THE KONDO LATTICE

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

T. Kasuya (1951)

- Doniach's Kondo Lattice Hypothesis
- Large Fermi Surface
- Exhaustion Myth
- Large N expansions and Gauge Theories
- Large N Expansion for the Kondo Lattice
- Conclusions and questions.

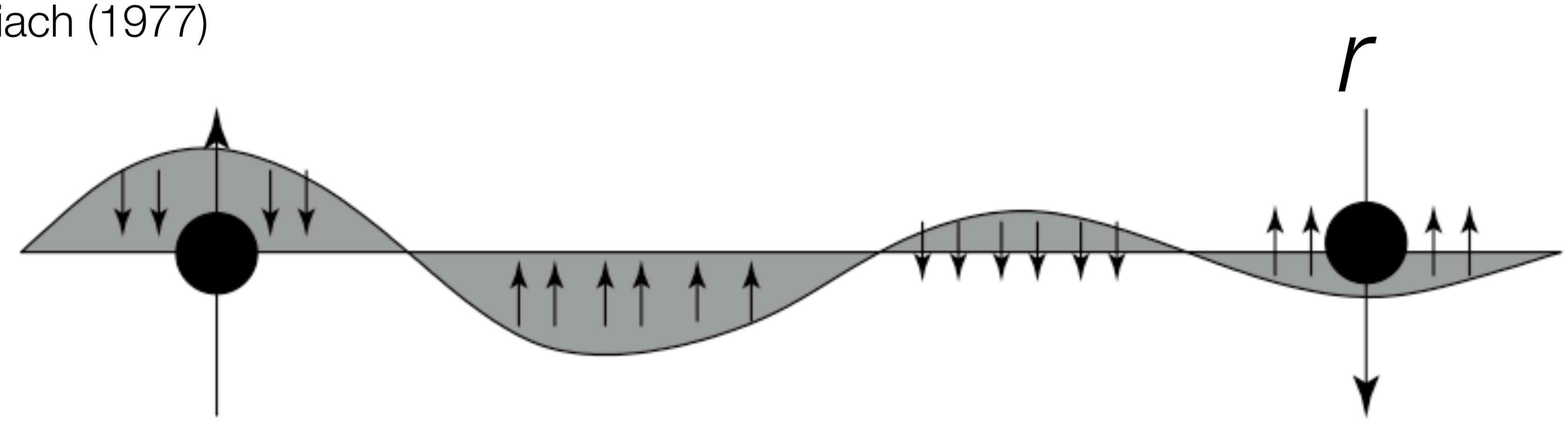
- Cotunneling and copairing

http://physics.rutgers.edu/~coleman/talks/Boulder3.pdf

DONIACH'S Hypothesis.

Doniach (1977)

Friedel Oscillations



$$\langle \vec{\sigma}(r) \rangle \sim -J\rho \frac{\cos 2k_F r}{|k_F r|^3}$$

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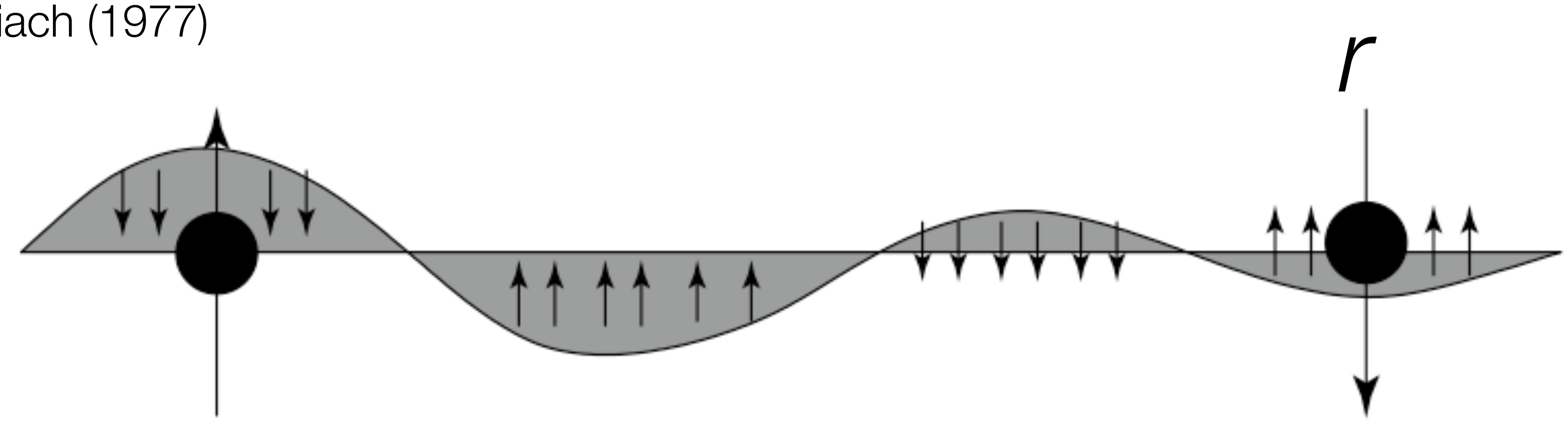

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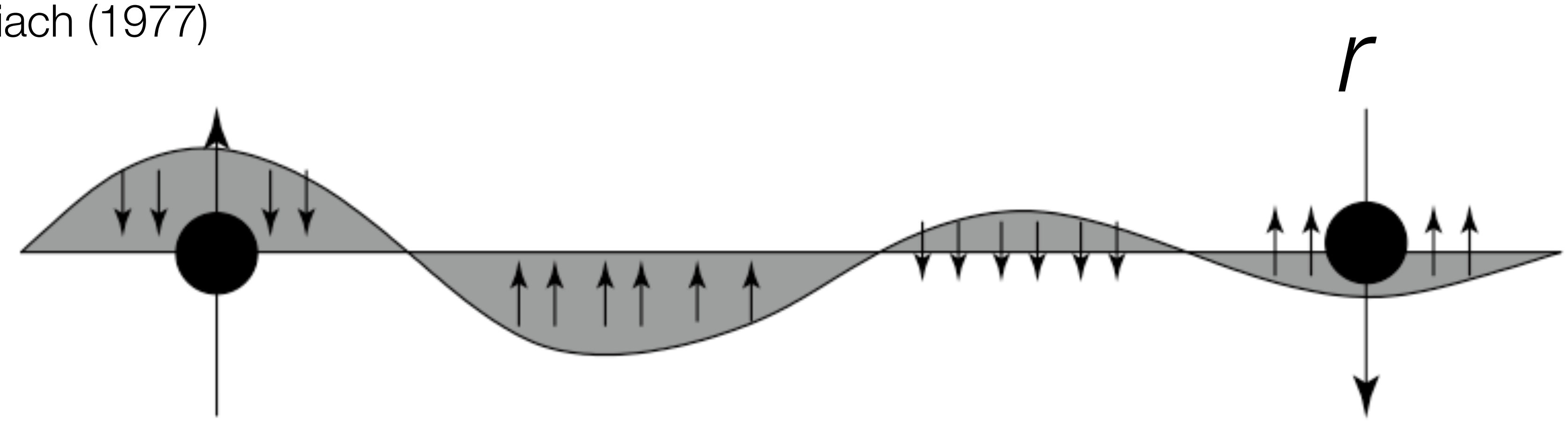

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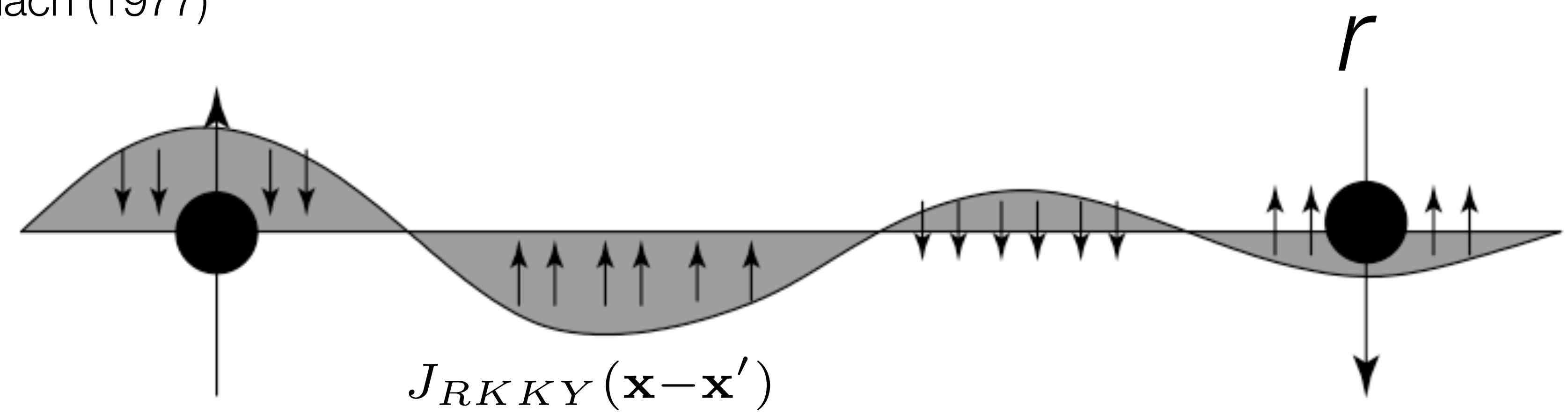

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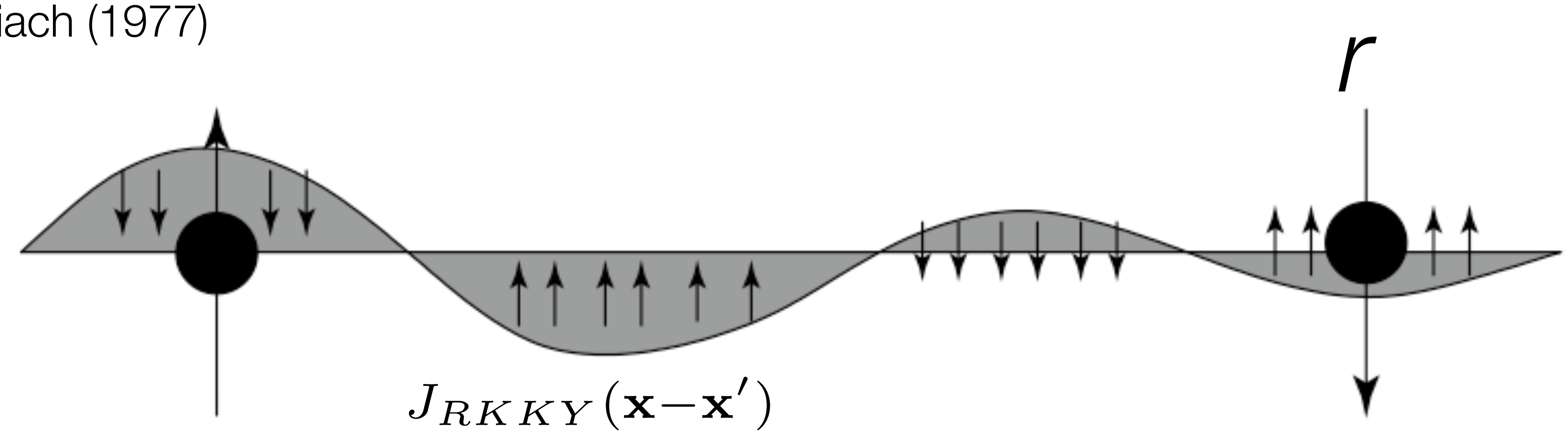

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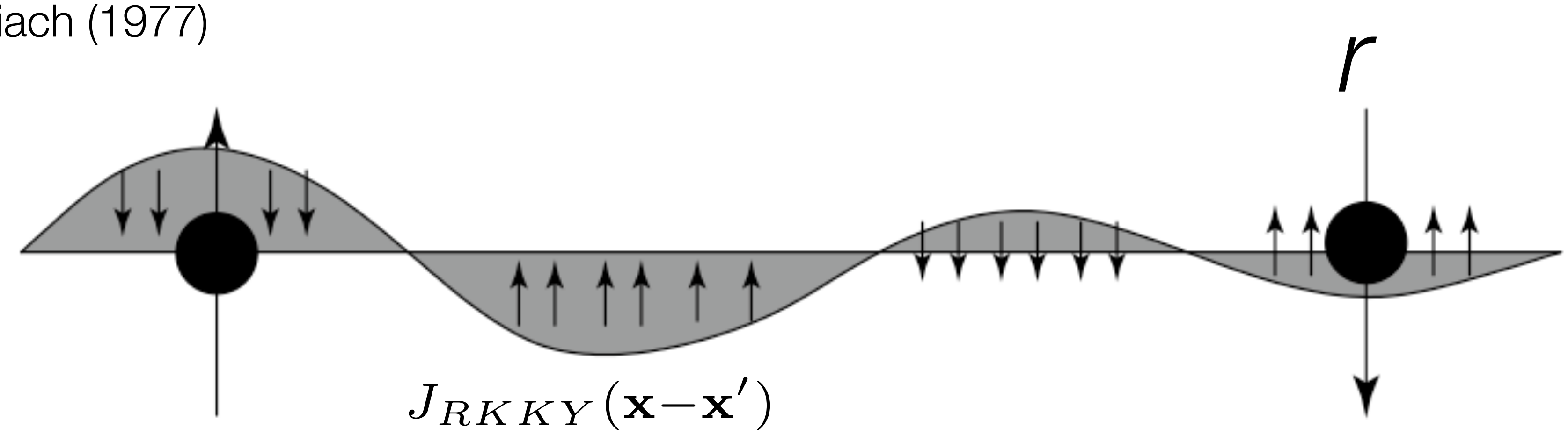

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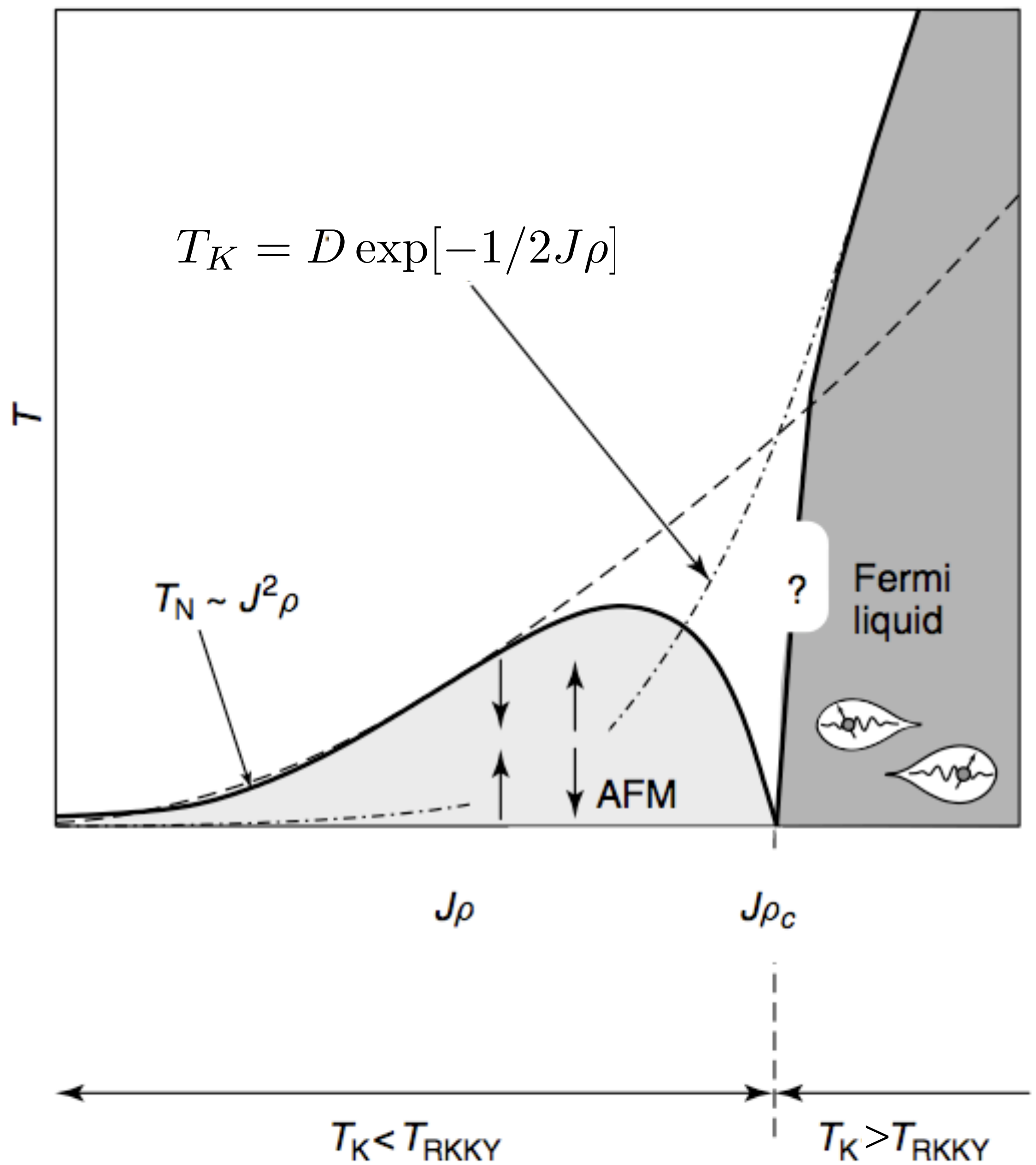

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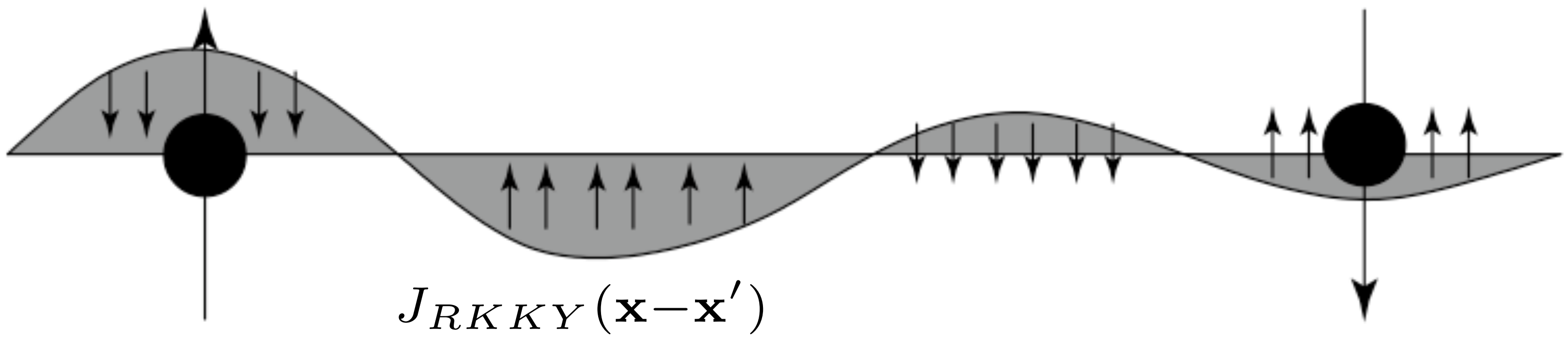

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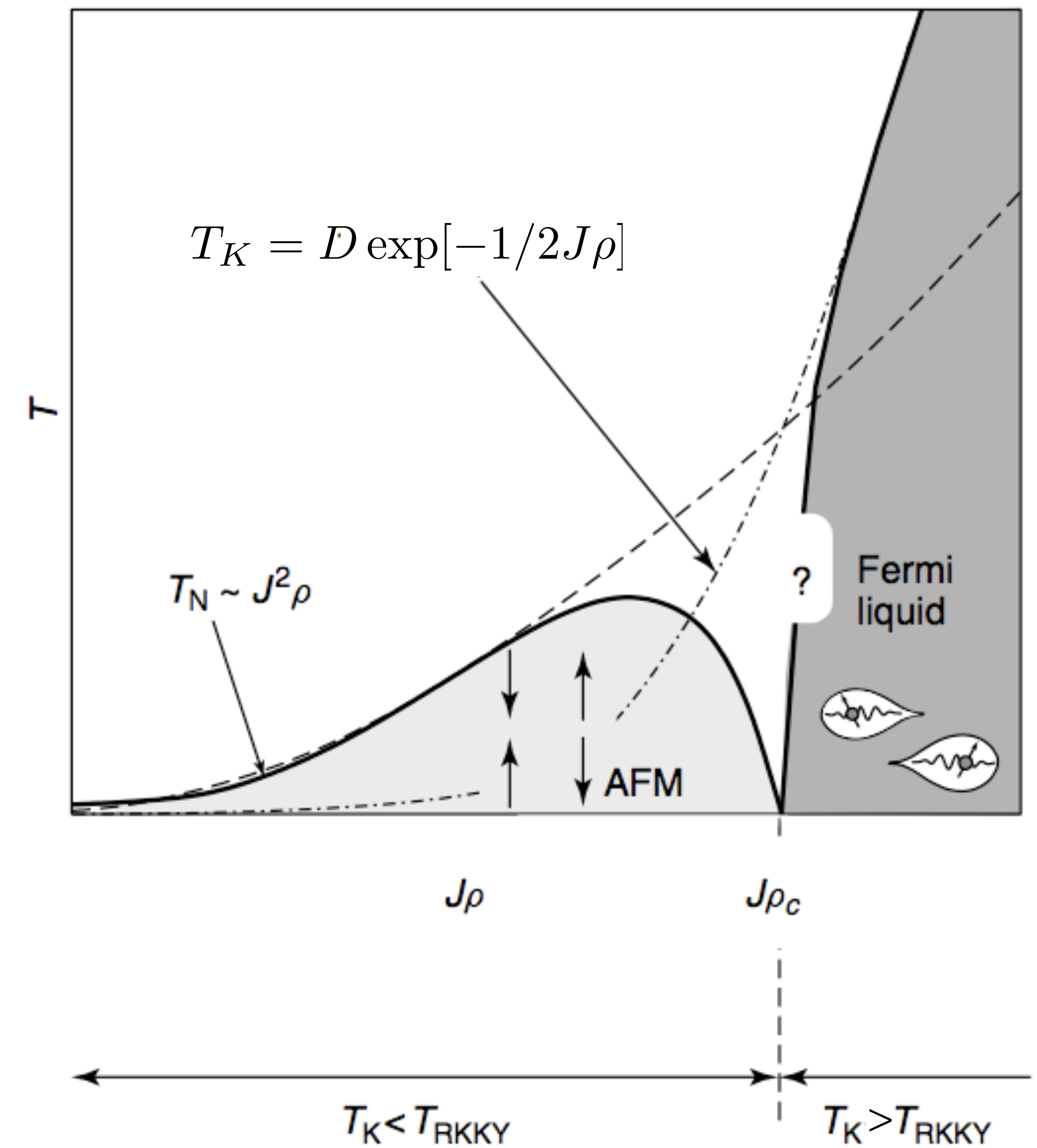
Increasing U: J ~ V²/U



