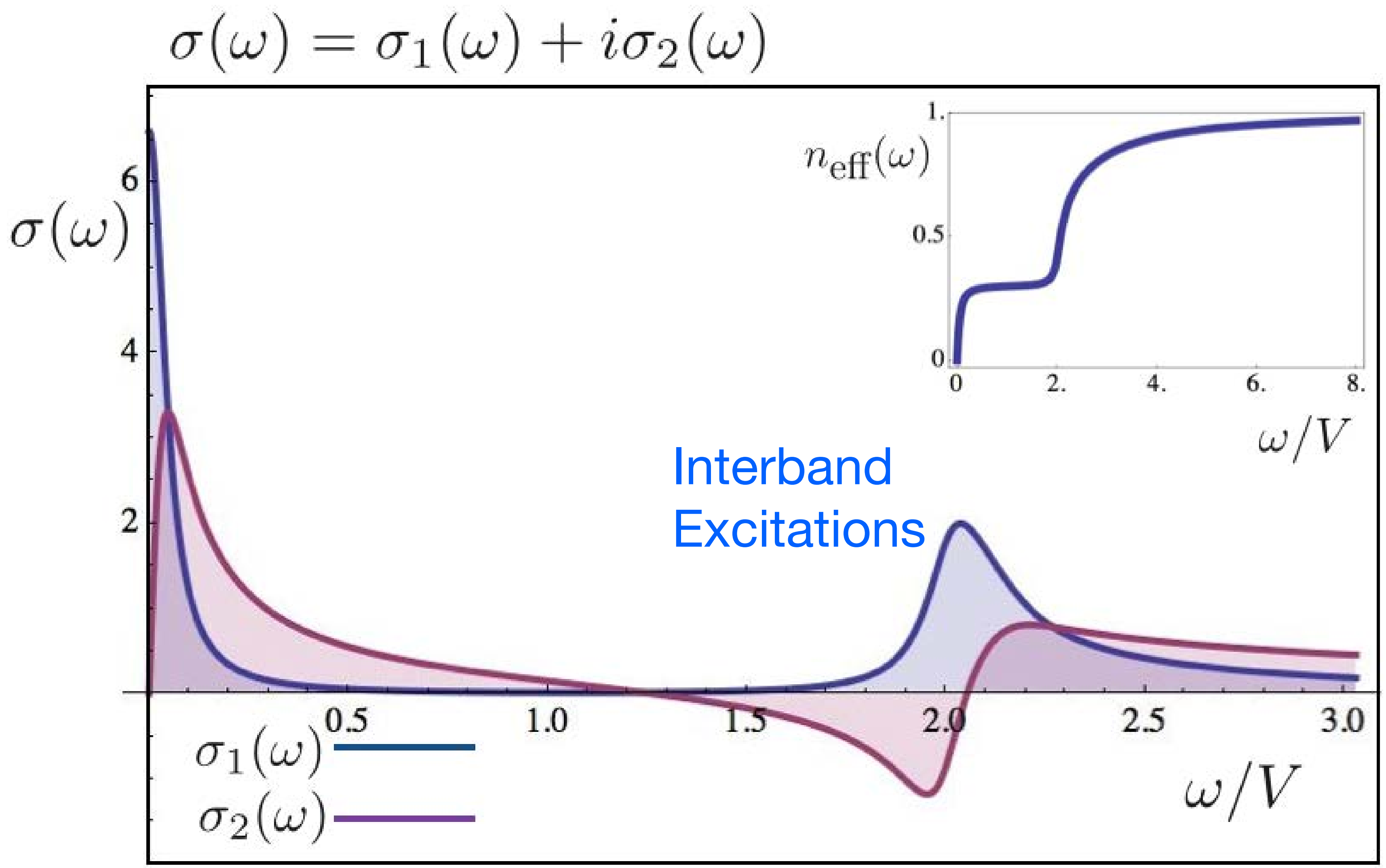

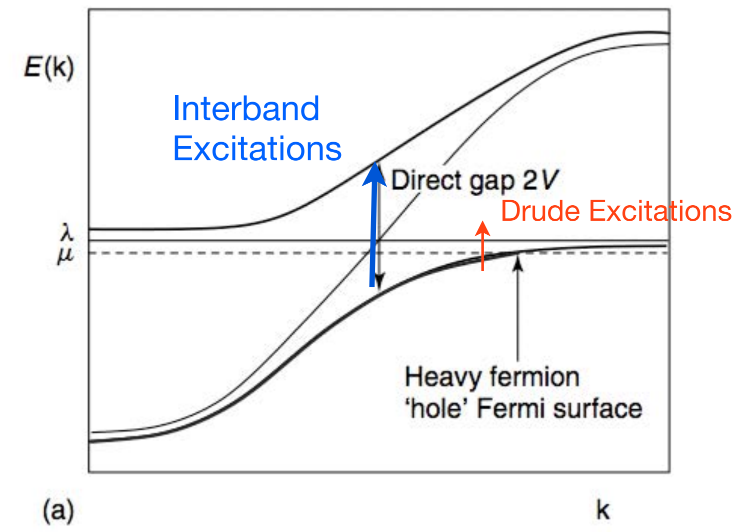