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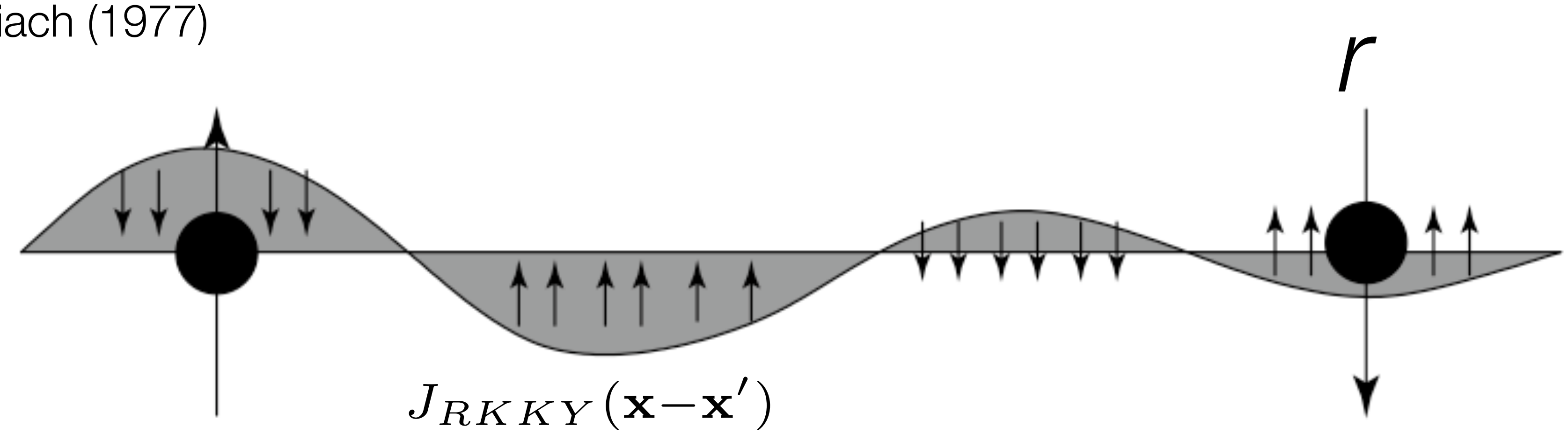

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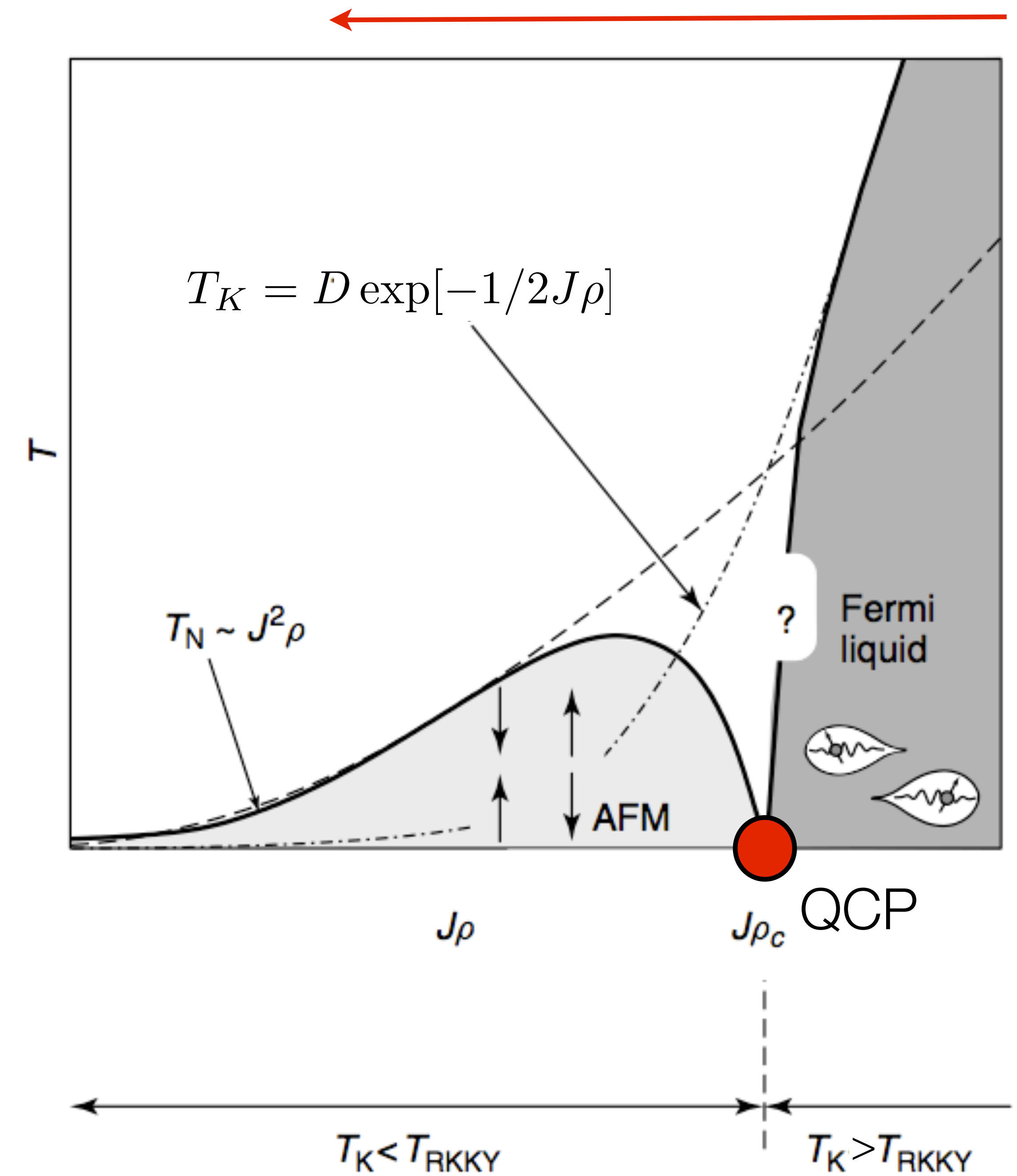
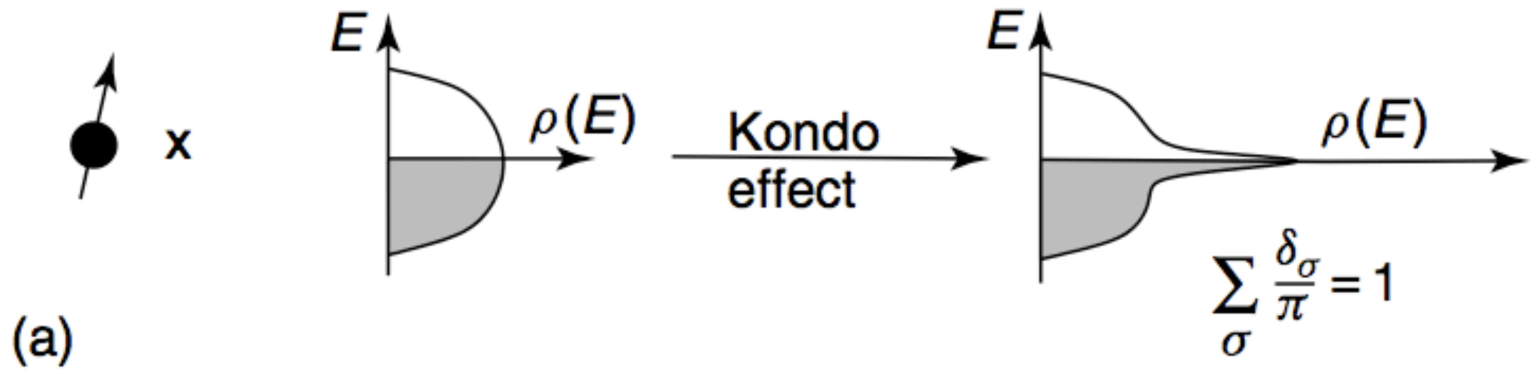


Large Fermi Surface of the Kondo Lattice.

Martin (1982)



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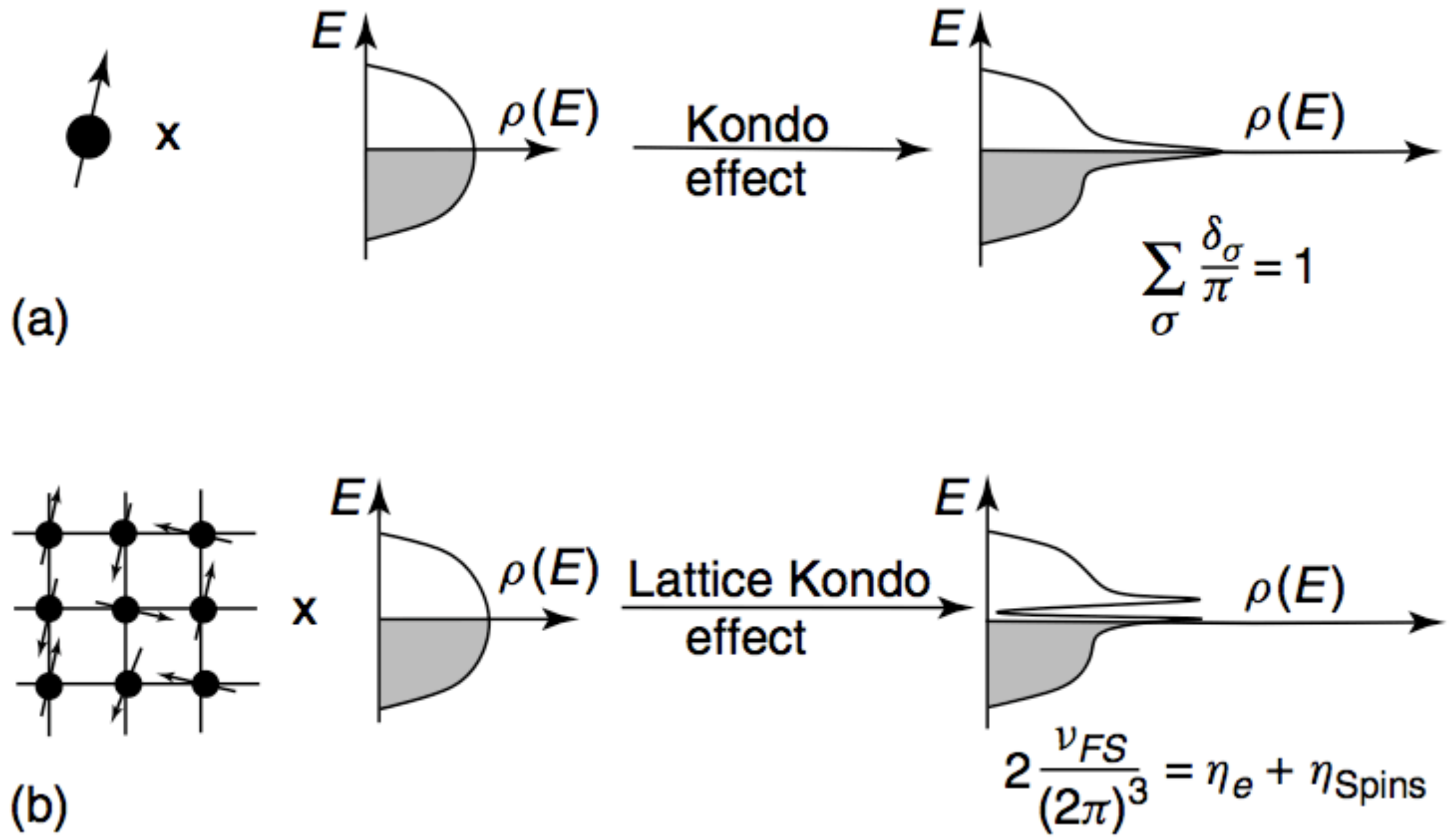

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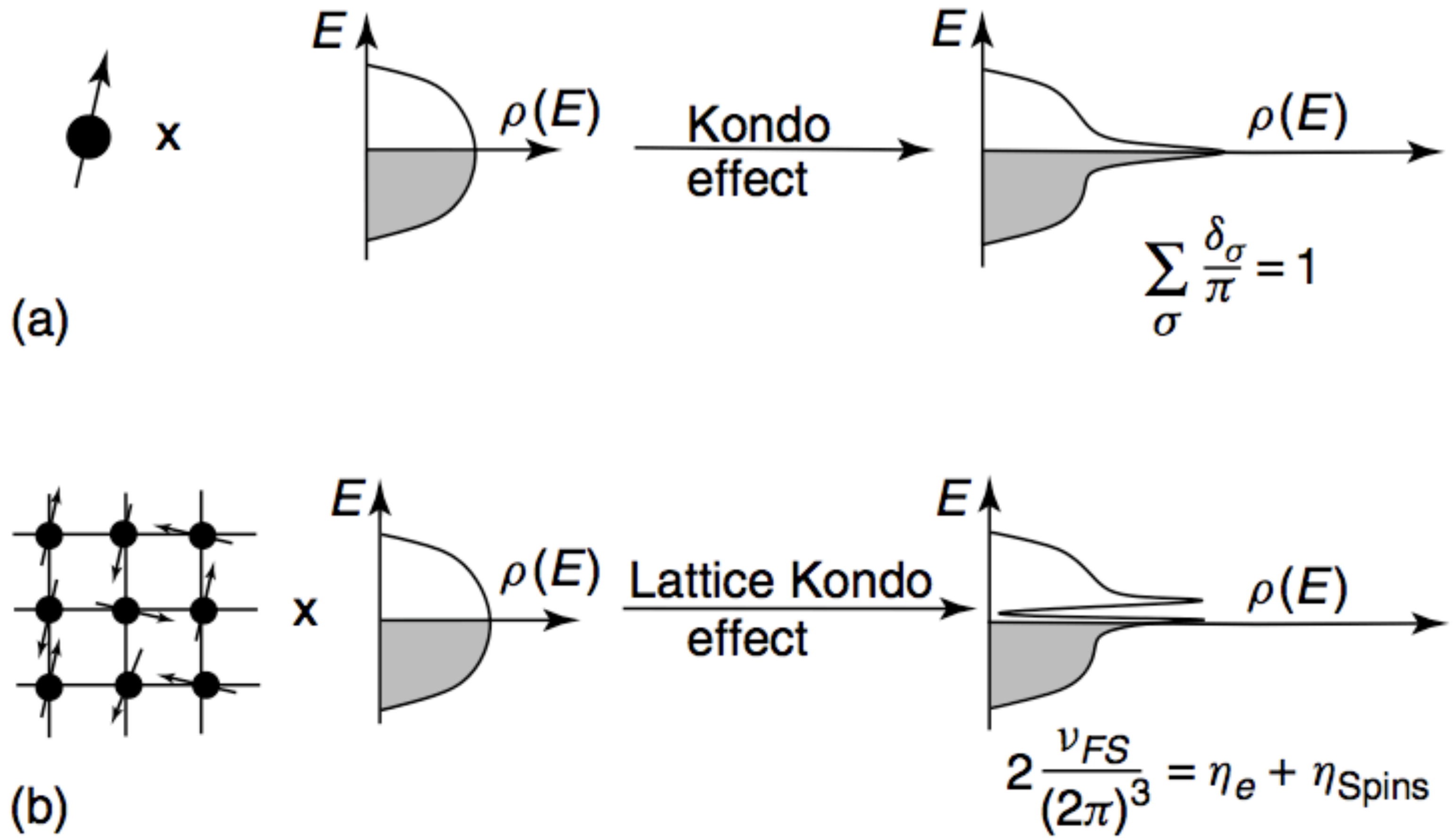


Taillefer & Lonzarich (1985)

$$f = A\left(\frac{\hbar^2}{2\pi e}\right)$$

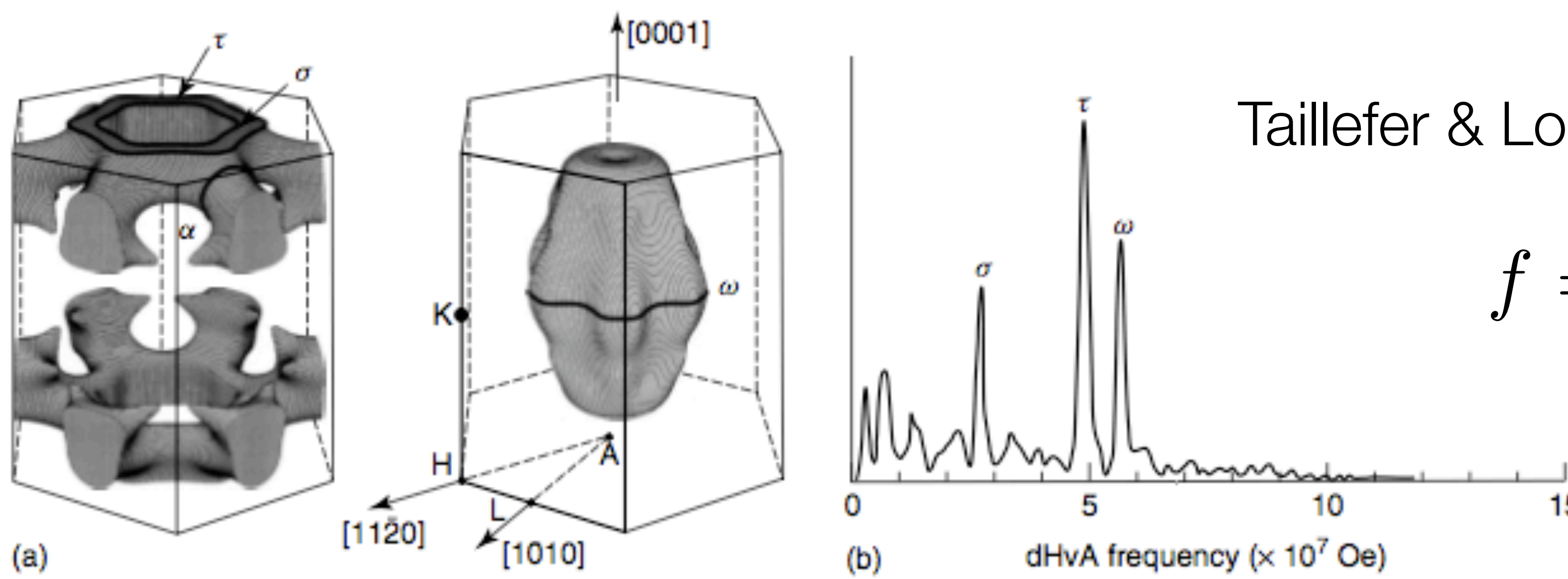
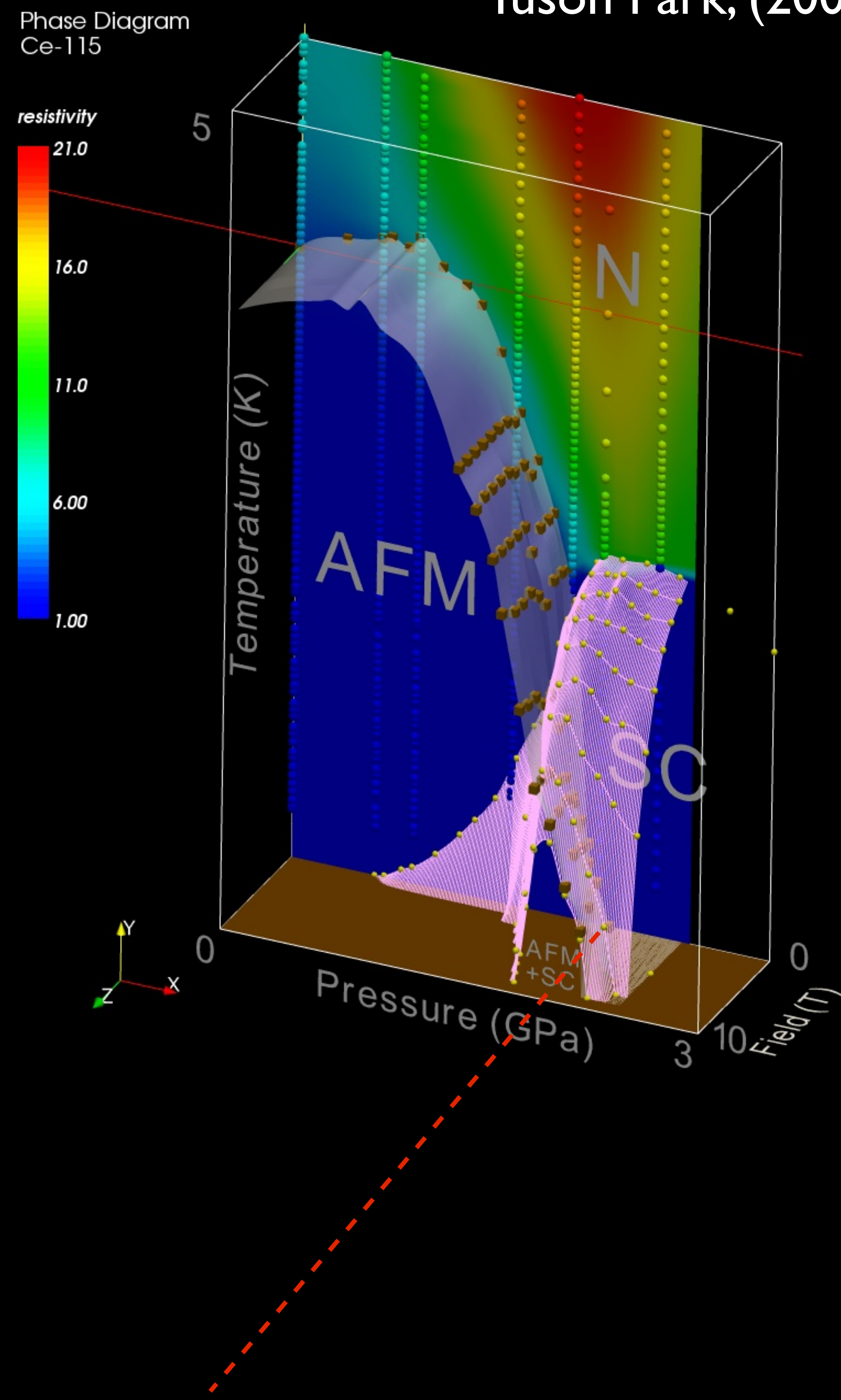


Figure 9. (a) Fermi surface of UPt_3 calculated from band theory assuming itinerant 5f electrons (Oguchi and Freeman, 1985; Wang *et al.*, 1987; Norman, Oguchi and Freeman, 1988), showing three orbits (σ, ω and τ) that are identified by dHvA measurements. (After Kimura *et al.*, 1998.) (b) Fourier transform of dHvA oscillations identifying σ, ω, and τ orbits shown in (a). (Kimura *et al.*, 1998.)

Reconstruction of the Fermi Surface and mass divergence

Tuson Park, (2007).



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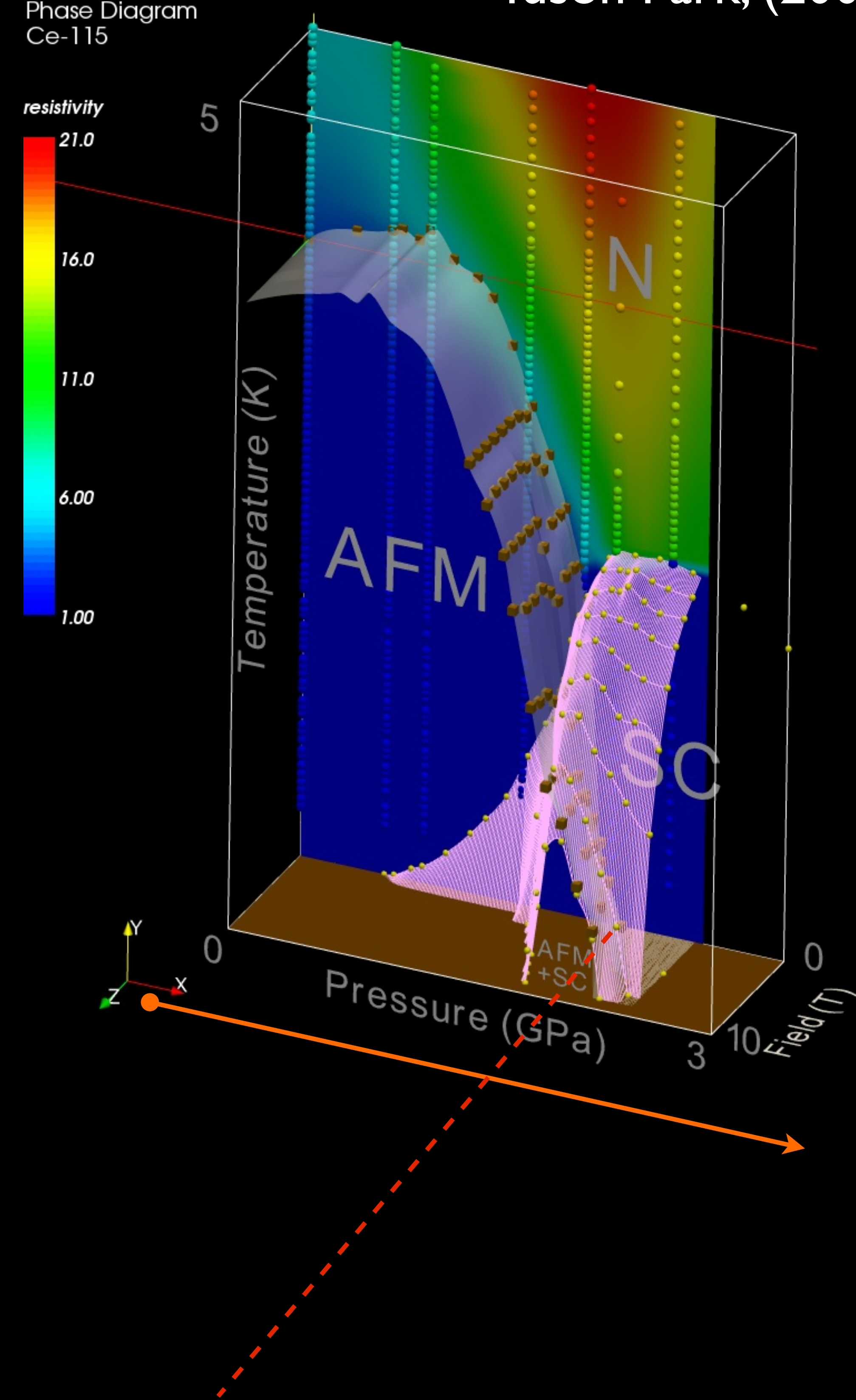

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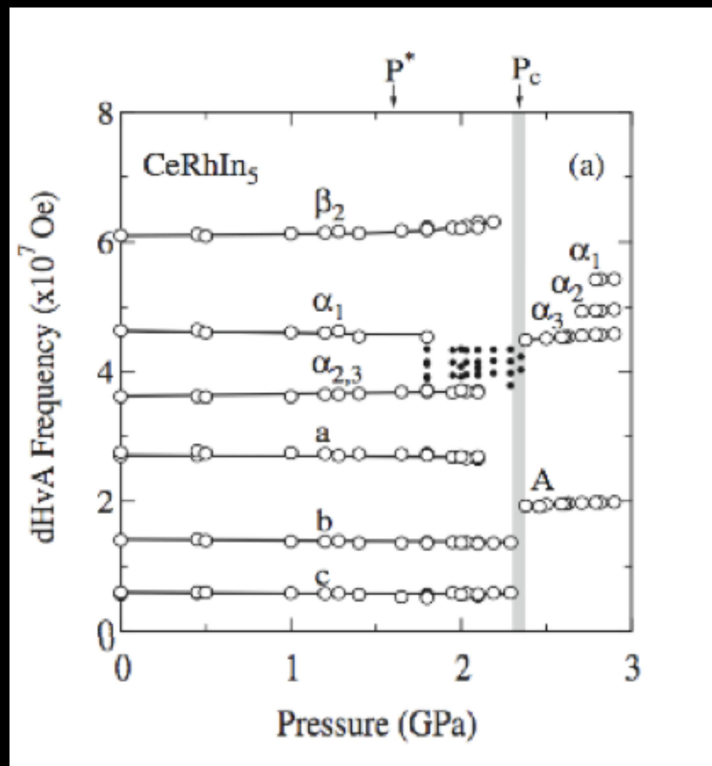

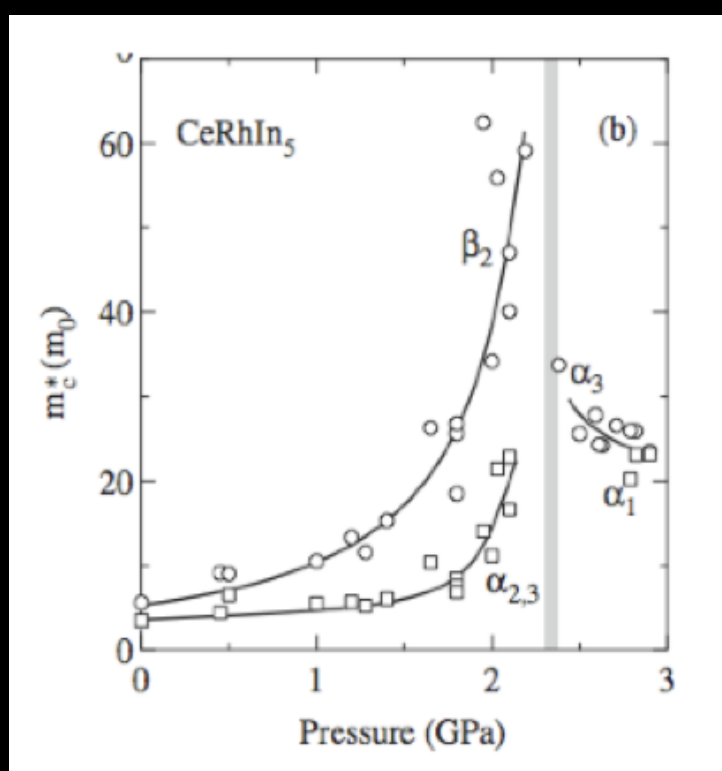

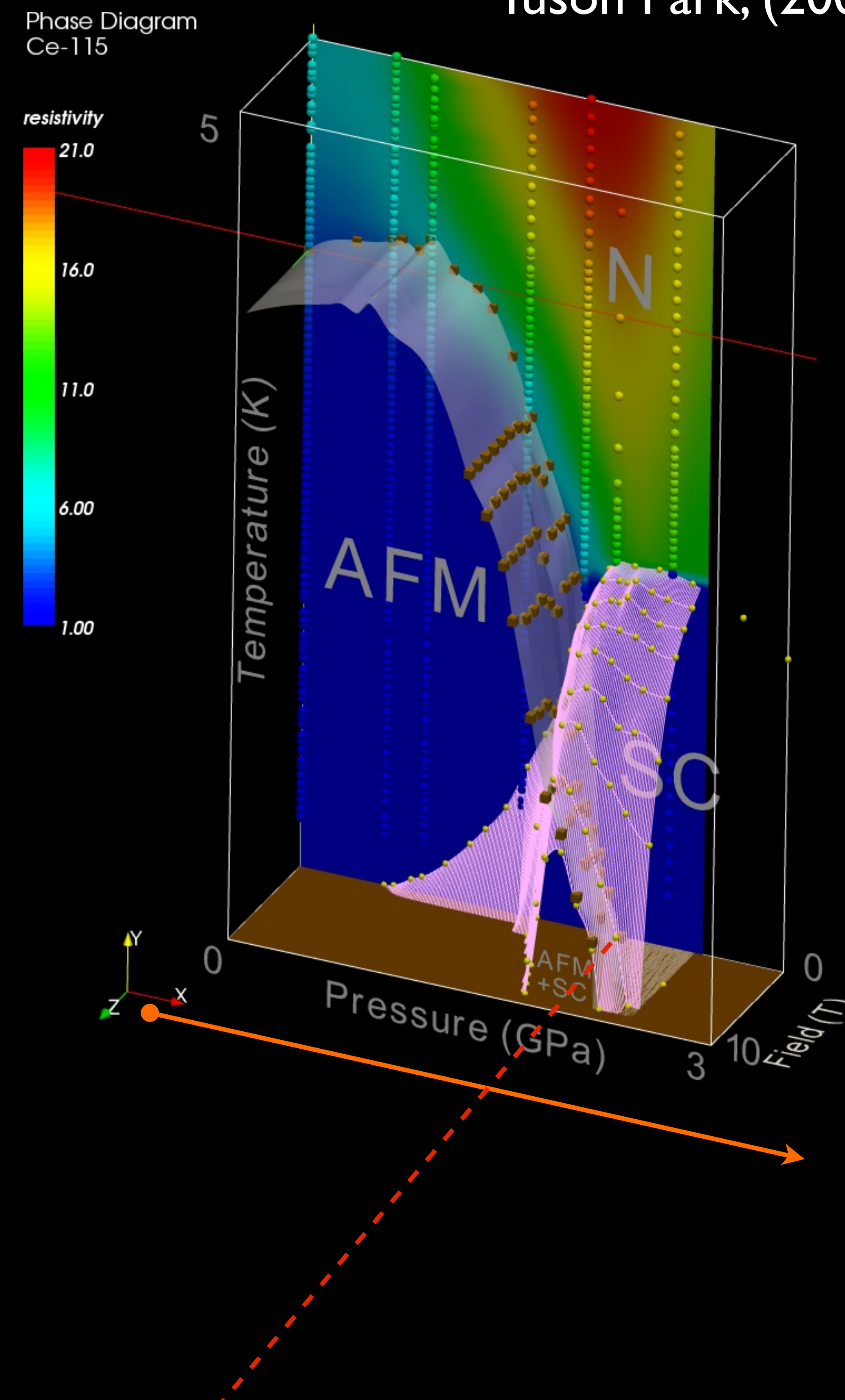

Shimuzu et al (2006)

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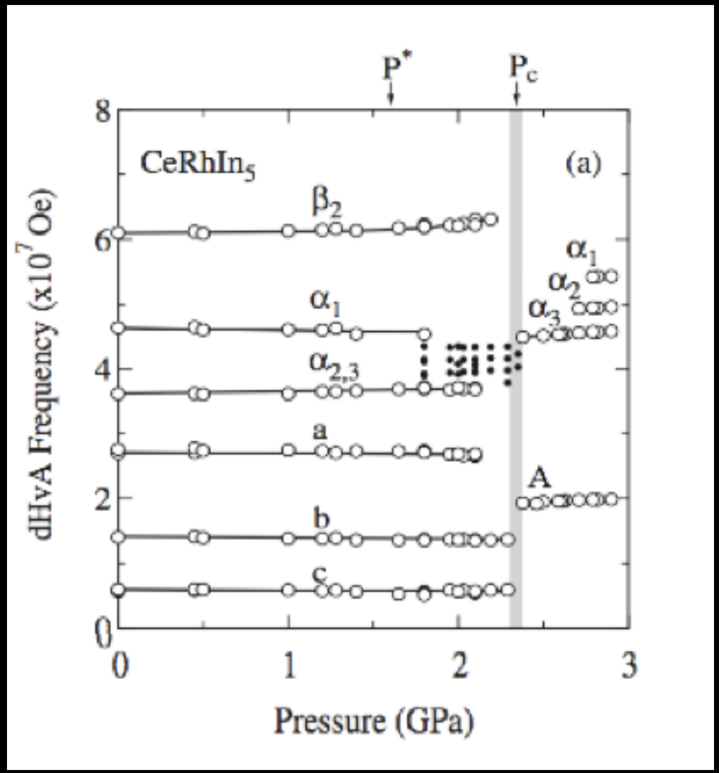

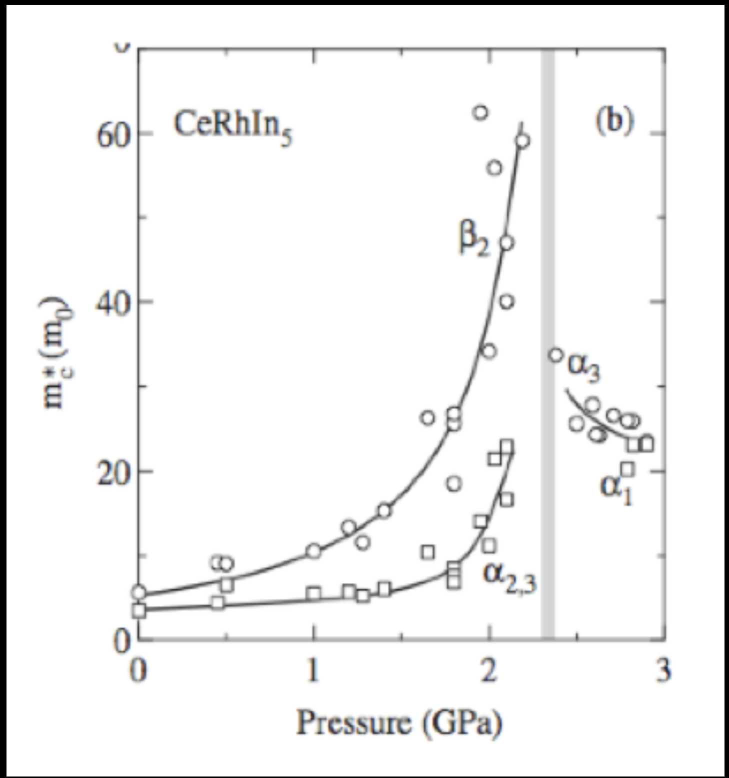

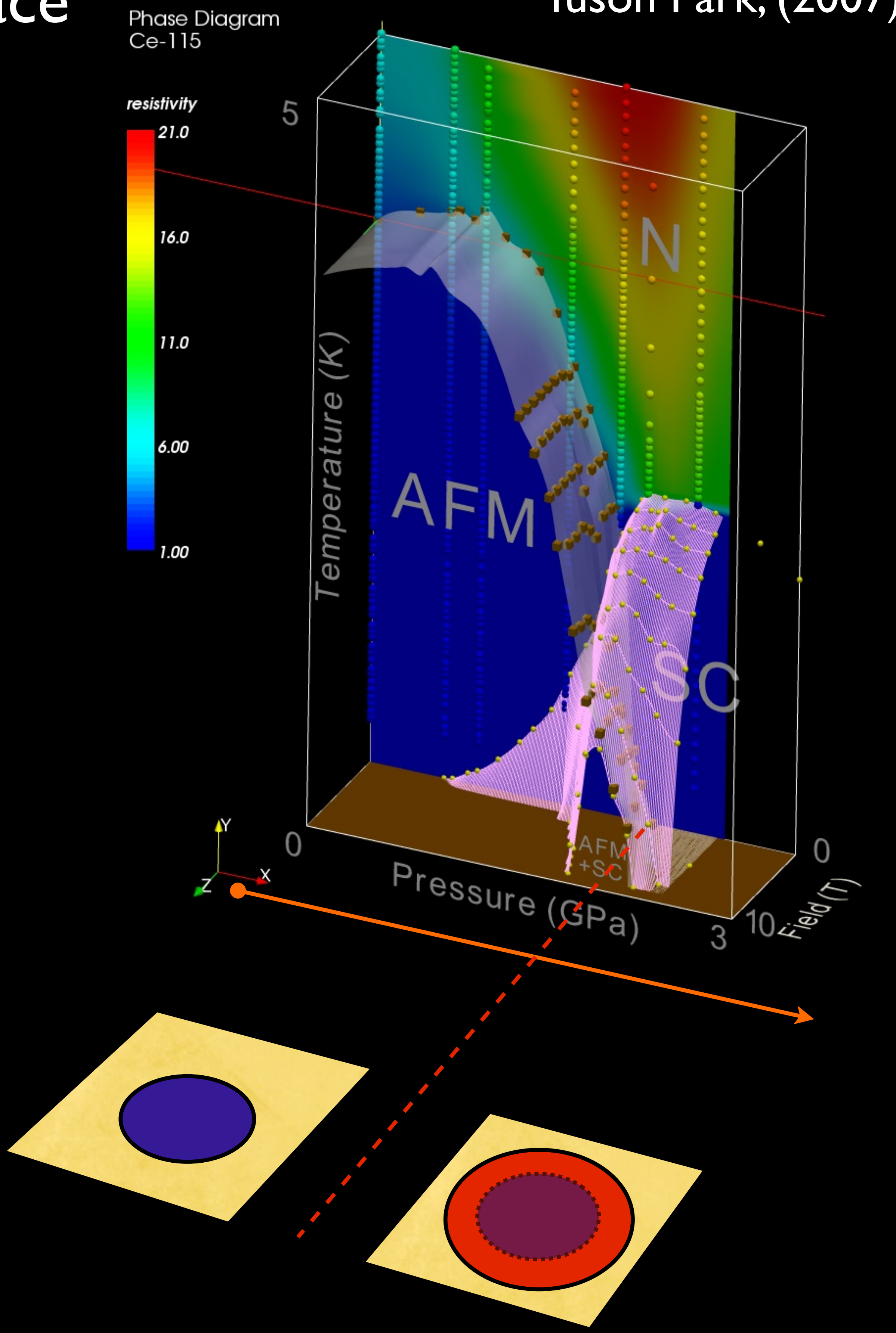

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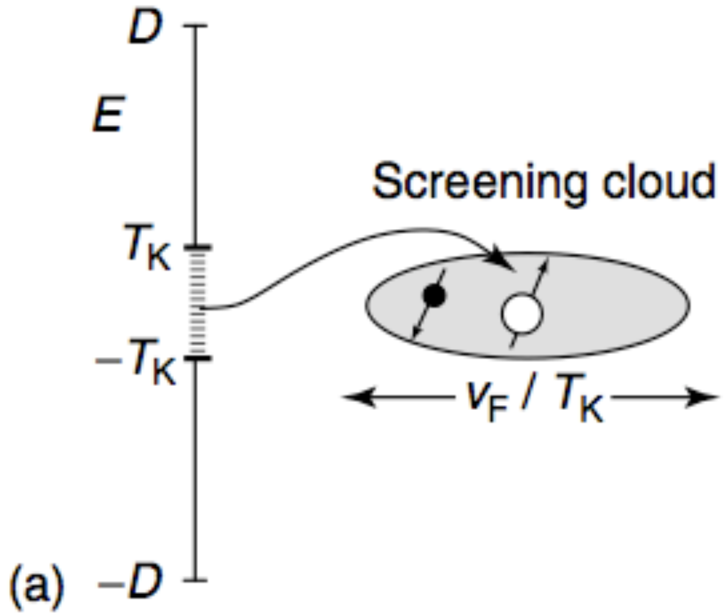
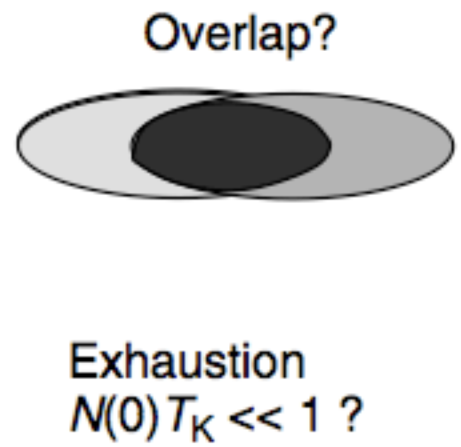
"Exhaustion" vs. Composite fermion.





Nozieres(1985)

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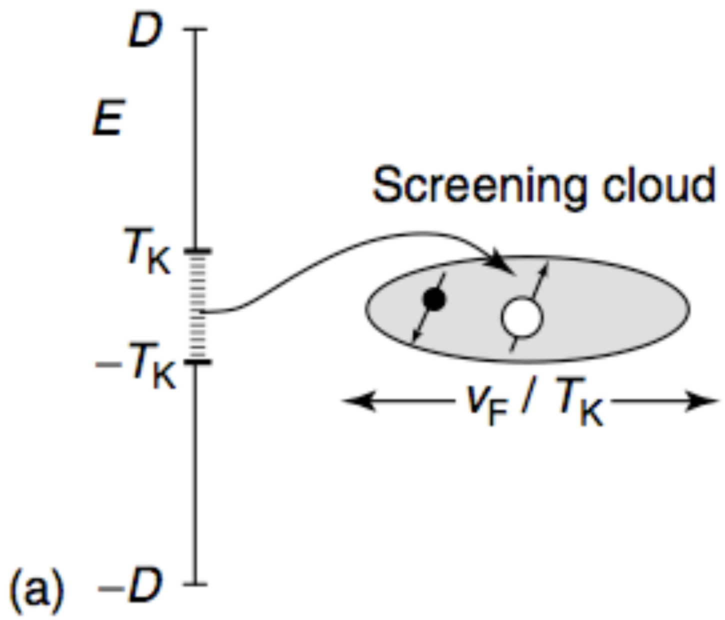

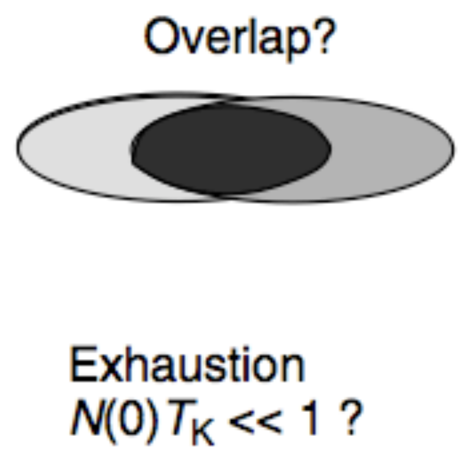

Nozieres(1985)