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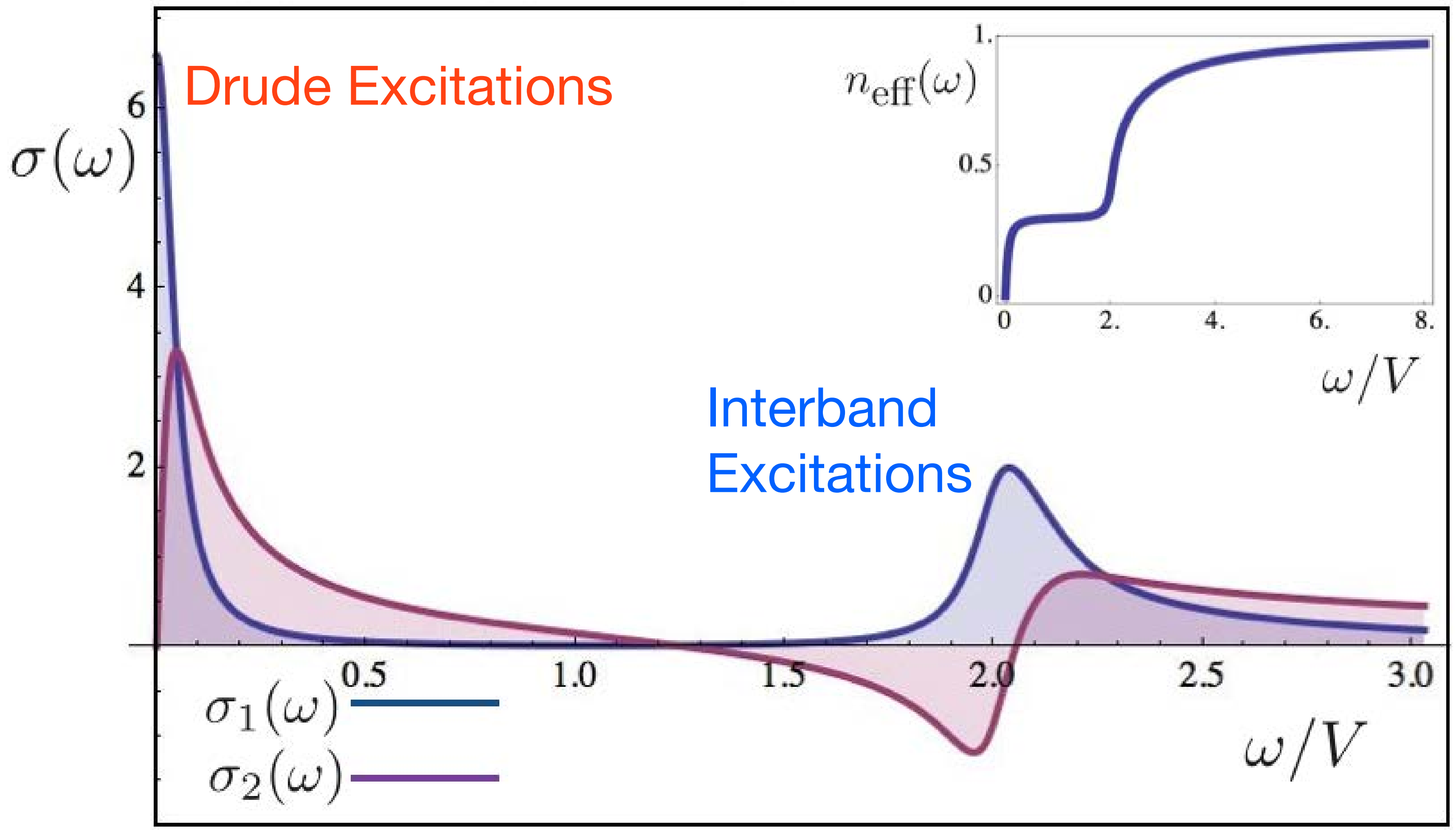
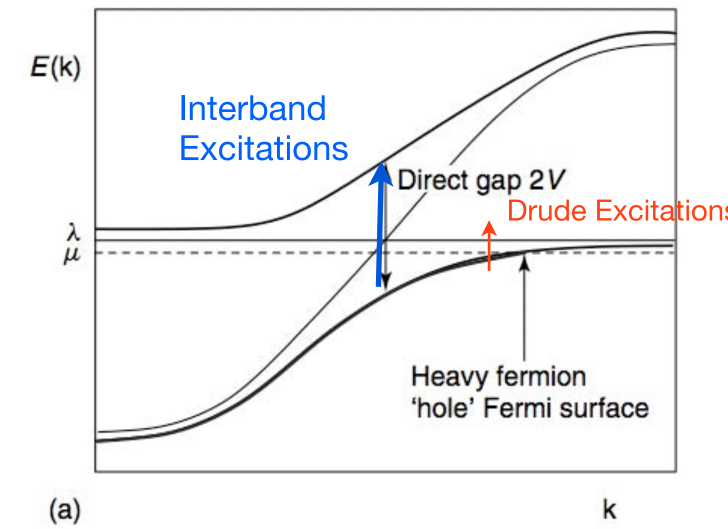
Optical Conductivity: Details