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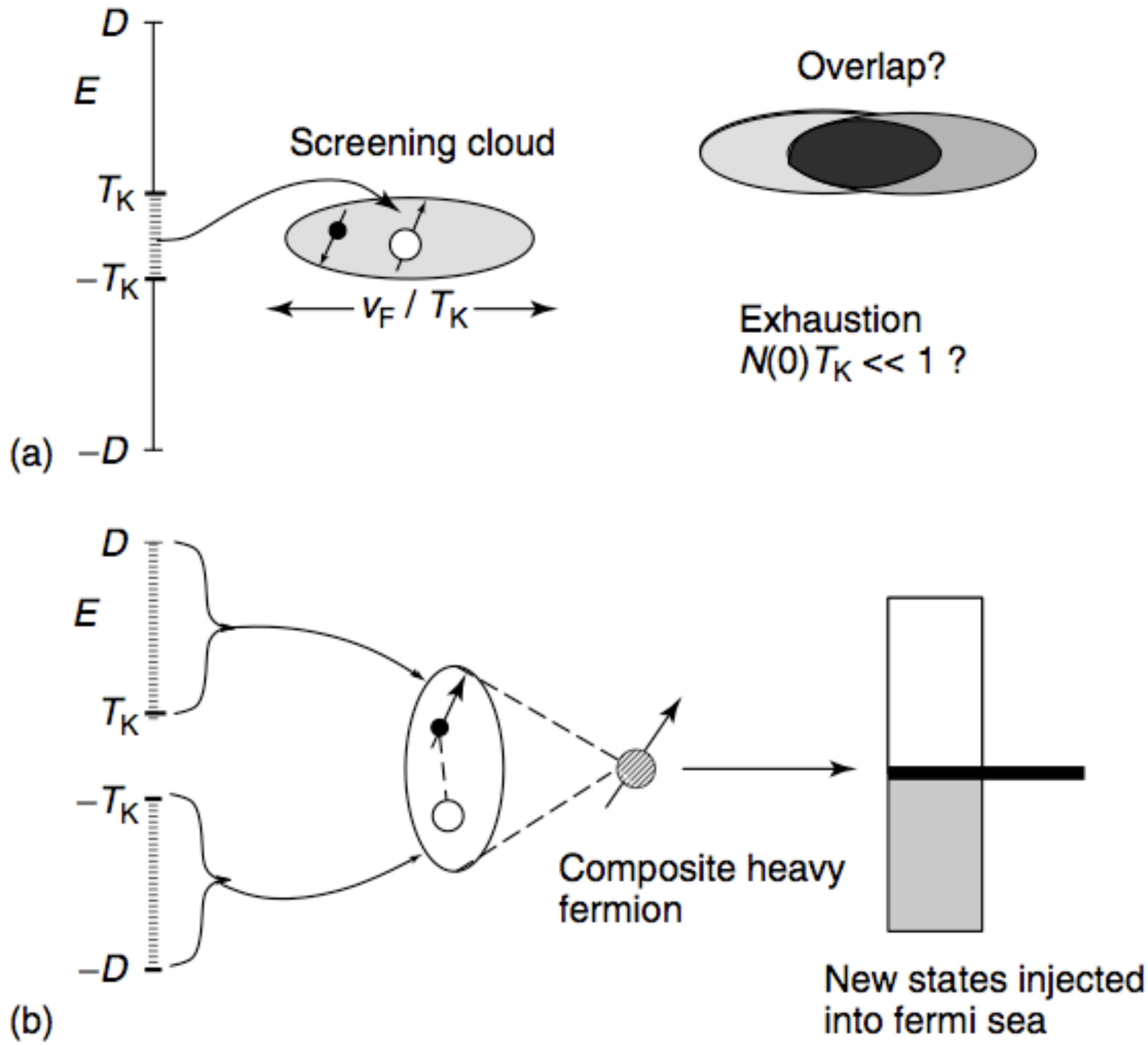

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Strongly correlated electron physics: no small parameter

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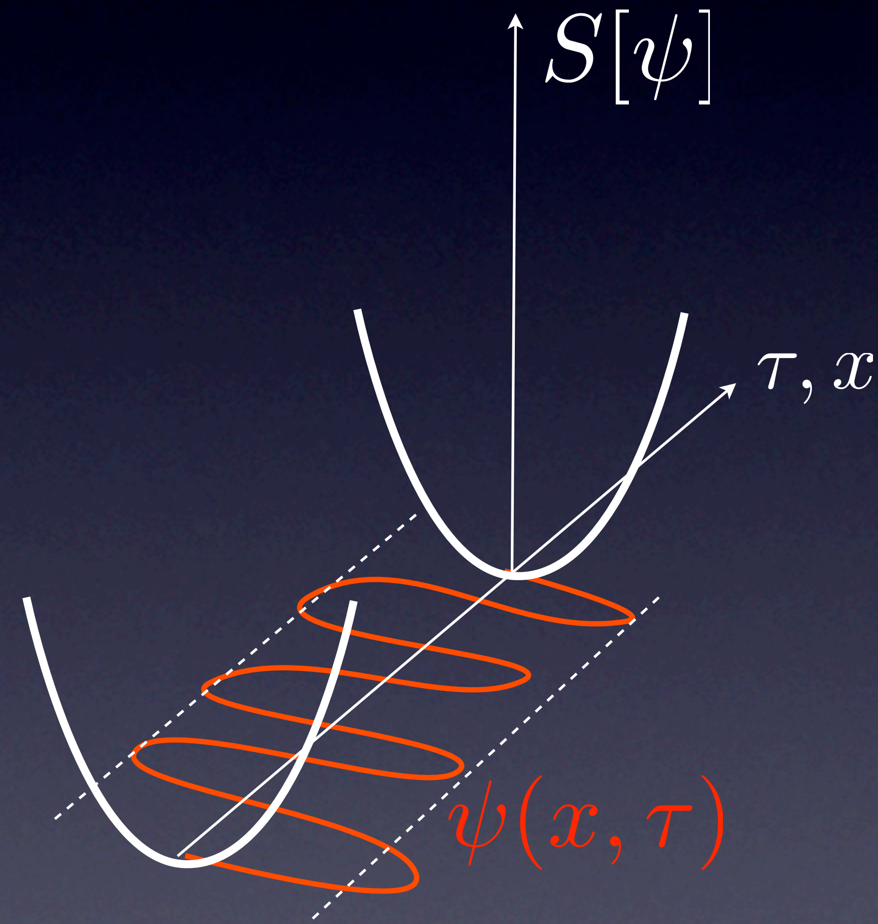

$$\frac{1}{N} \sim \hbar_{eff}$$

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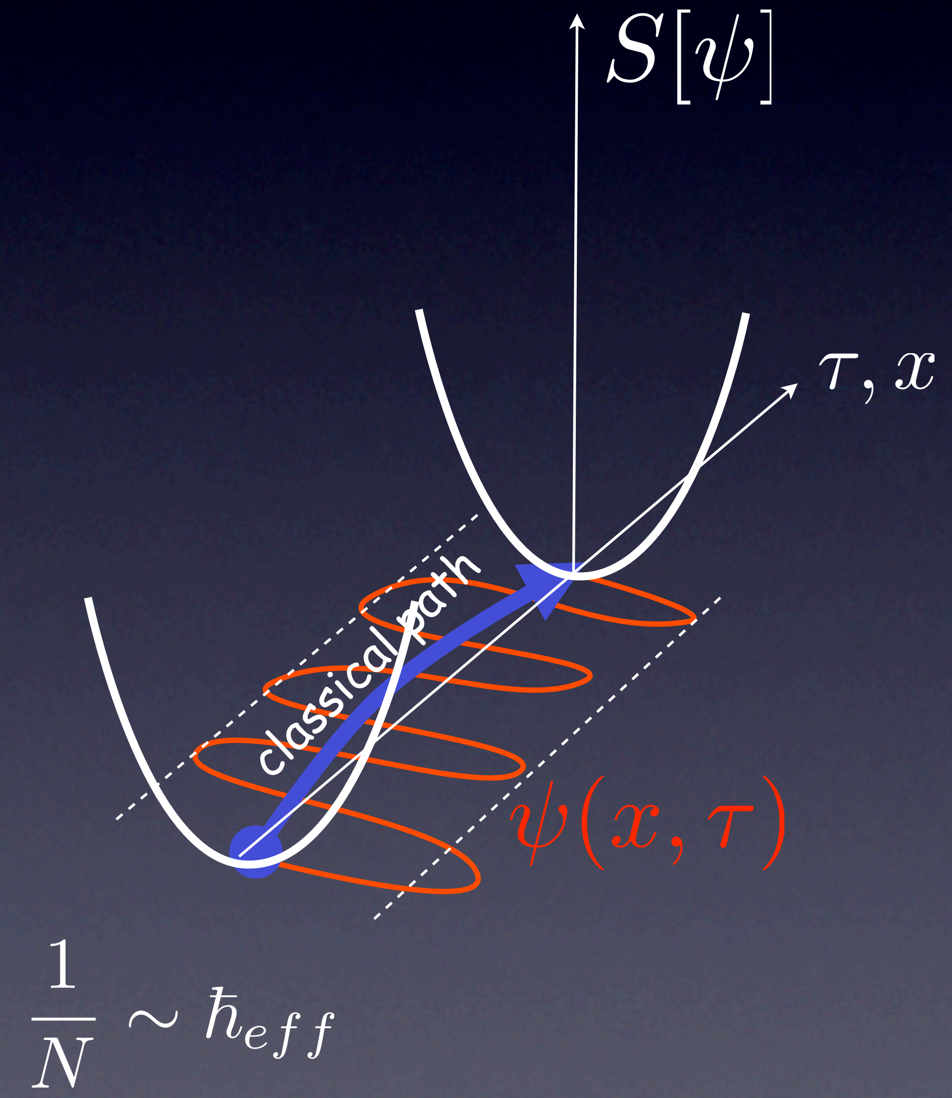

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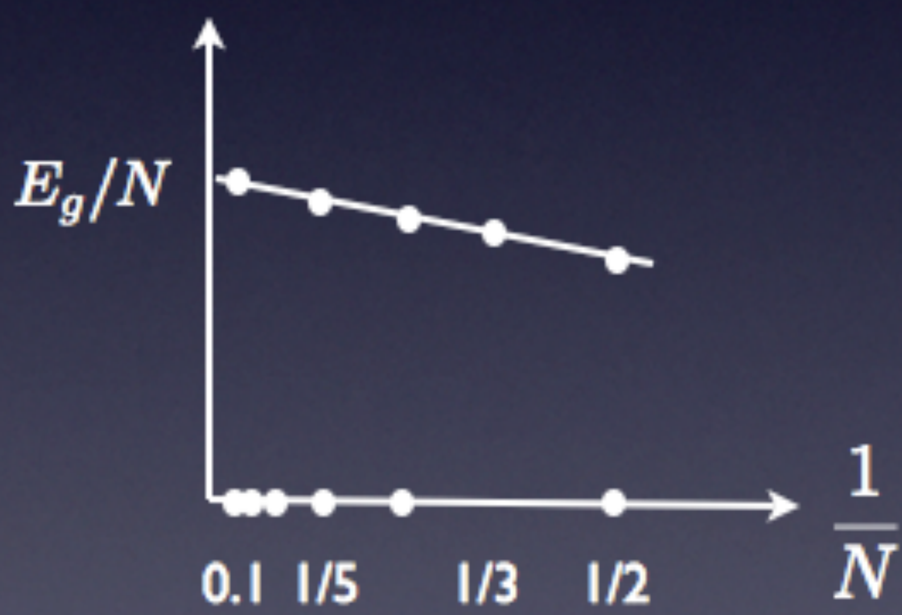

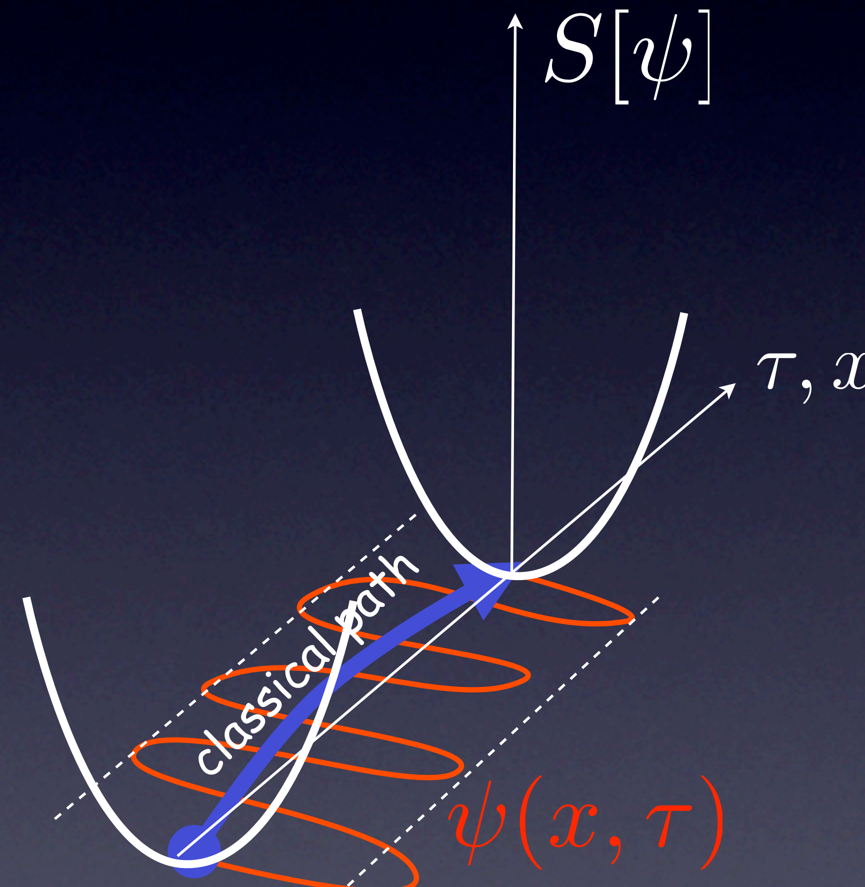

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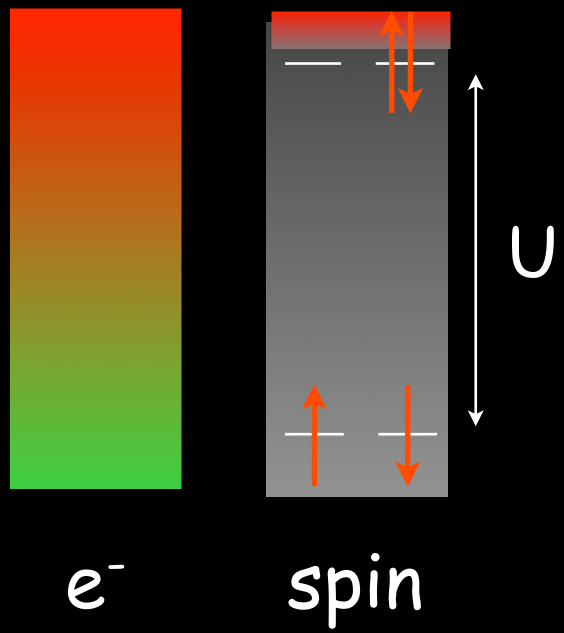
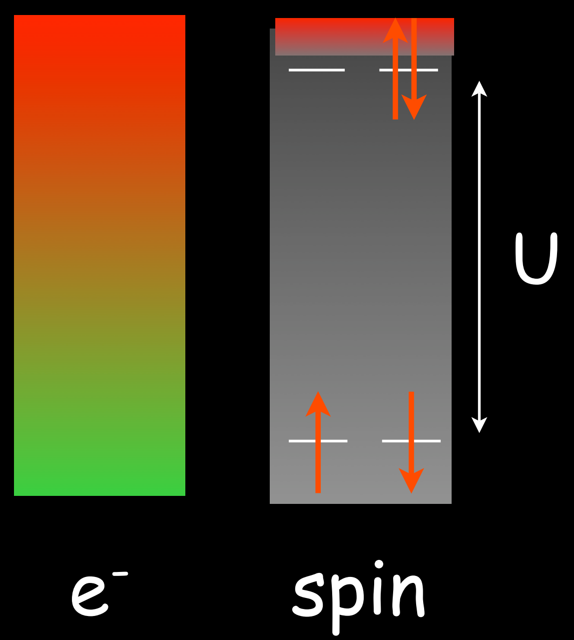
Gauge Theories and Strong Correlation.



Gauge Theories and Strong Correlation.

Strong correlation ↔ Constrained Hilbert space

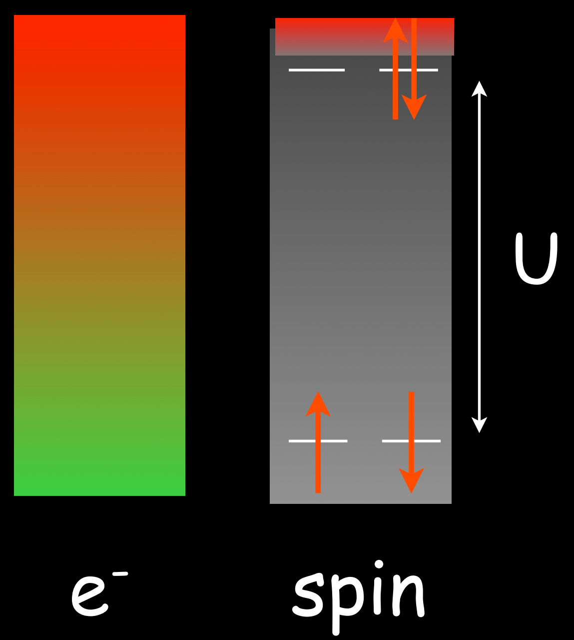
↔ Gauge theories



Gauge Theories and Strong Correlation.

Strong correlation $\leftrightarrow$ Constrained Hilbert space

$\leftrightarrow$ Gauge theories



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

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

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

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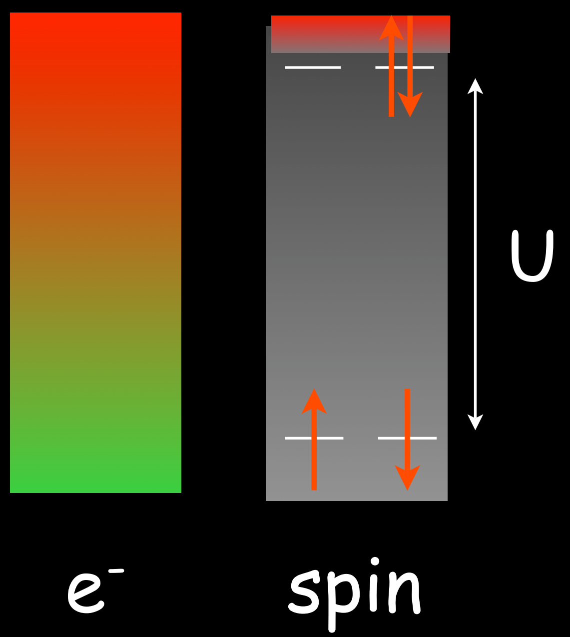

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$$H = \sum \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \frac{J}{N} \sum_j c^\dagger_{j\alpha} c_{j\beta} S_{\beta\alpha}(j) + H_g$$

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

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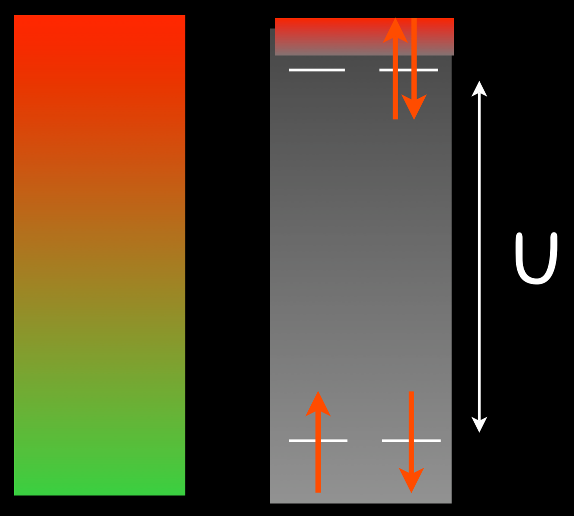

e^- spin

Φ λ

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

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$$H_g = (\Phi - \mu) c^\dagger_j c_j + \lambda_j (f^\dagger_j f_j - Q),$$

$$(Q = qN = 1)$$

Large N Approach.

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

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Large N Approach.

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

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

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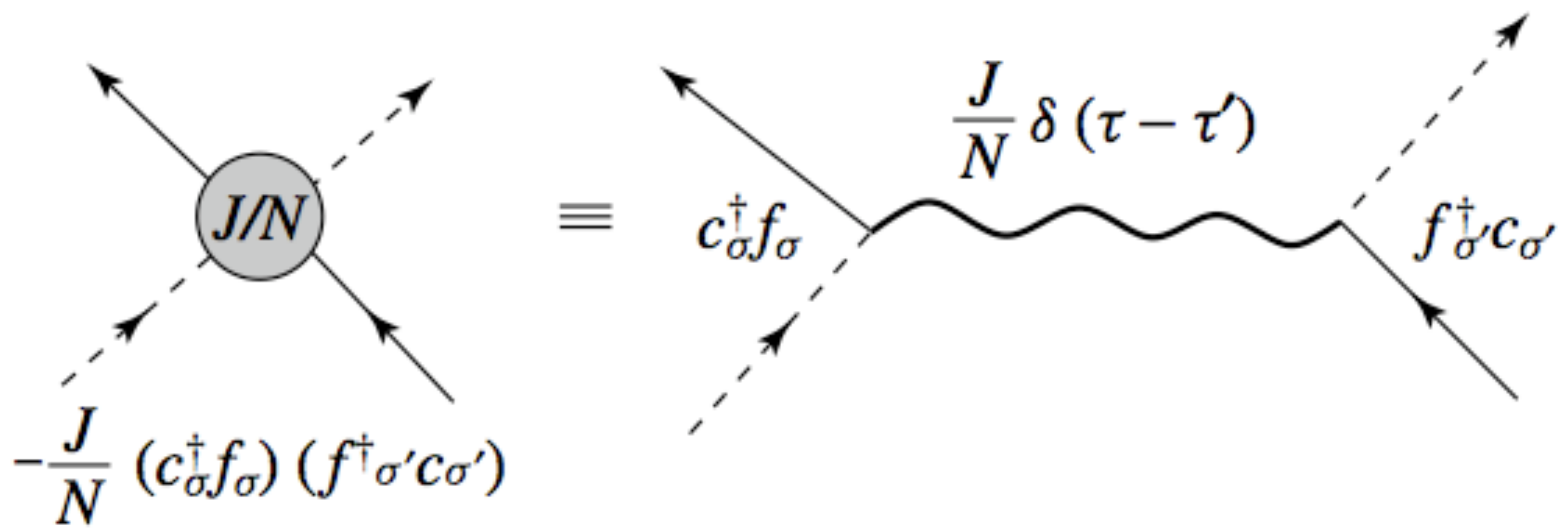
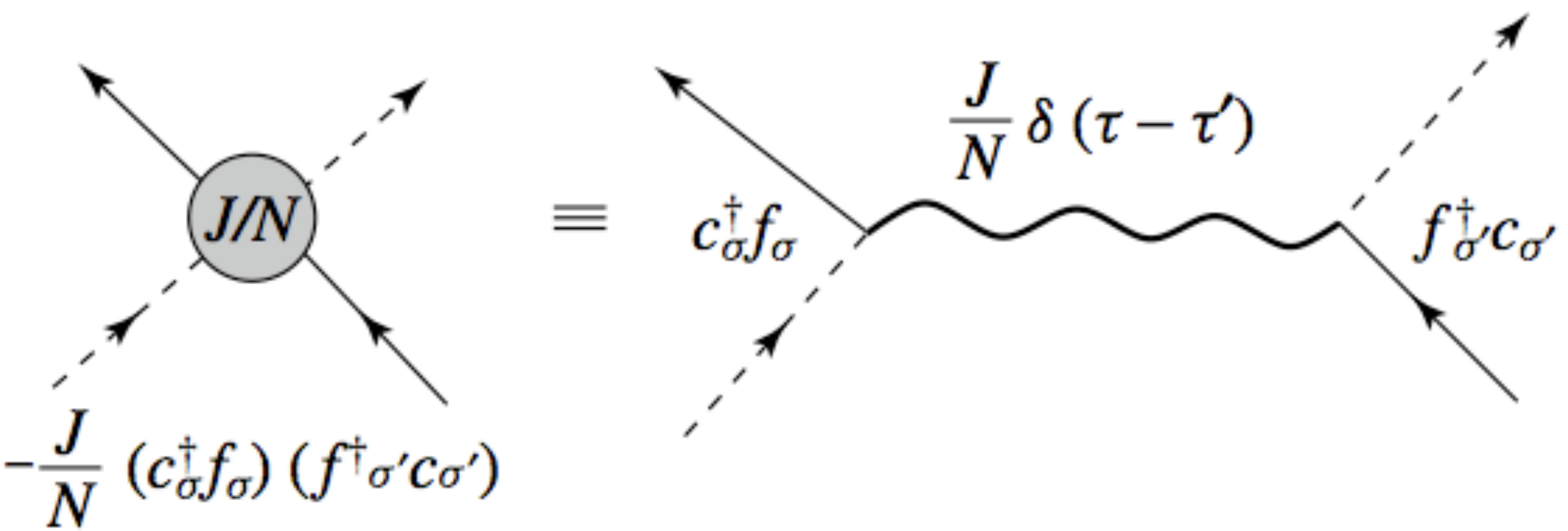


(81)

Large N Approach.