$$\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$$





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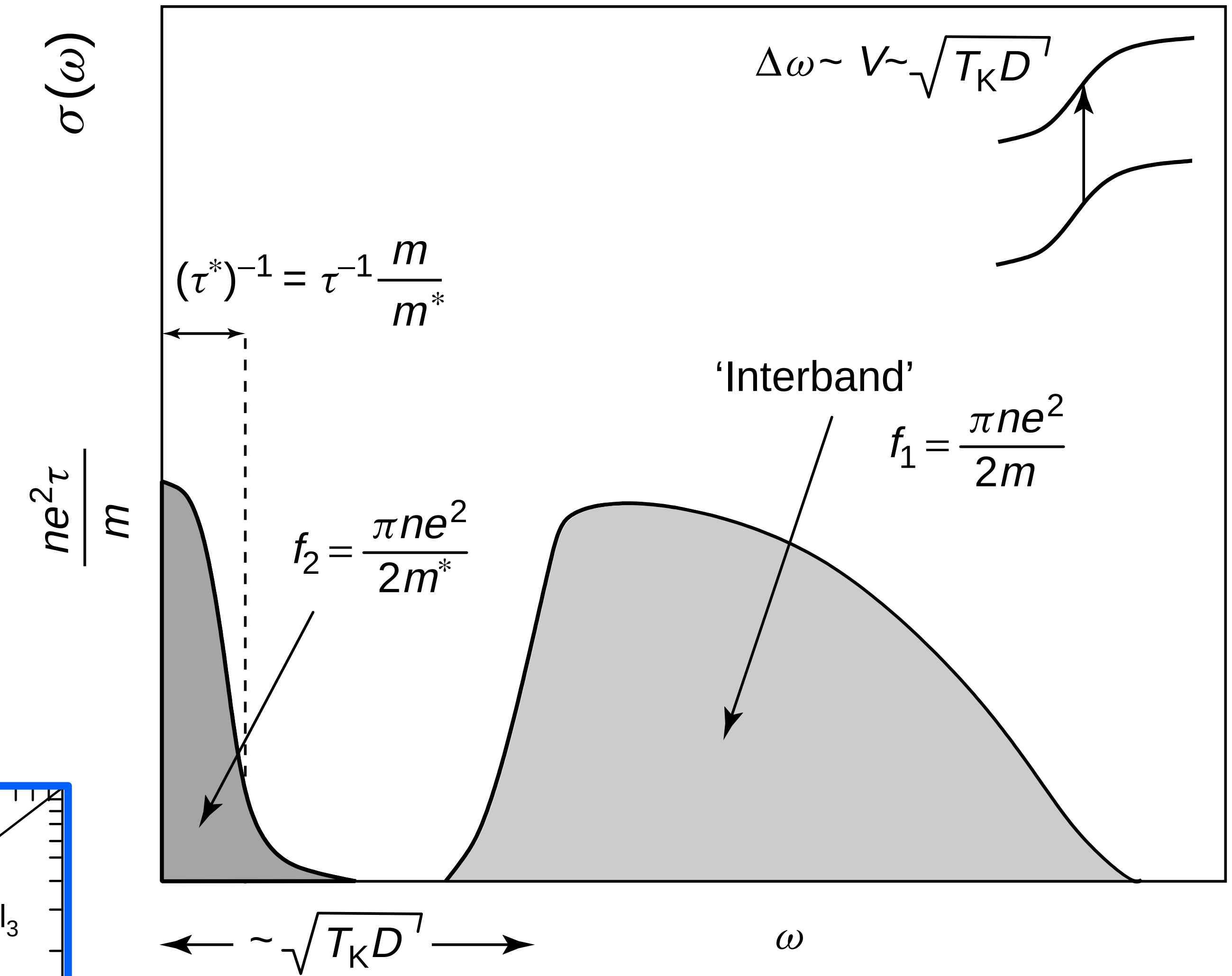
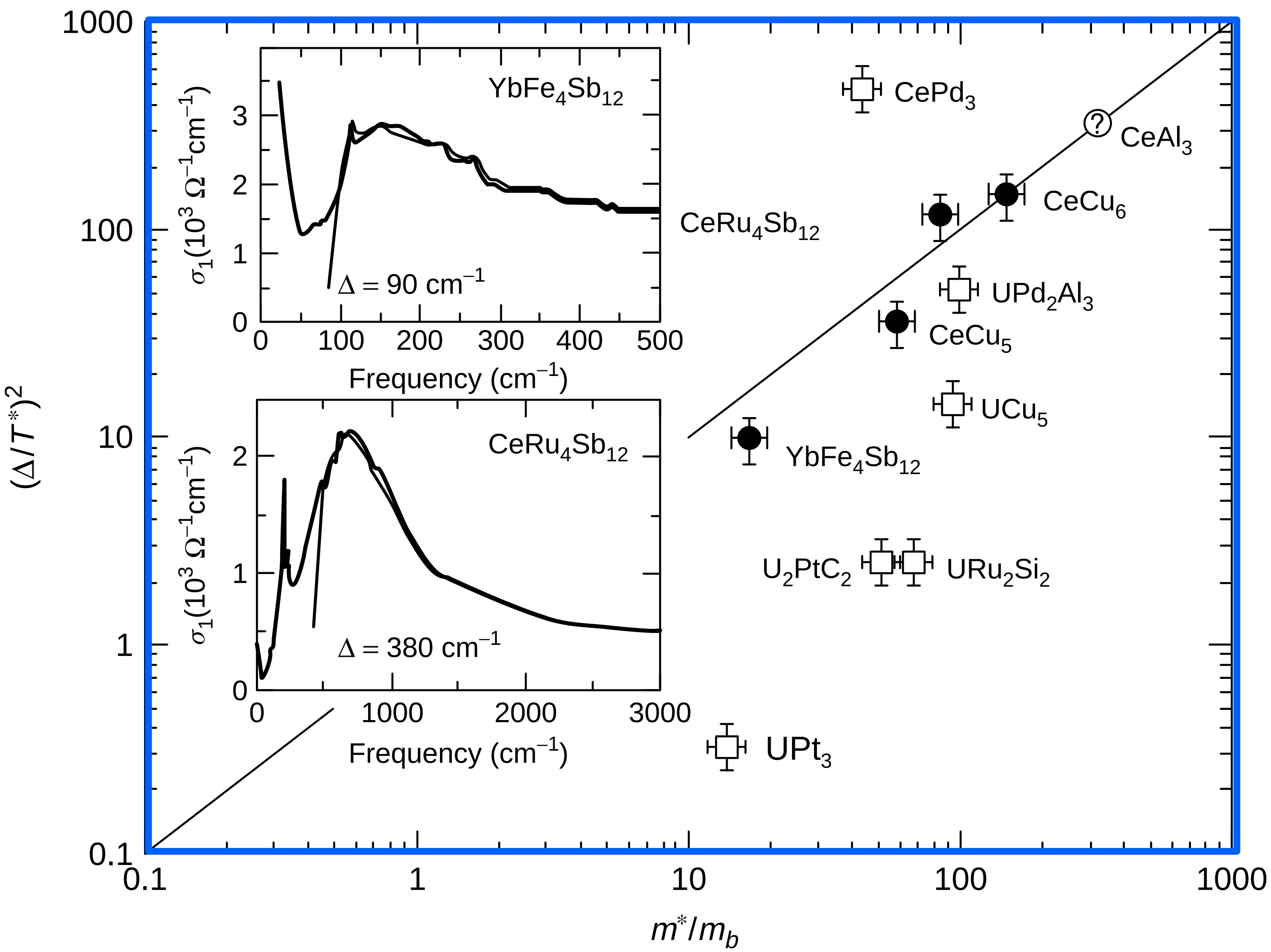
Optical Conductivity.

Millis and Lee, 1987



$$V^2/D \sim T_K \Rightarrow V \sim \sqrt{T_K D}$$

S.V. Dordevic, D.N. Basov, N.R. Dilley, E.D. Bauer, and M.B. Maple, *Phys. Rev. Lett.* **86**, 2001, 684,



$$\int_0^\infty \frac{d\omega}{\pi}\sigma(\omega) = f_1 = \frac{\pi}{2}\left(\frac{n_c e^2}{m}\right)$$

$$\int_0^{\sim V} d\omega\,\sigma(\omega) = f_2 = \frac{\pi}{2}\frac{n_{HF}e^2}{m^*}$$

Physics of Heavy Fermion Superconductivity Lecture II:

1. The large N approach to the Kondo lattice.

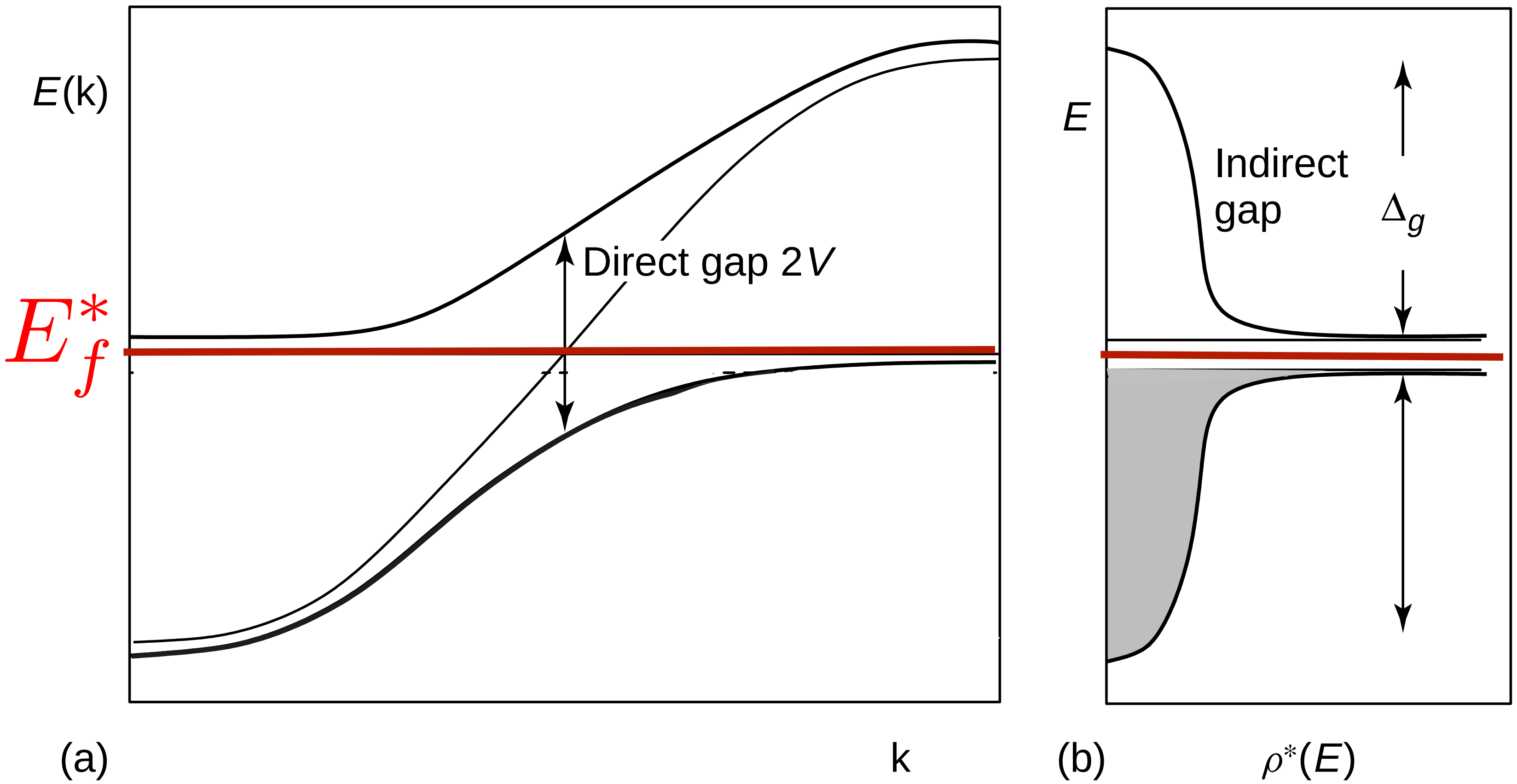
2. Heavy Fermion Metals.

3. Optical Conductivity of Heavy Fermion Metals

4. Kondo Insulators

Mott Phil Mag, 30,403,1974

“Kondo Insulator”



Mott Phil Mag, 30,403,1974

pressure are discussed. It is suggested that the low-pressure form of SmS is an excitonic insulator. In SmB_6 and high-pressure SmS a very small gap separates occupied from unoccupied states, this in our view being due to hybridization of 4f and 5d bands. The electrical properties are discussed ; if kT is greater than the gap

energy, then the gap does not affect the metallic behaviour. Finally metallic compounds such as $CeAl_3$ are described, in which there is no magnetic ordering at

MAGNETIC AND SEMICONDUCTING PROPERTIES OF SmB_6†

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and

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Department of Applied Physics, Stanford University, Stanford, California,
and Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 21 November 1968)