(81)

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

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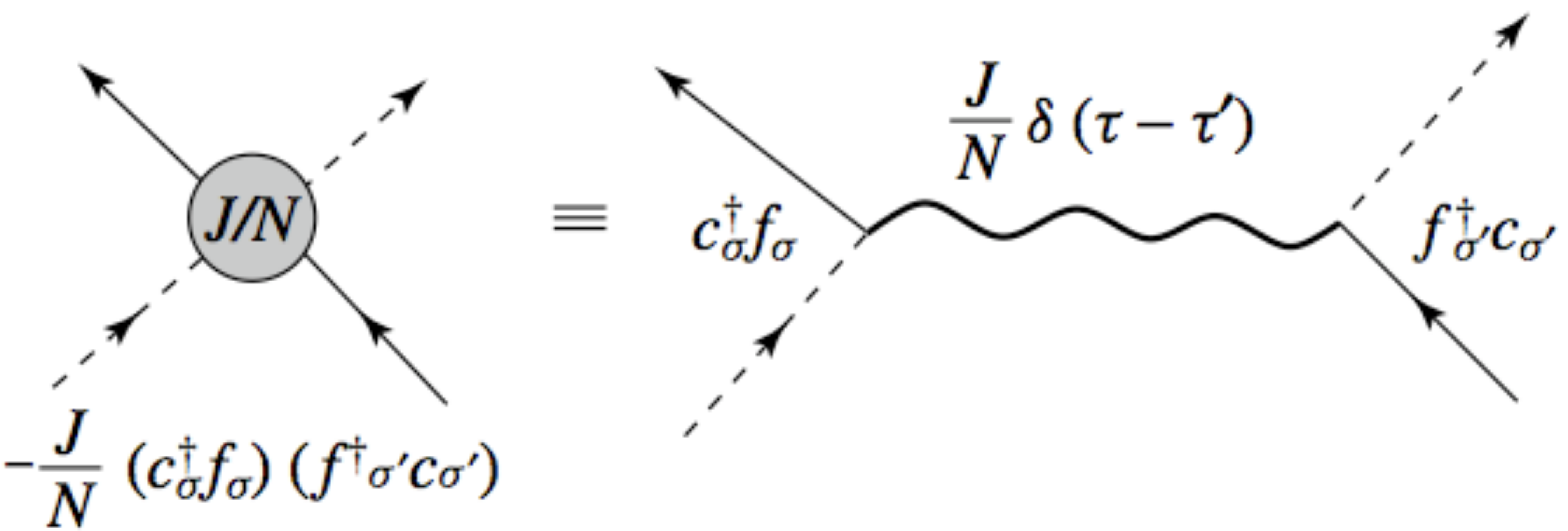

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$$Z = \int \mathcal{D}[V,\lambda] \overbrace{\int \mathcal{D}[c,f] \exp\left[-\int_0^\beta \left(\sum_{k\sigma} c^\dagger_{\mathbf{k}\sigma}\partial_\tau c_{\mathbf{k}\sigma} + \sum_{j\sigma} f^\dagger_{j\sigma}\partial_\tau f_{j\sigma} + H[V,\lambda]\right)\right]}^{=\mathrm{Tr}\left[Texp\left(-\int_0^\beta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

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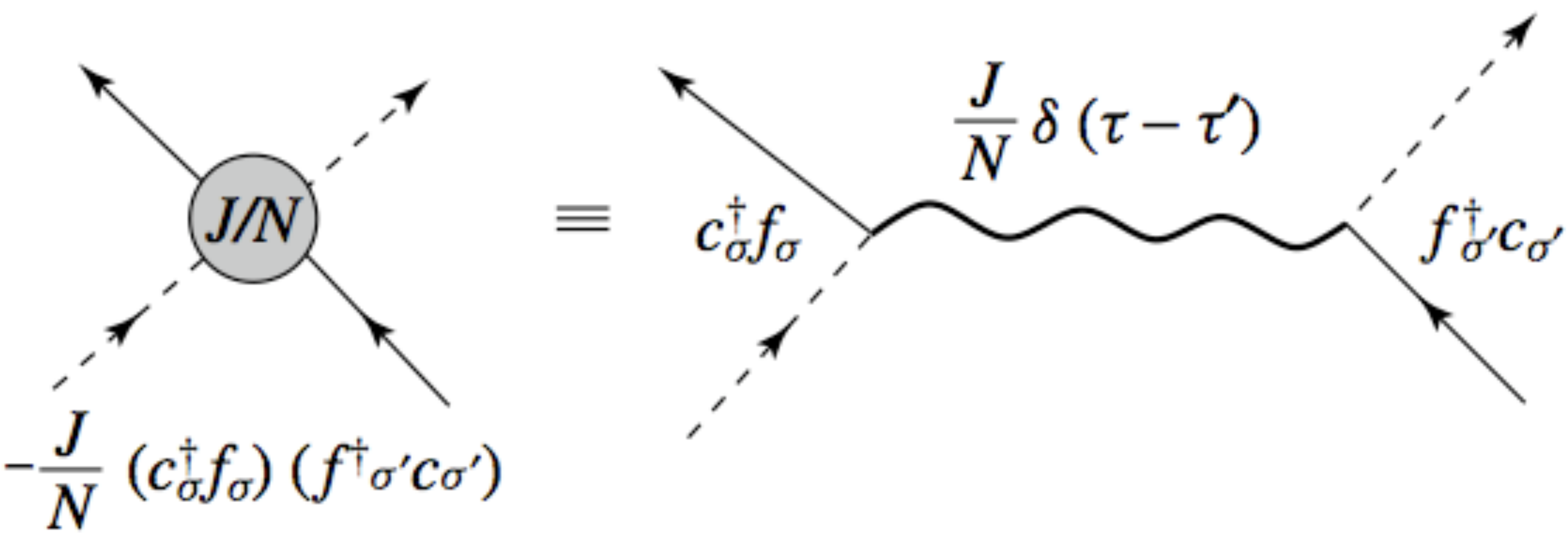

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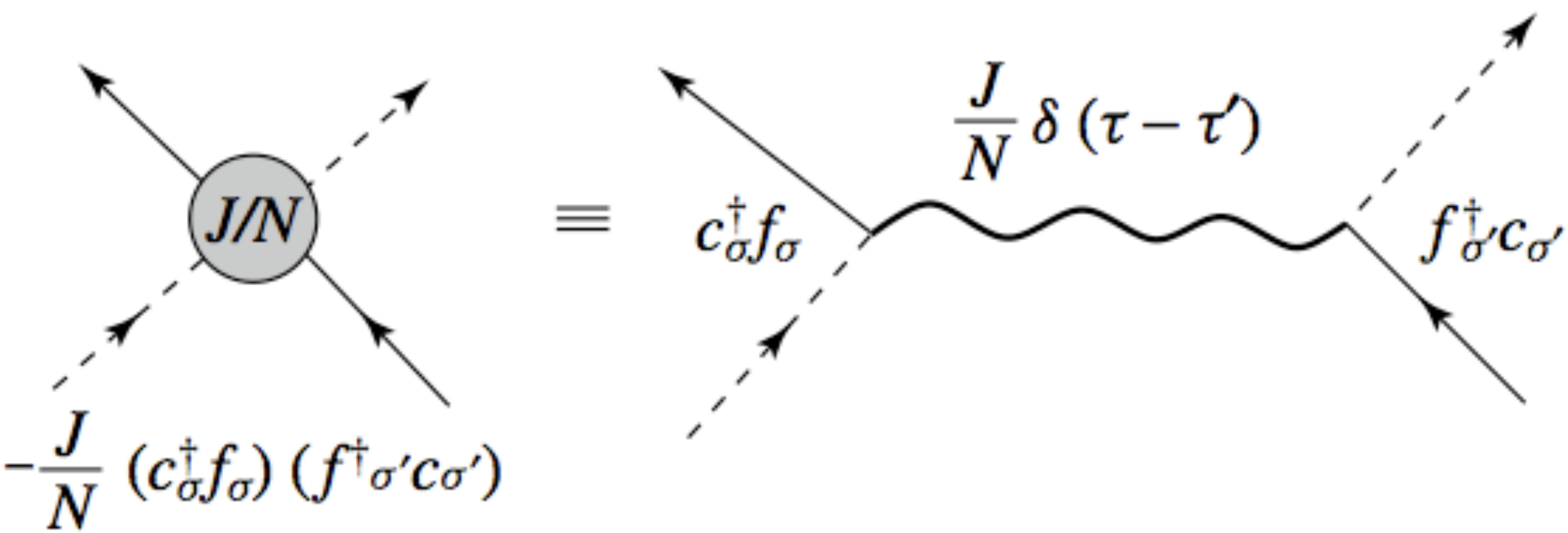

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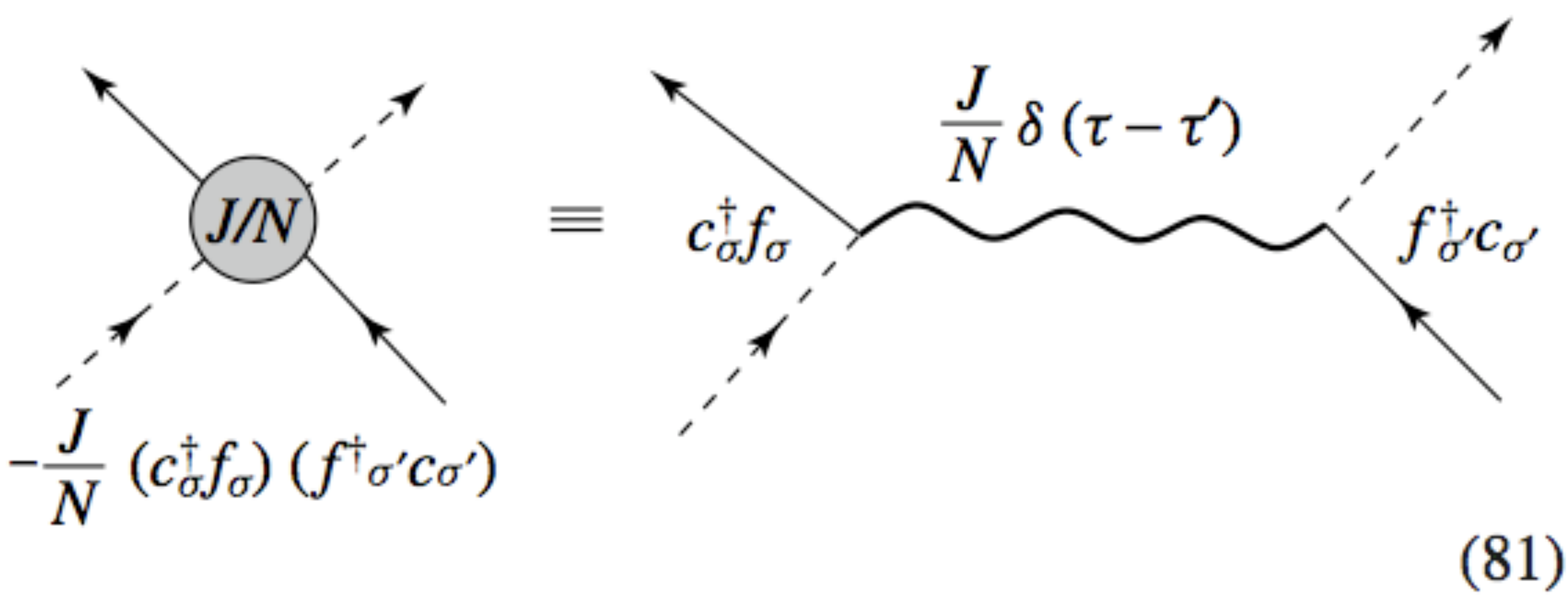

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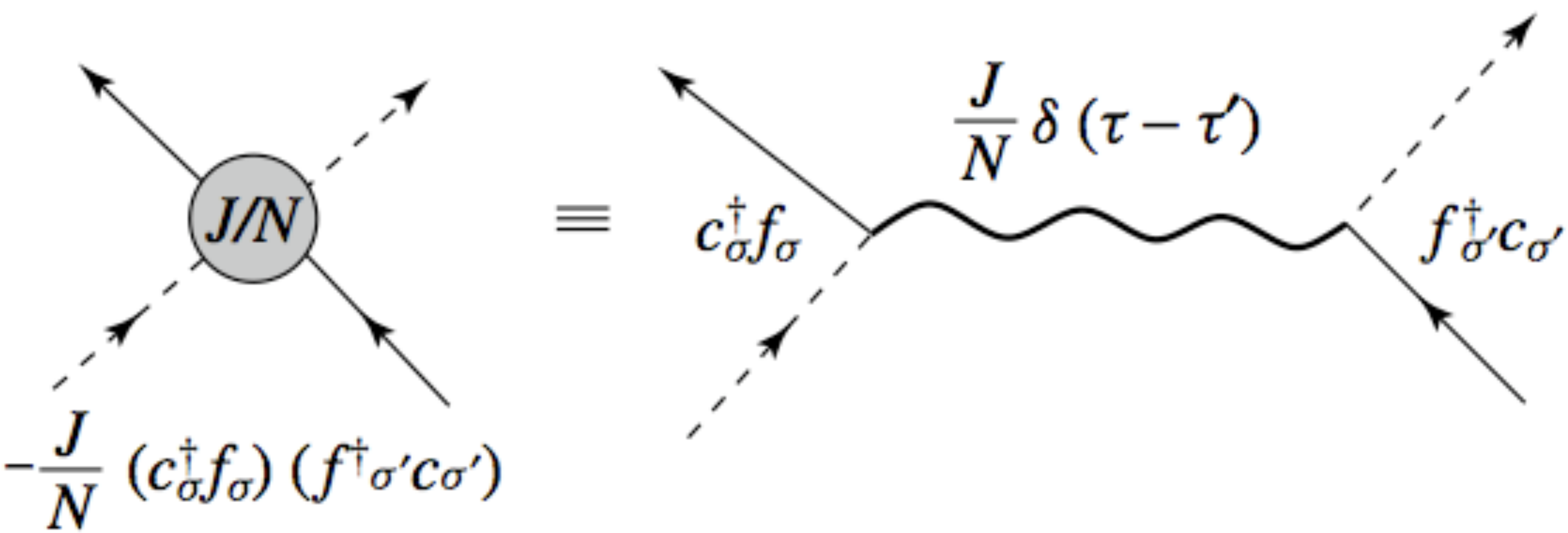

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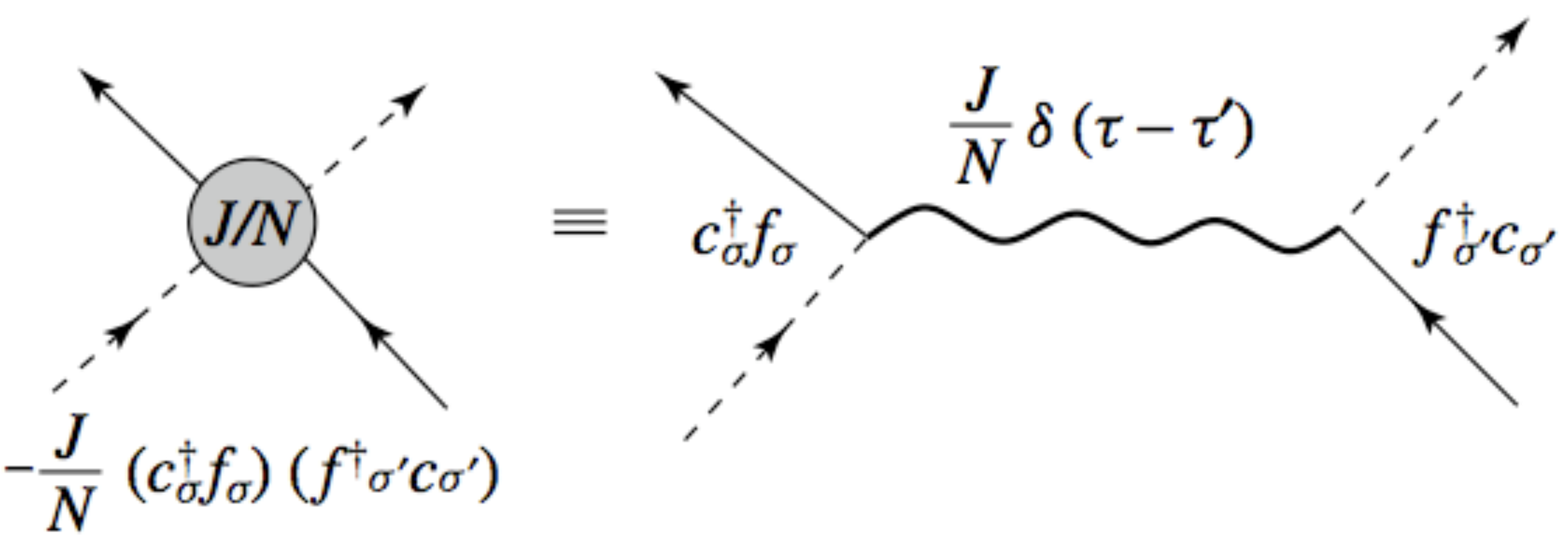

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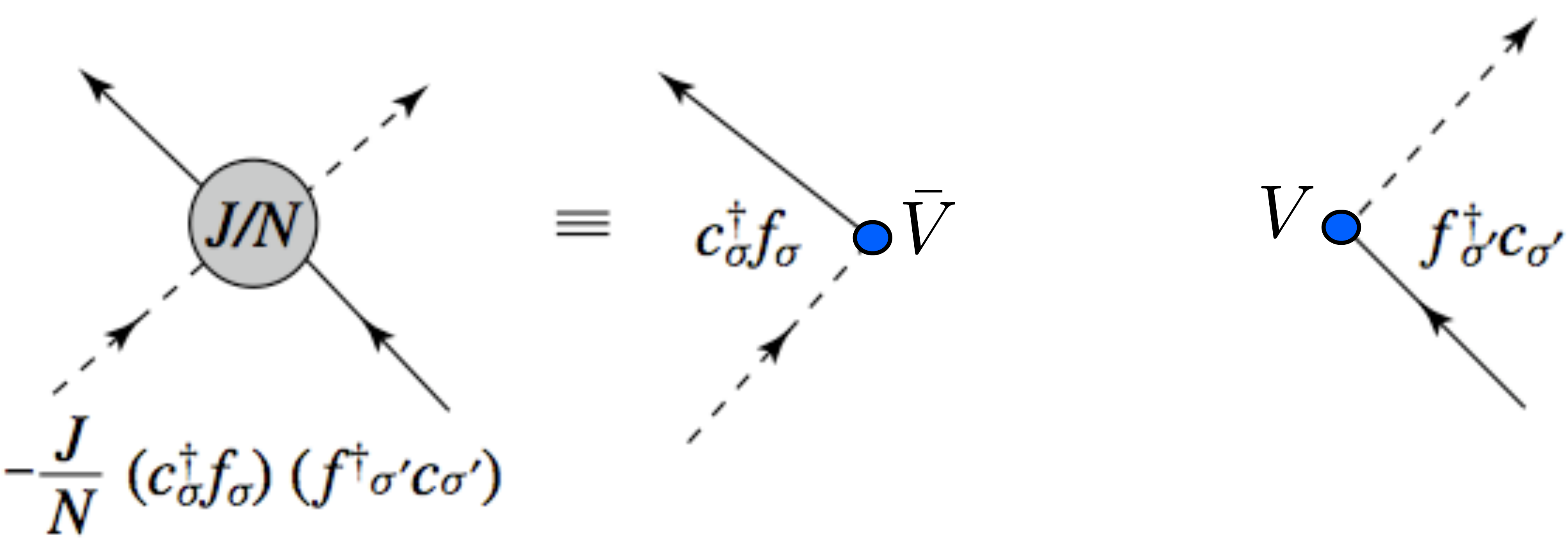

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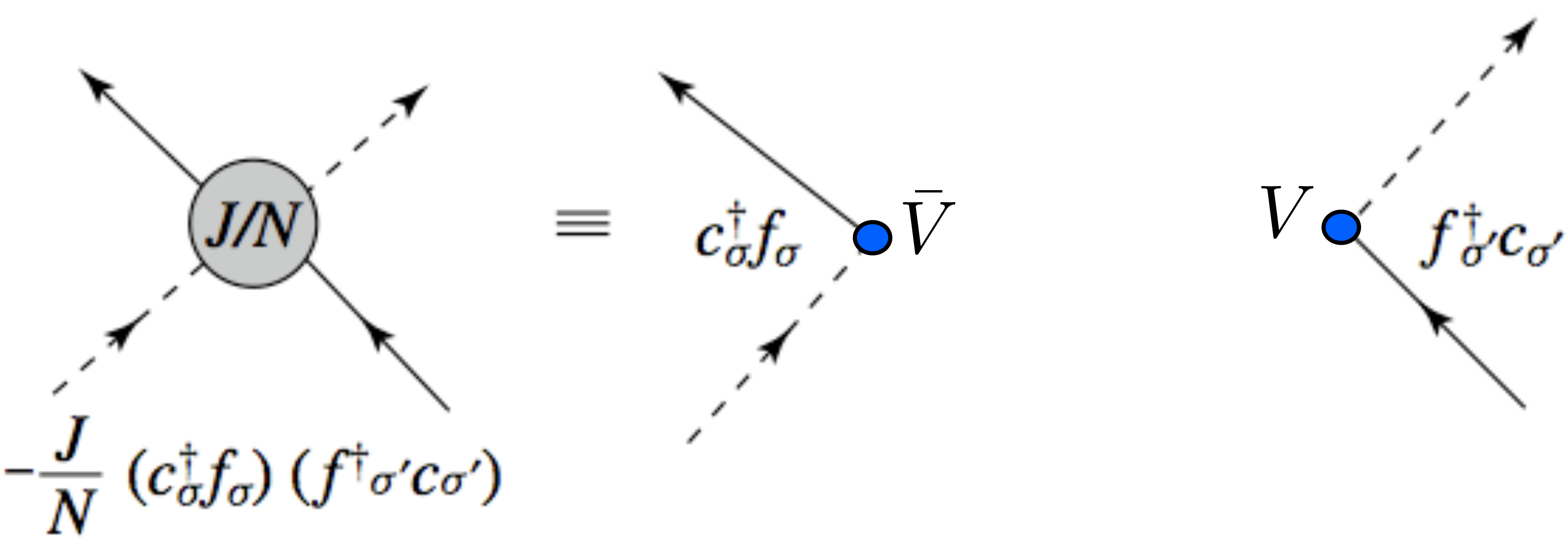