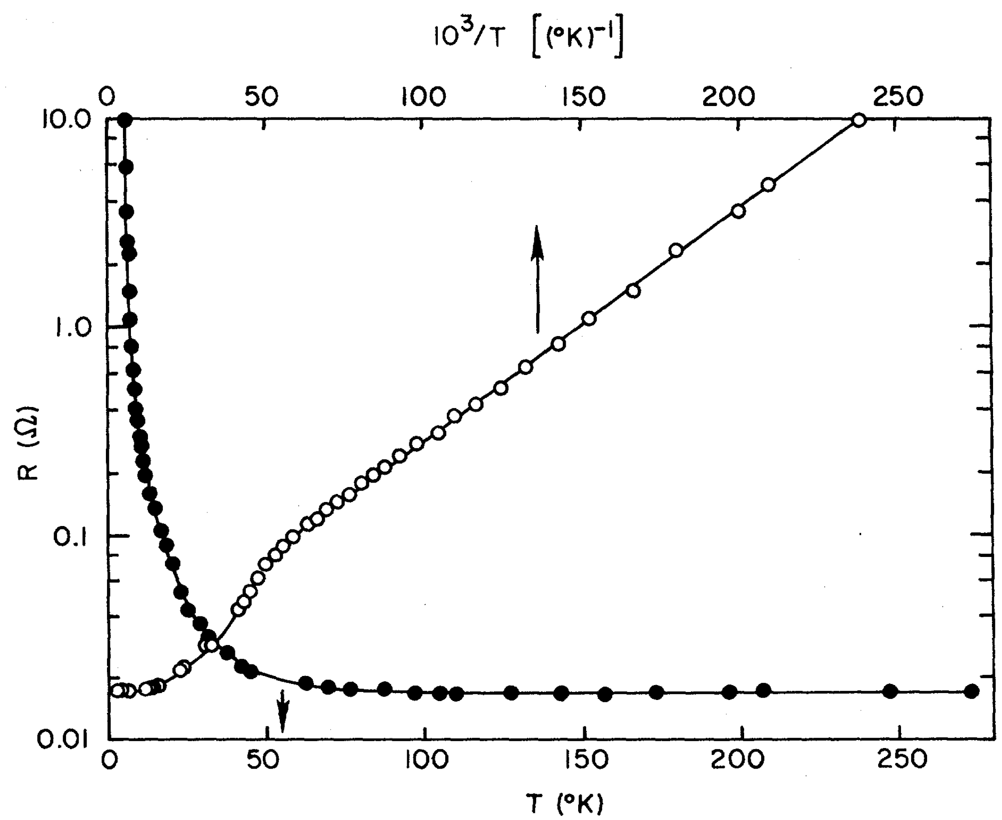

FIG. 1. Resistance of SmB_6 as a function of temperature. Closed circles: resistance versus T; open circles: resistance versus $10^3/T$.

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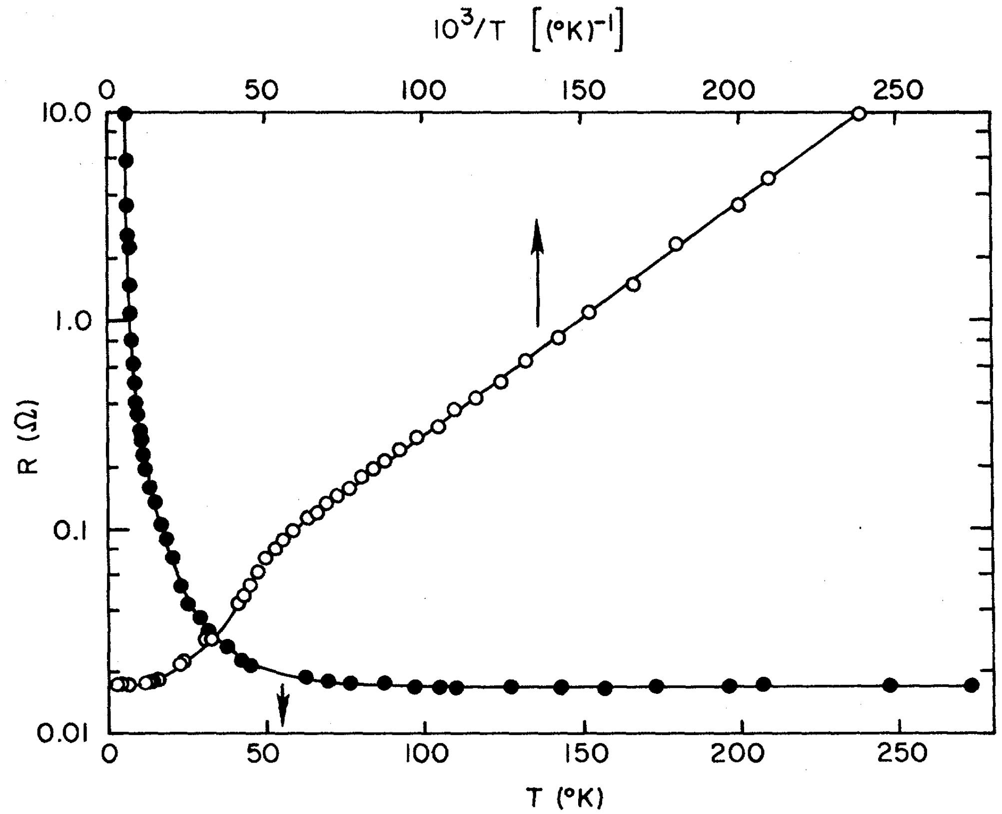

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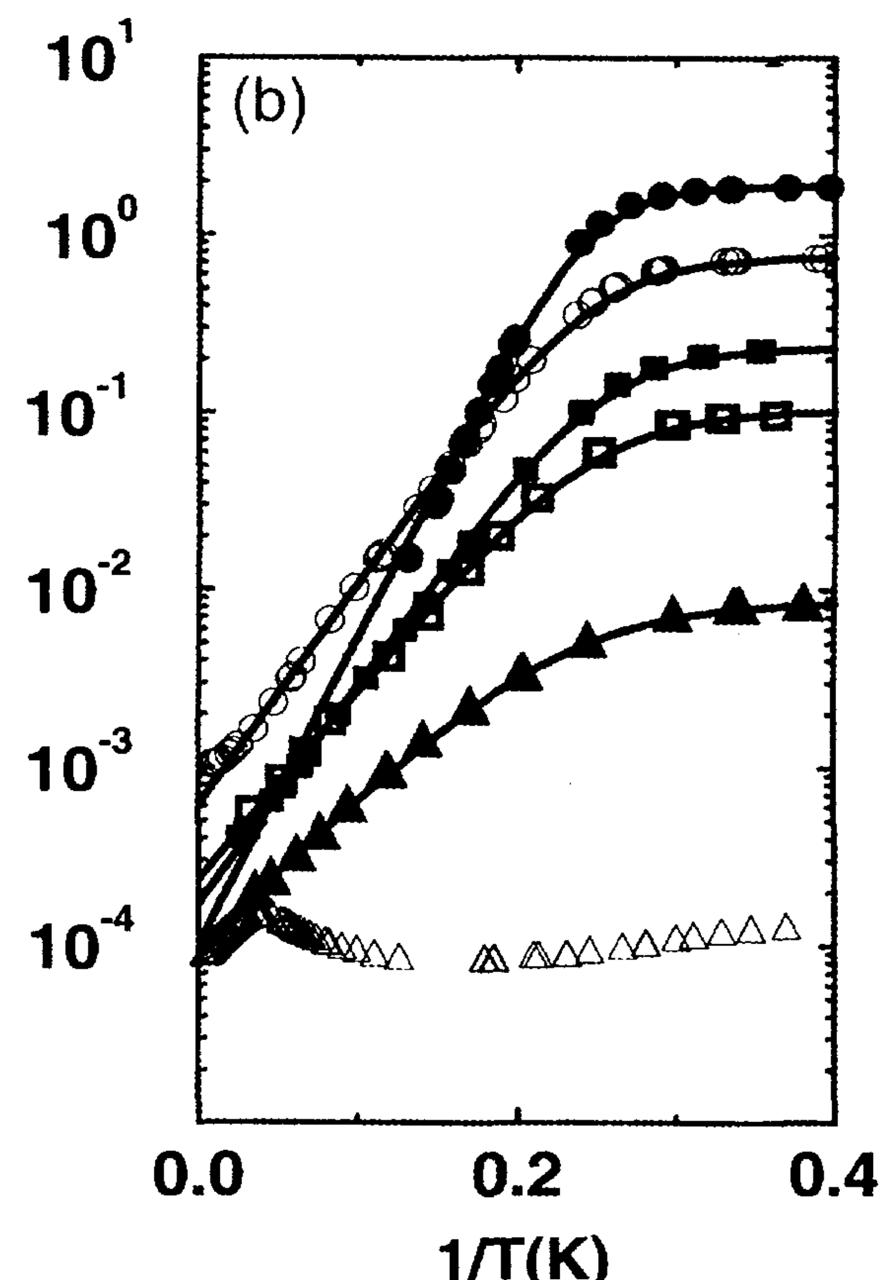
Persistent conductivity Plateau



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Frustrated magnetism: pairing of spinons SP(N).

Read and Sachdev, PRL, 66, 1773 (1991)

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SP(N):	$\bar{q}q$	$q_a q_{-a}$

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"Symplectic Large N" R. Flint and PC '08

$$S^{ba} = f^\dagger_b f_a - \mathrm{sgn}(a)\mathrm{sgn}(b) f^\dagger_{-b} f_{-a}$$

SU(N):	*Mesons*	*Baryons*
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