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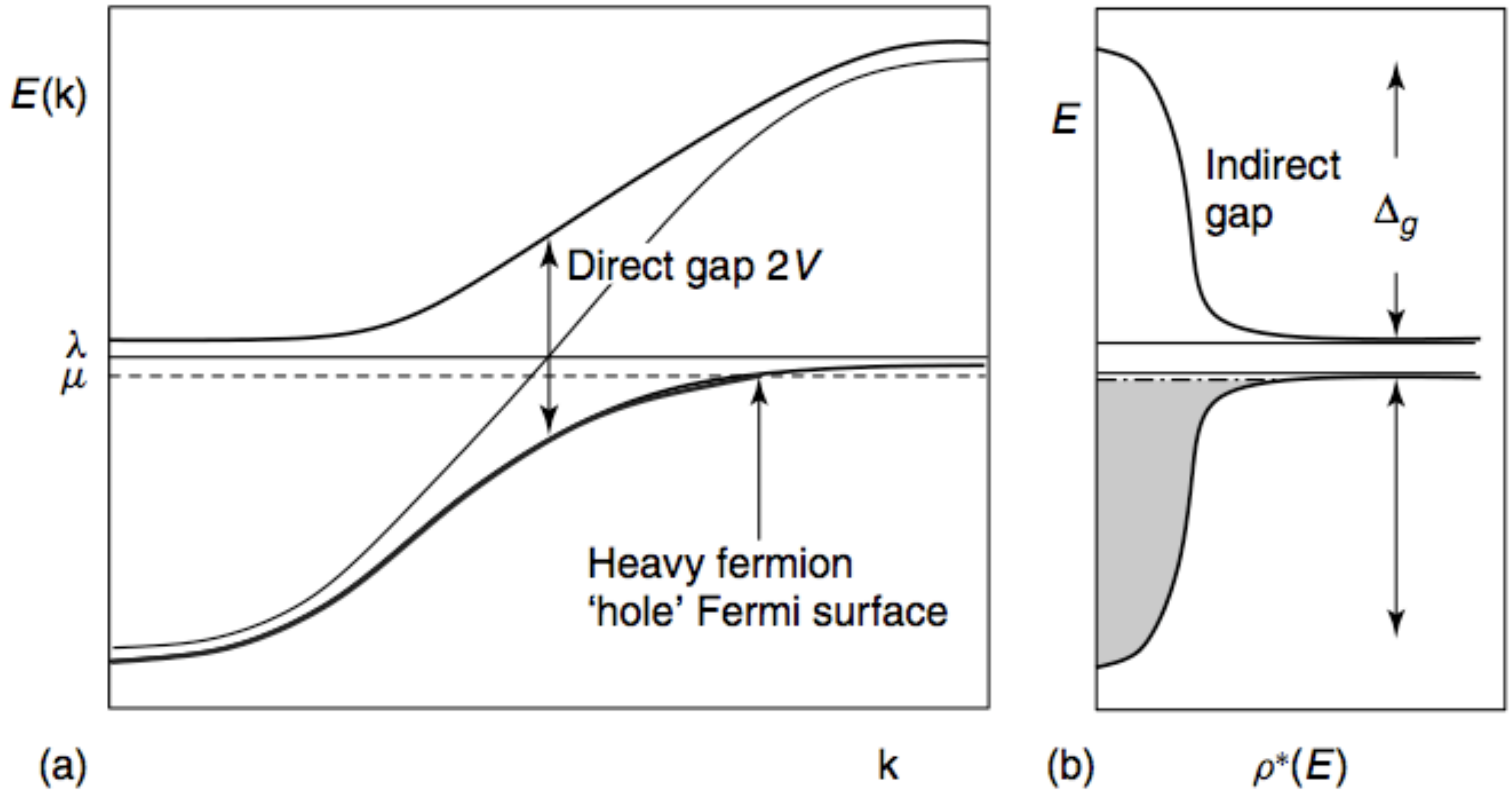
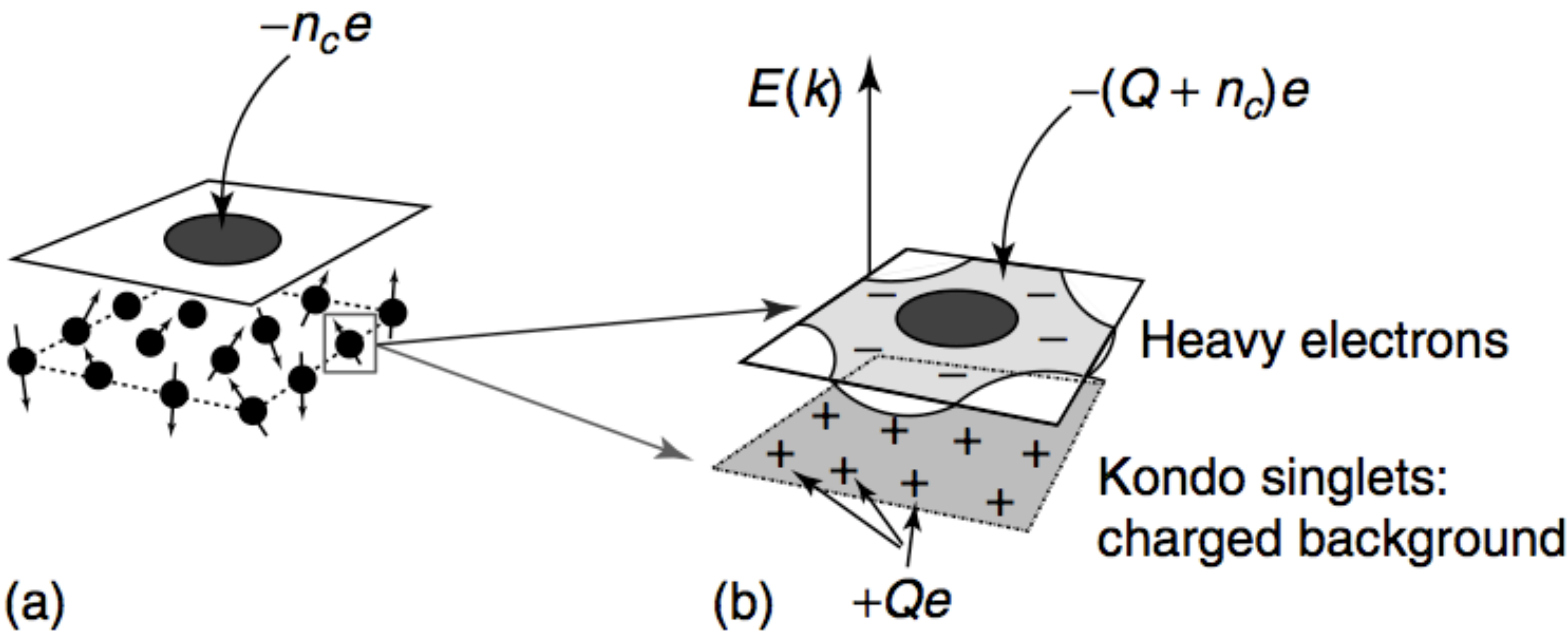


Large Fermi surface and the charge of the f-electron



Conclusions / Open Questions.

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- Heavy electrons: extreme example of Landau's adiabatic principle.

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Spin --> Composite electron + background charge.

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Spin --> Composite electron + background charge.

- What is the nature of the zero modes (fermionic?) at a heavy electron QCP.
- How do we unify the Kondo effect with (i) Superconductivity and (ii) Magnetism.

Possible close links with (a) atom traps and (b) quantum dots.

$$H = \sum \varepsilon_k c_{k\sigma}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

"THE BATTLEGROUND"

Kondo Lattice Model

(Kasuya, 1951)

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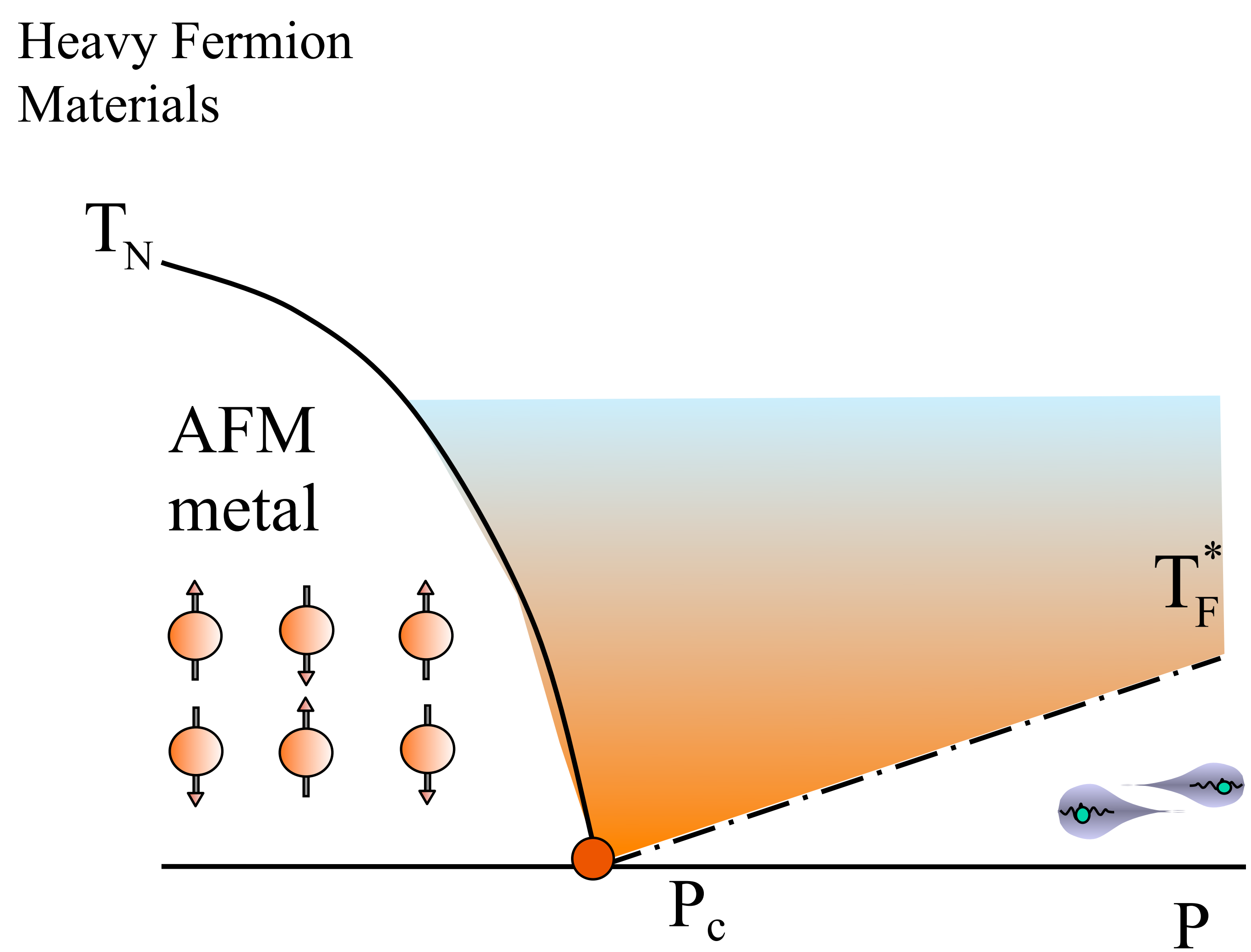

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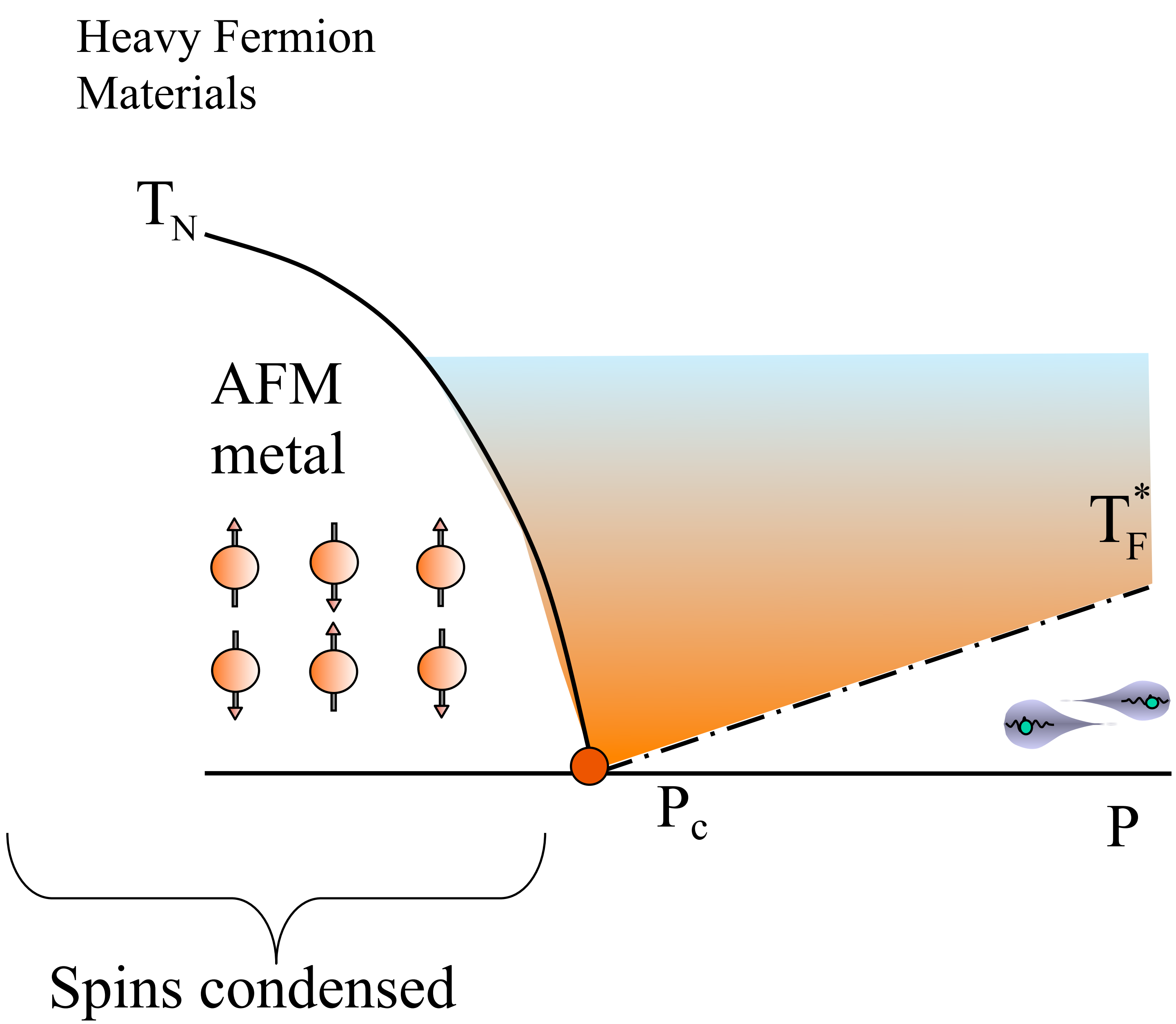

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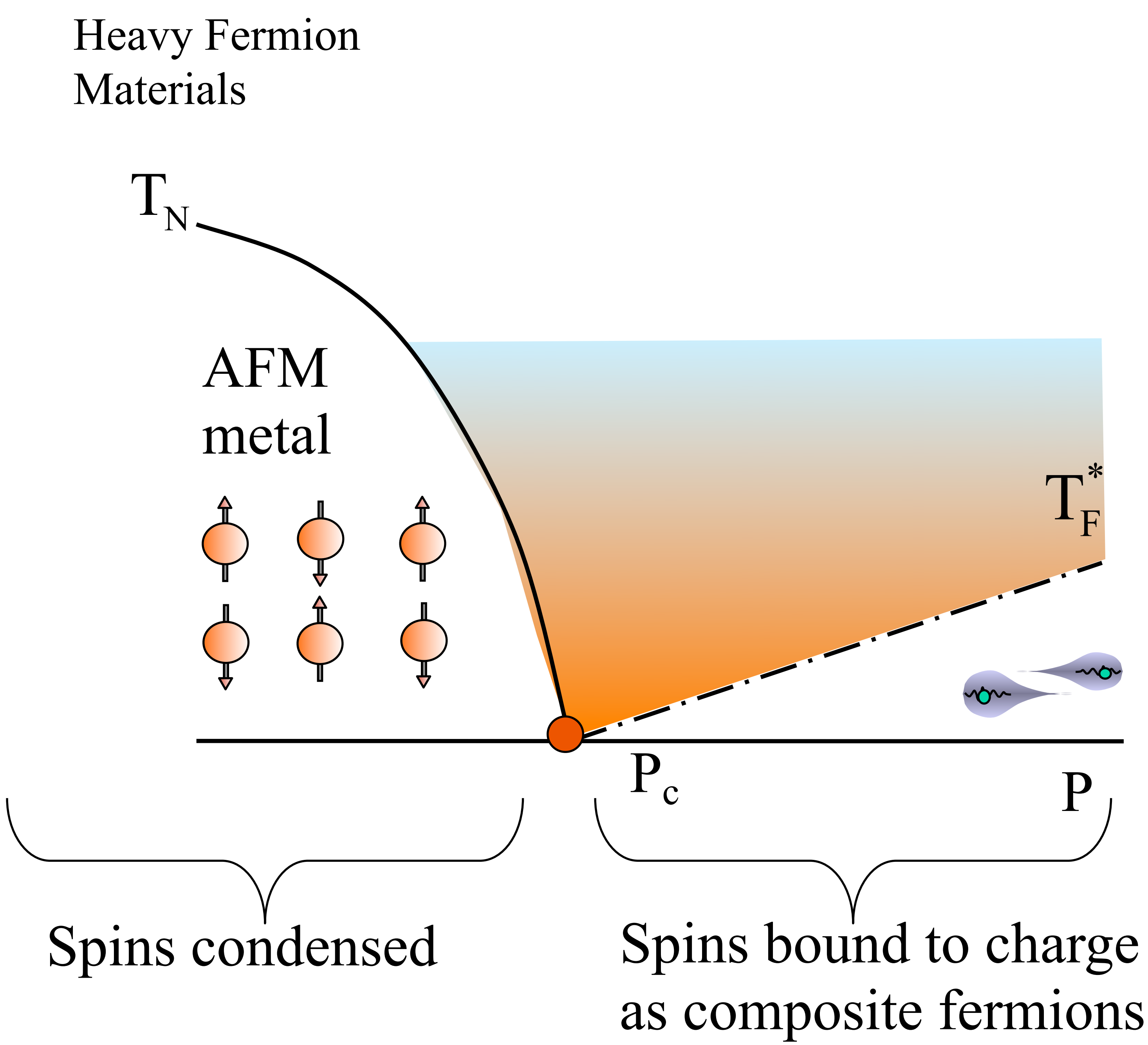

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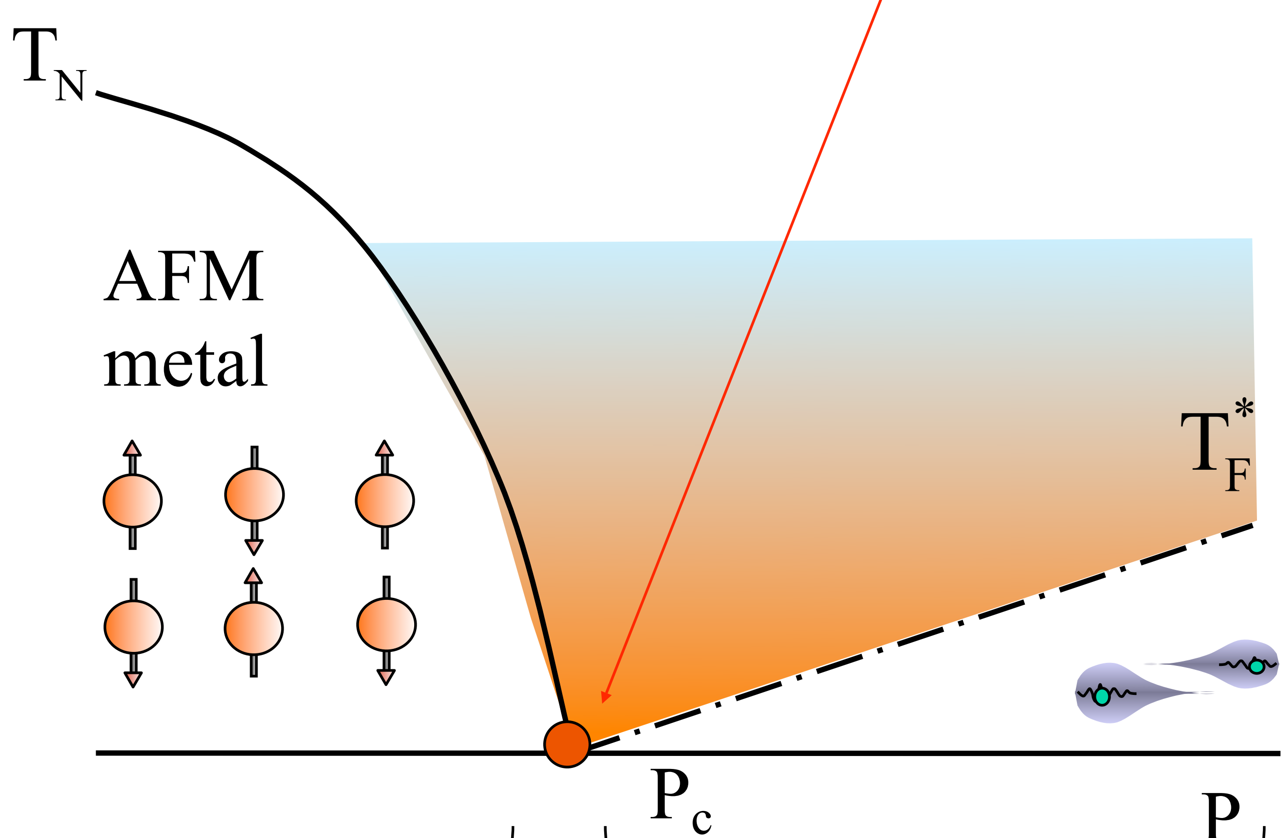
Deconfinement of spin: fundamentally new kind of zero mode.

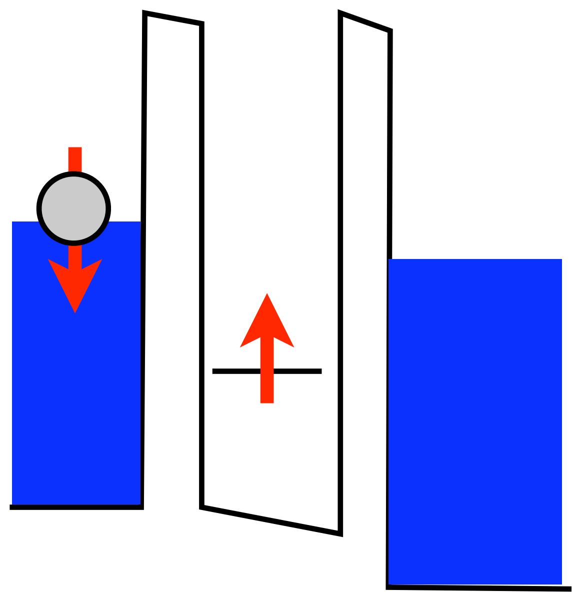
Heavy Fermion Materials



Spins condensed

Spins bound to charge as composite fermions

Cotunneling and copairing:



Cotunneling
(Glazman +Pustilnik)
(quantum dots)

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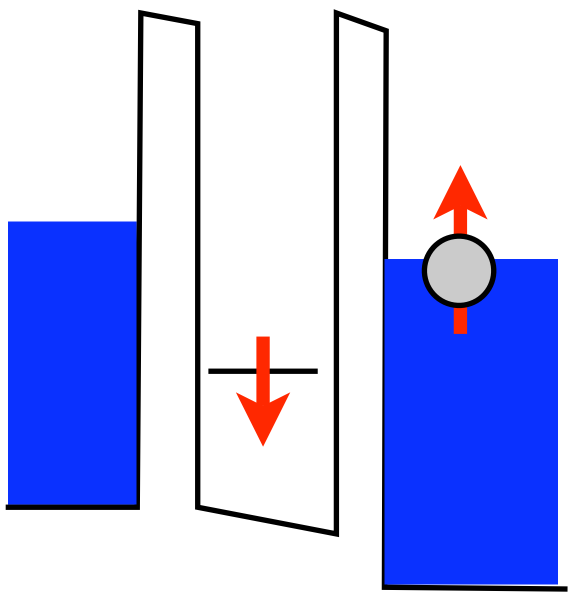

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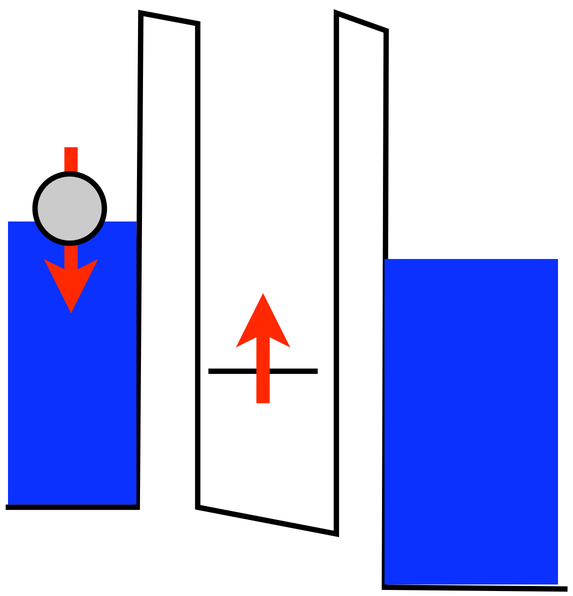

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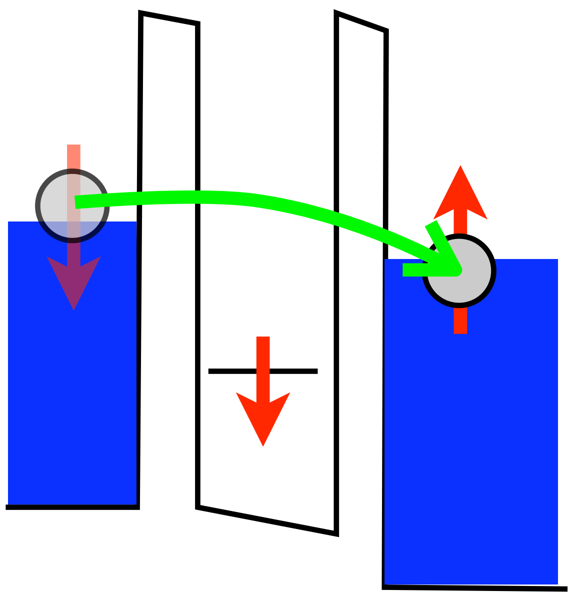

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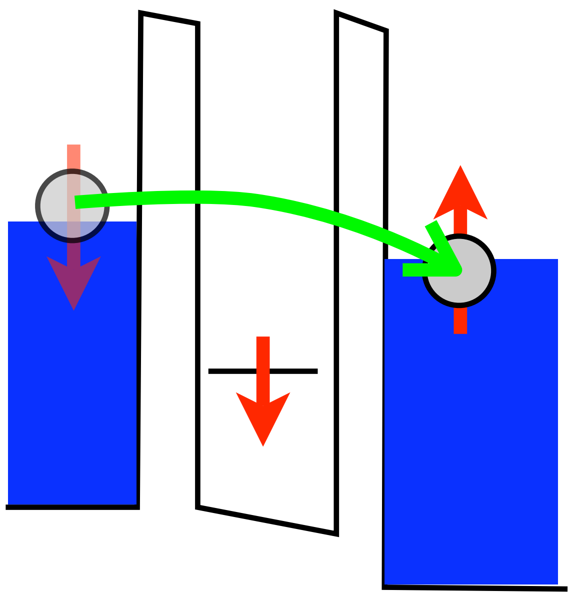

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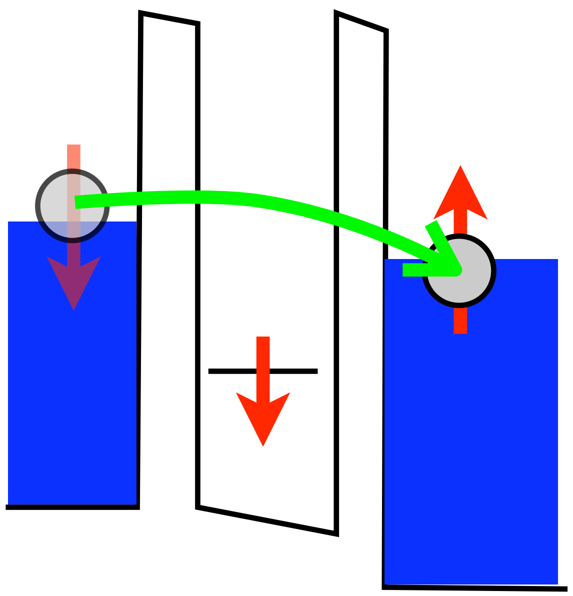

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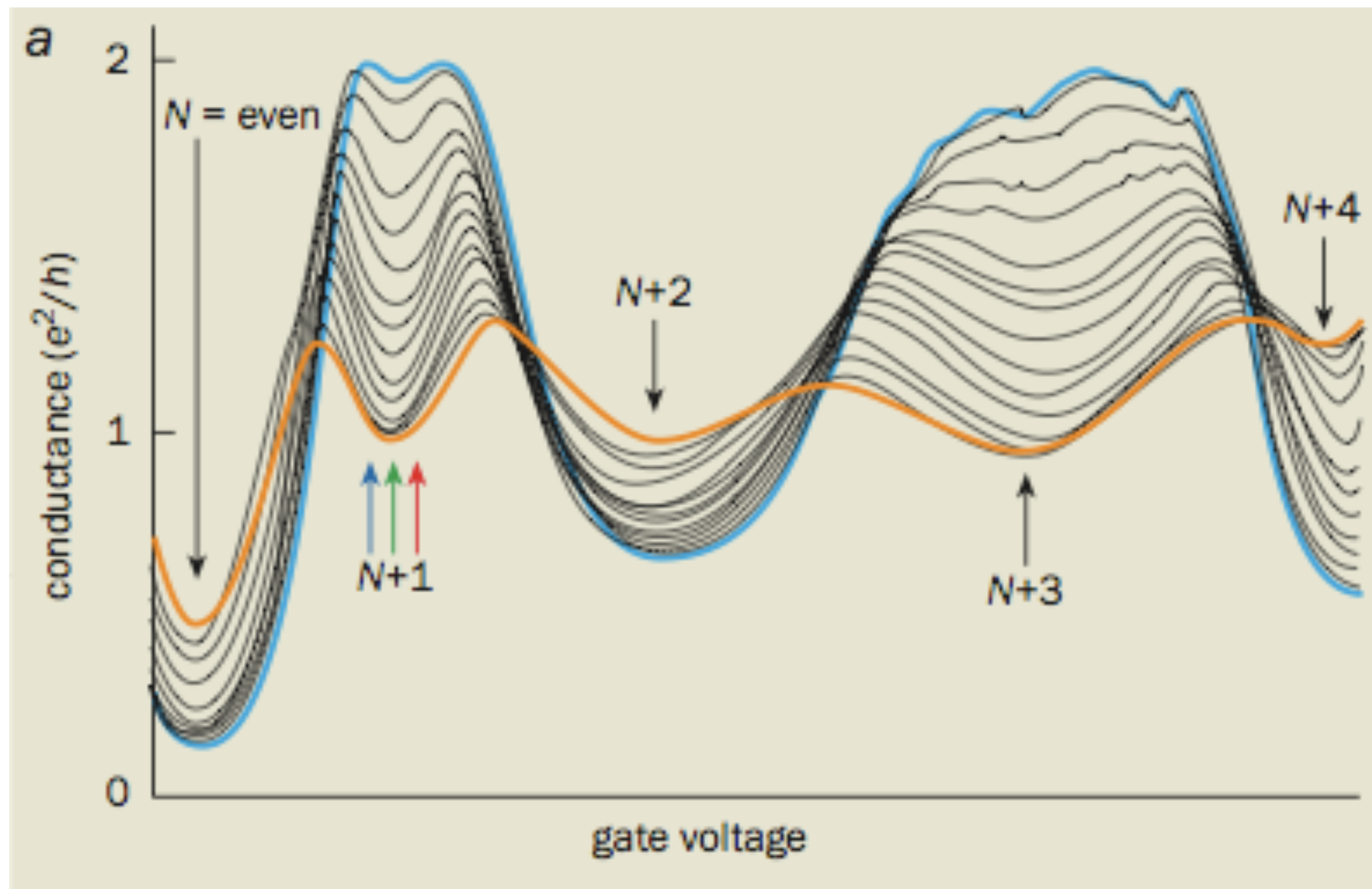
van der Wiel et al, Science (2000)



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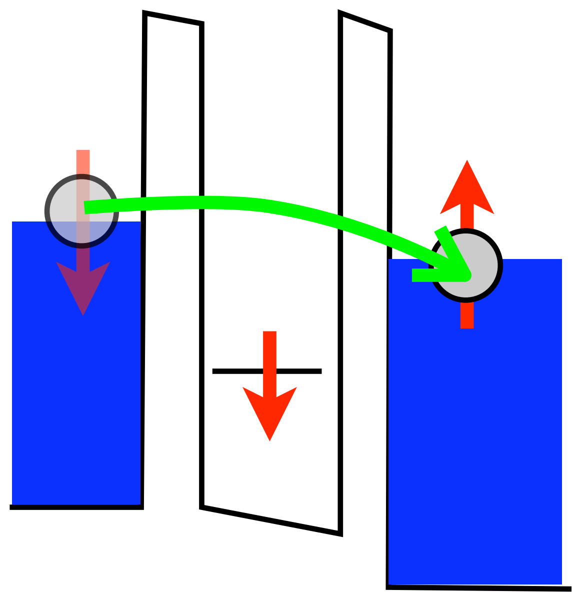

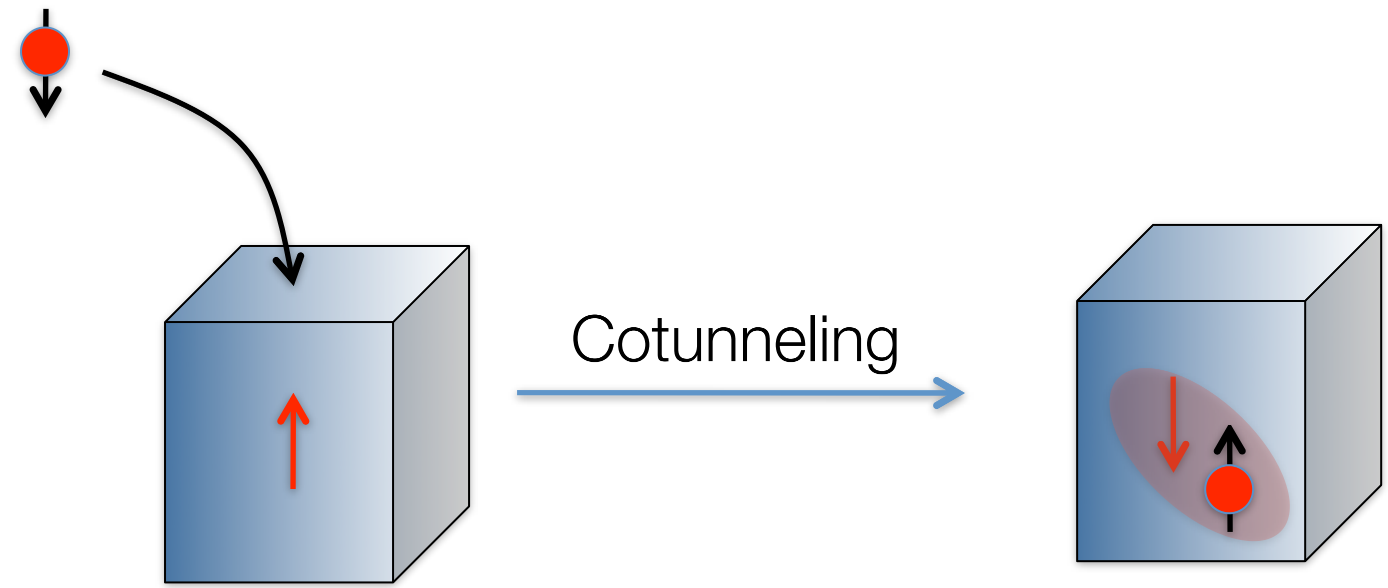

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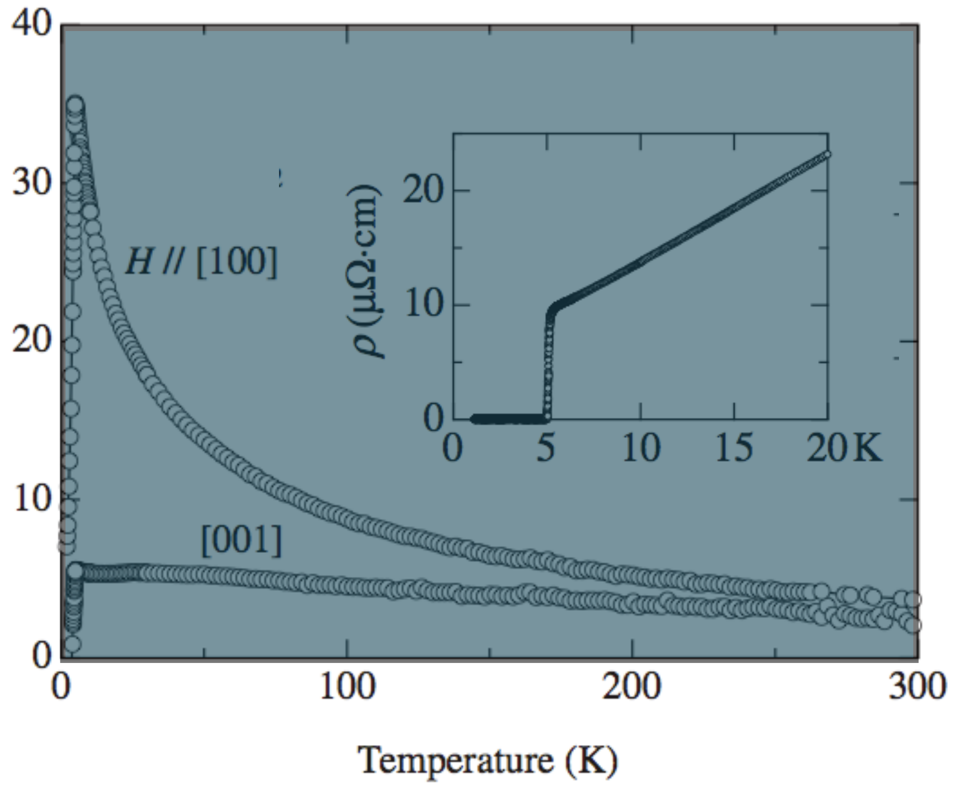
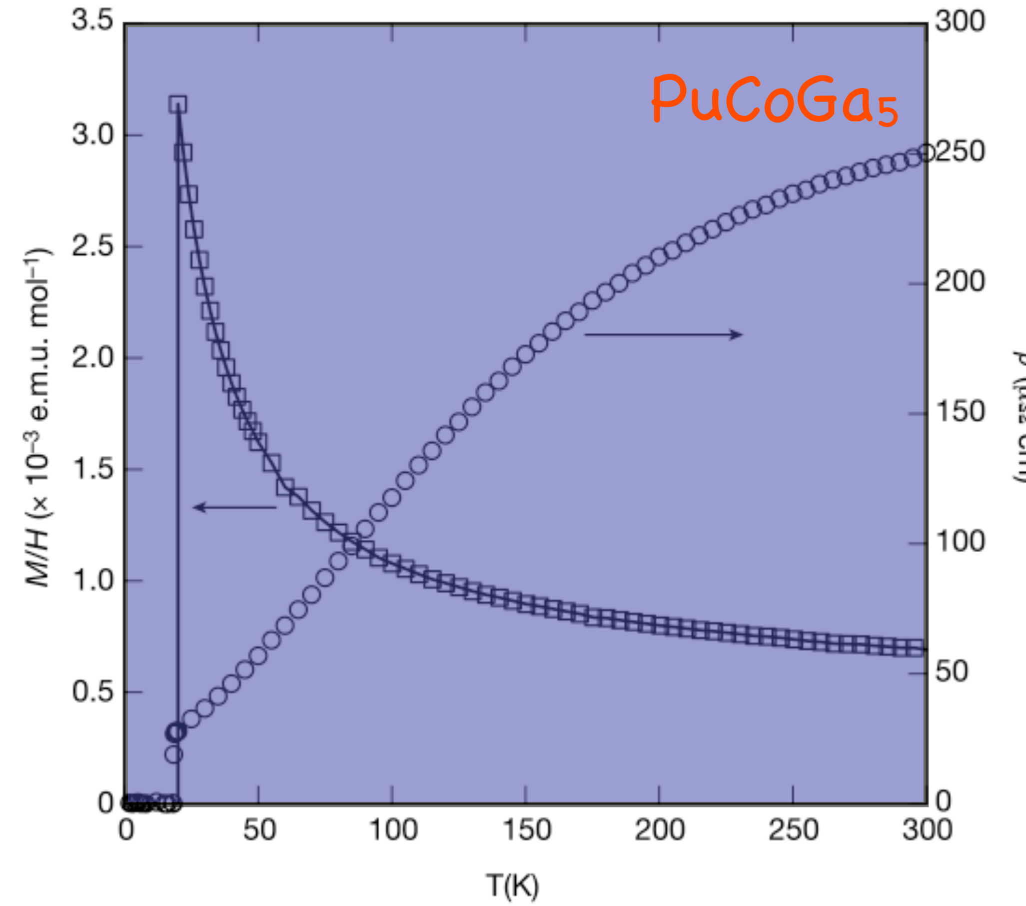
Heavy electron = (electron x spinflip)

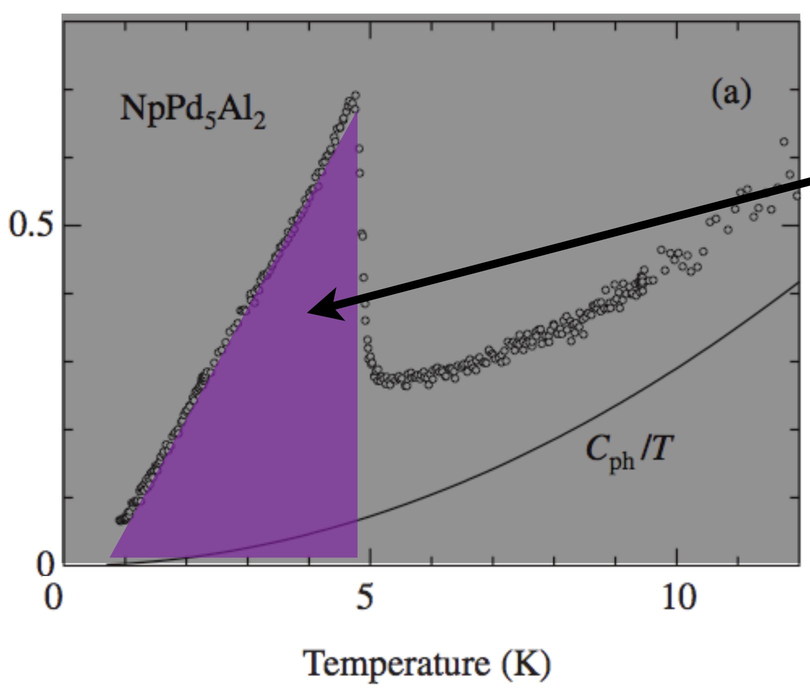
New HF Superconductors: $PuCoGa_5$ & $NpAl_2Pd_5$



Directly Curie PM to SC



Substantial fraction of spin entropy.
1/3 R ln 2



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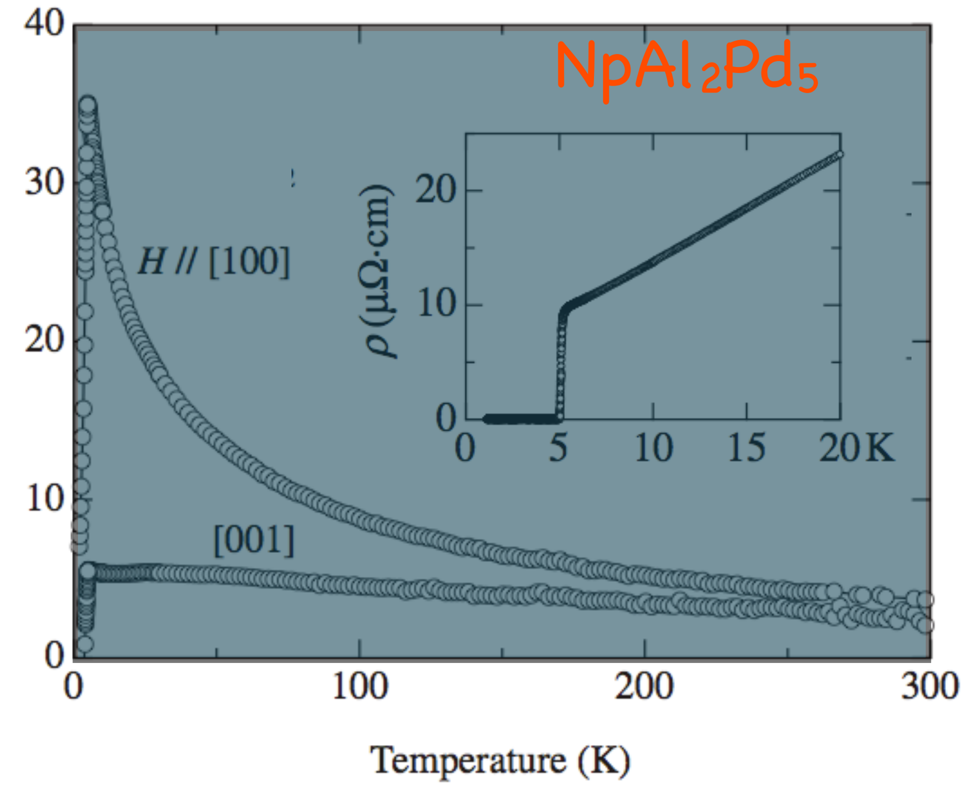

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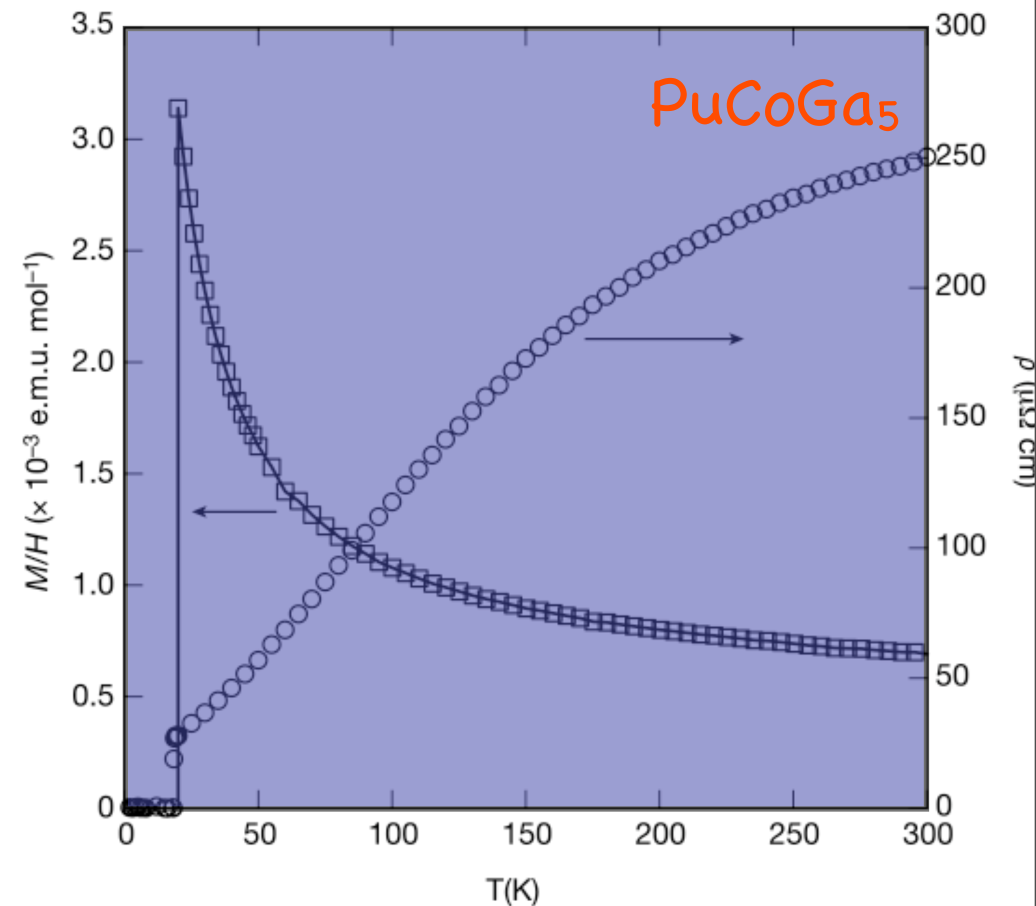

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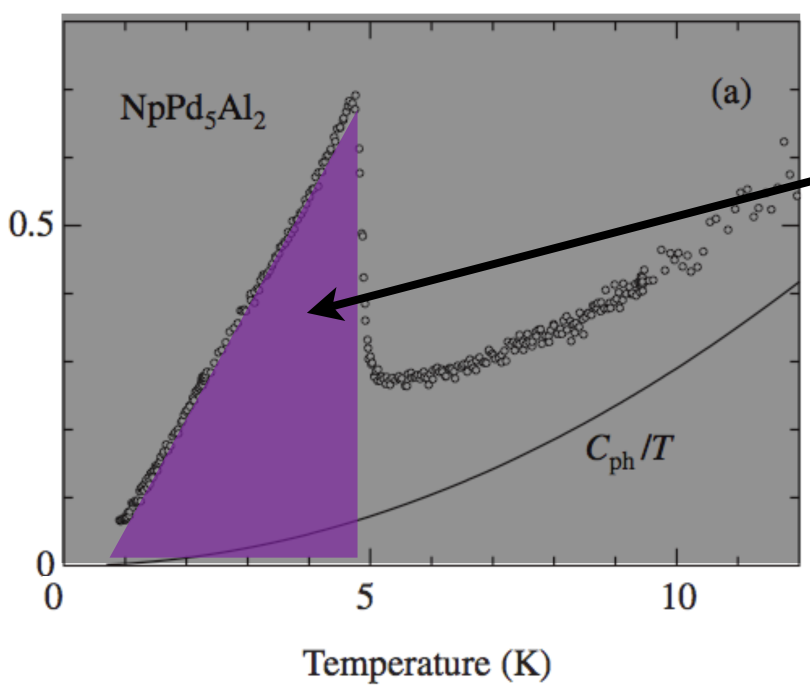
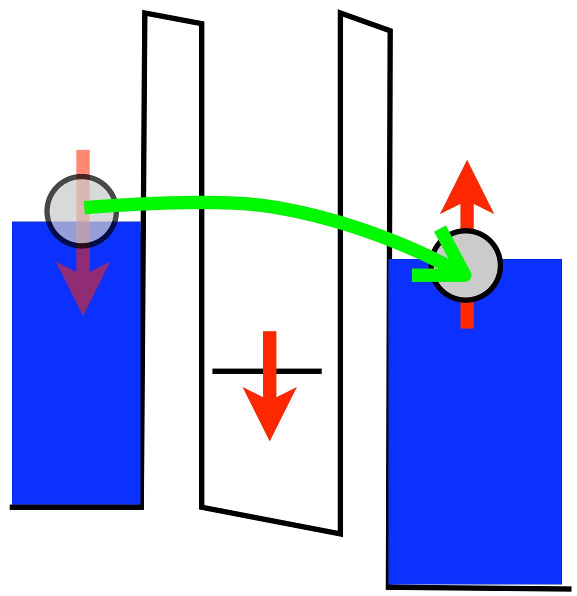
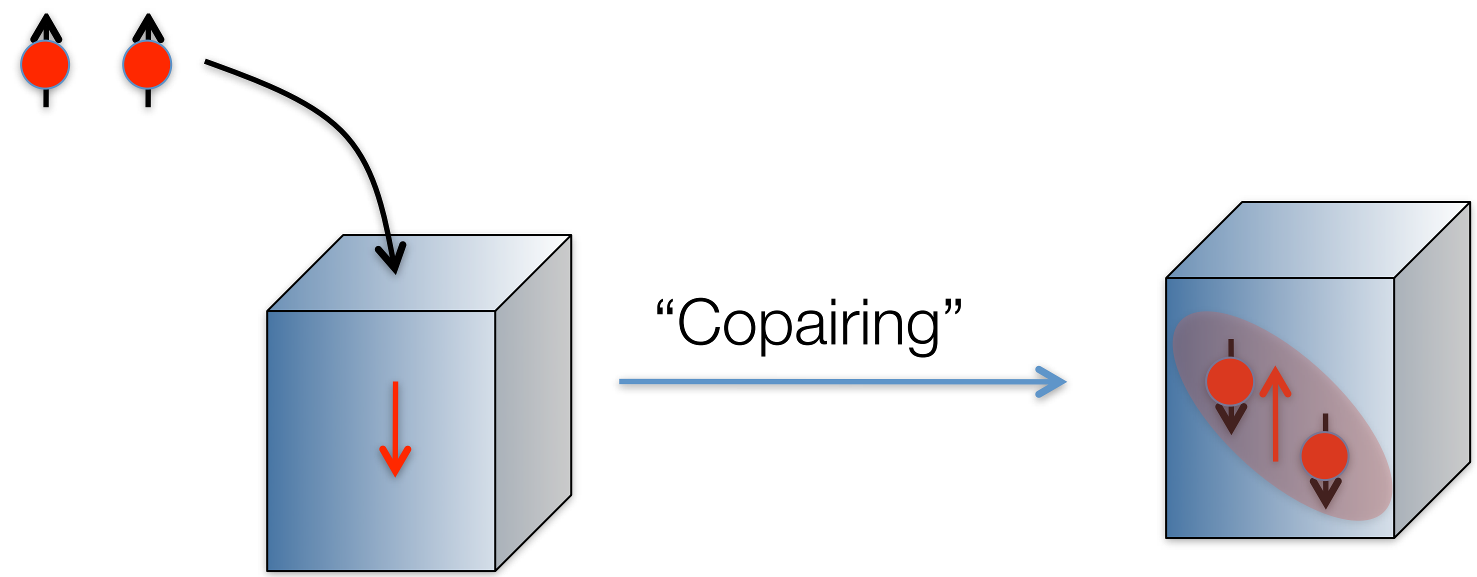


•Suggests Kondo spin quenching and superconductivity develop simultaneously.

•Spin is not the glue, but the *fabric*

Cotunneling and copairing:





Cotunneling

(Glazman +Pustilnik)

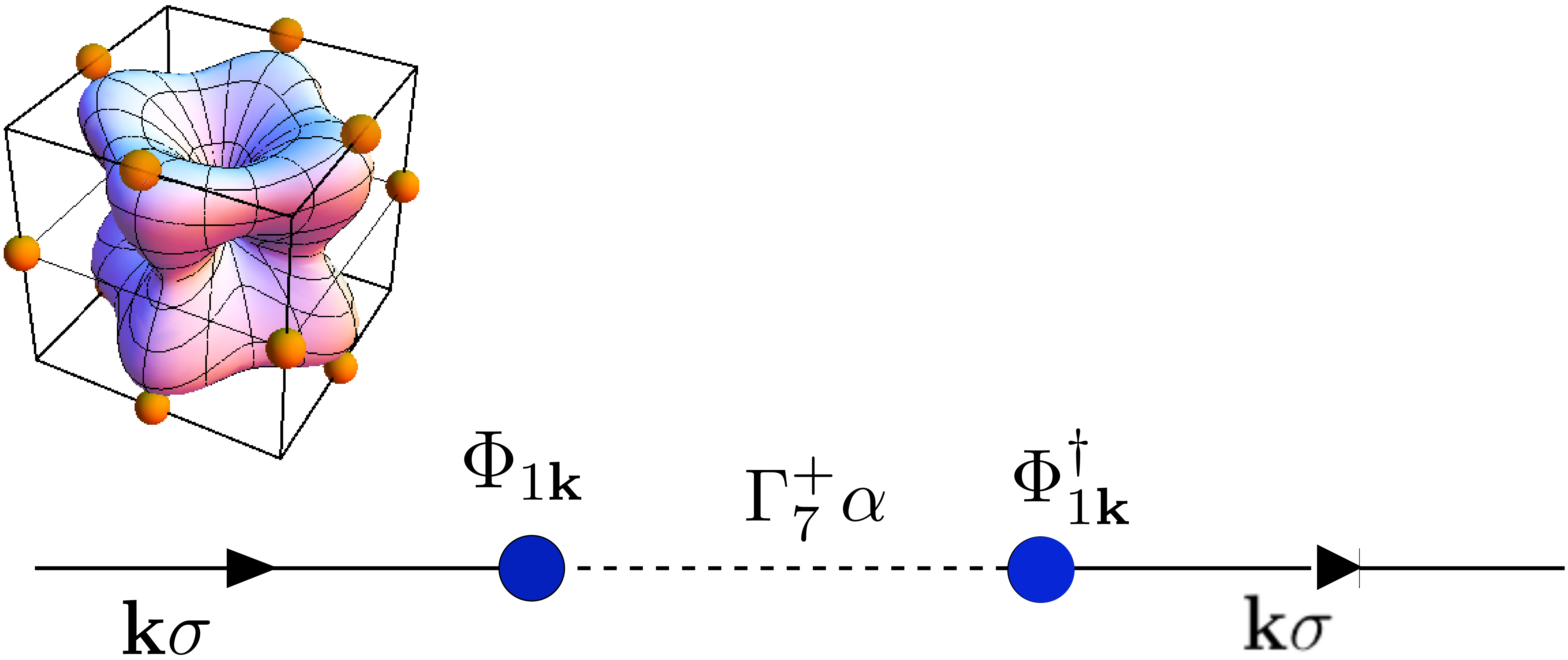
(quantum dots)

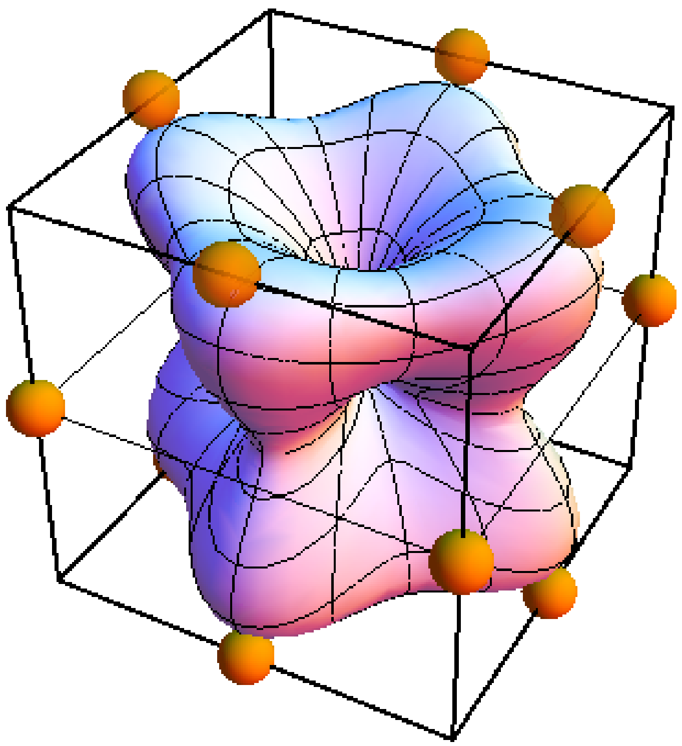
Heavy Cooper pair = (pair x spinflip)

$$f^\dagger_\downarrow = c^\dagger_\uparrow S_-$$

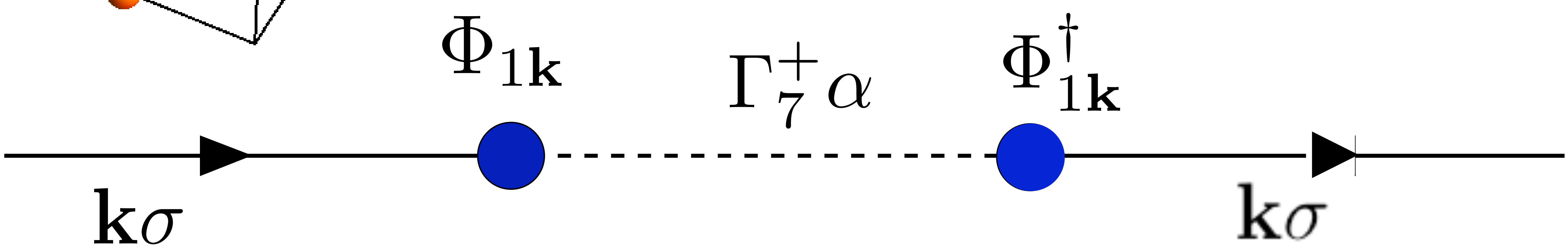
$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

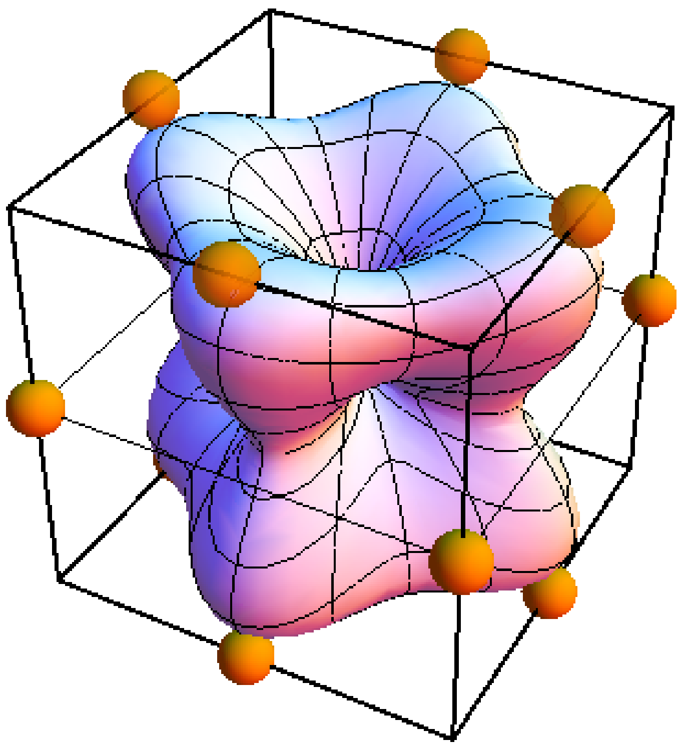
R. Flint et al, Nature Physics, 11 July, 2008.


$\Phi_{1\mathbf{k}}$
$\Gamma_7^+\alpha$
$\Phi^\dagger_{1\mathbf{k}}$
$\mathbf{k}\sigma$
$\mathbf{k}\sigma$



$$= \Phi^{\dagger}_{1\mathbf{k}} . \Phi_{1\mathbf{k}}$$





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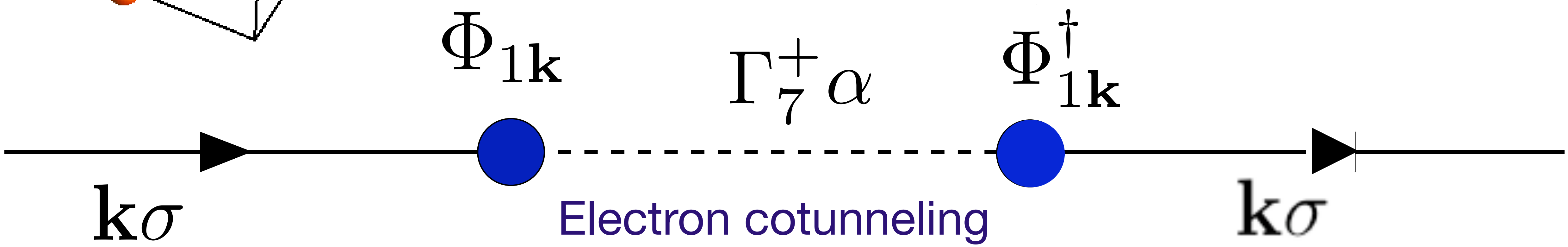
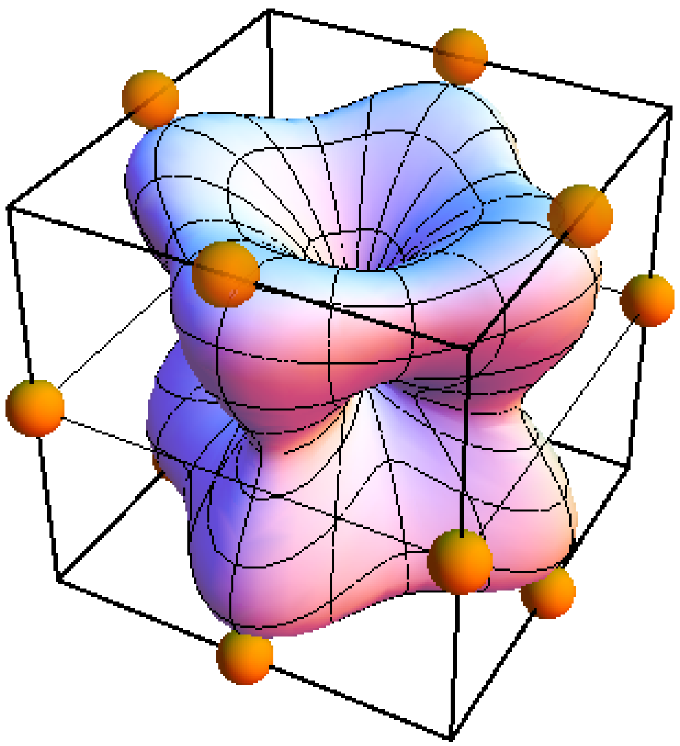
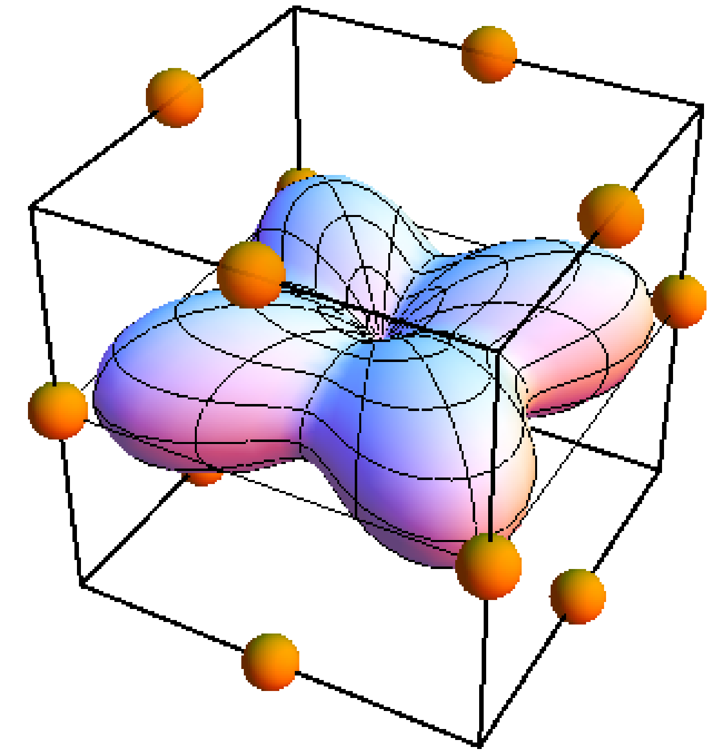
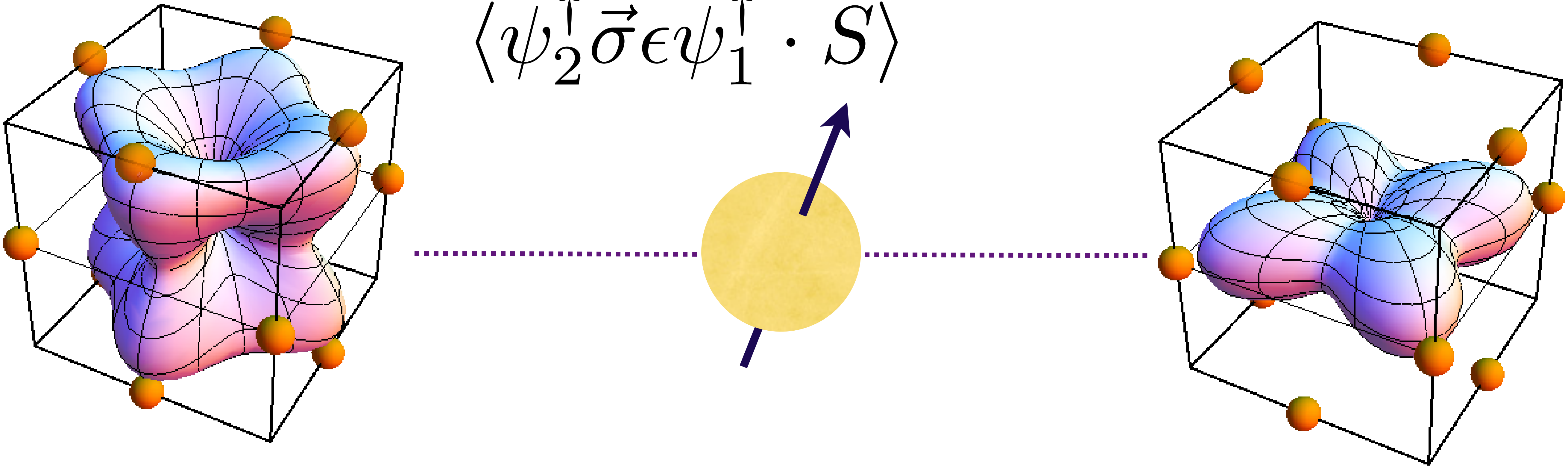
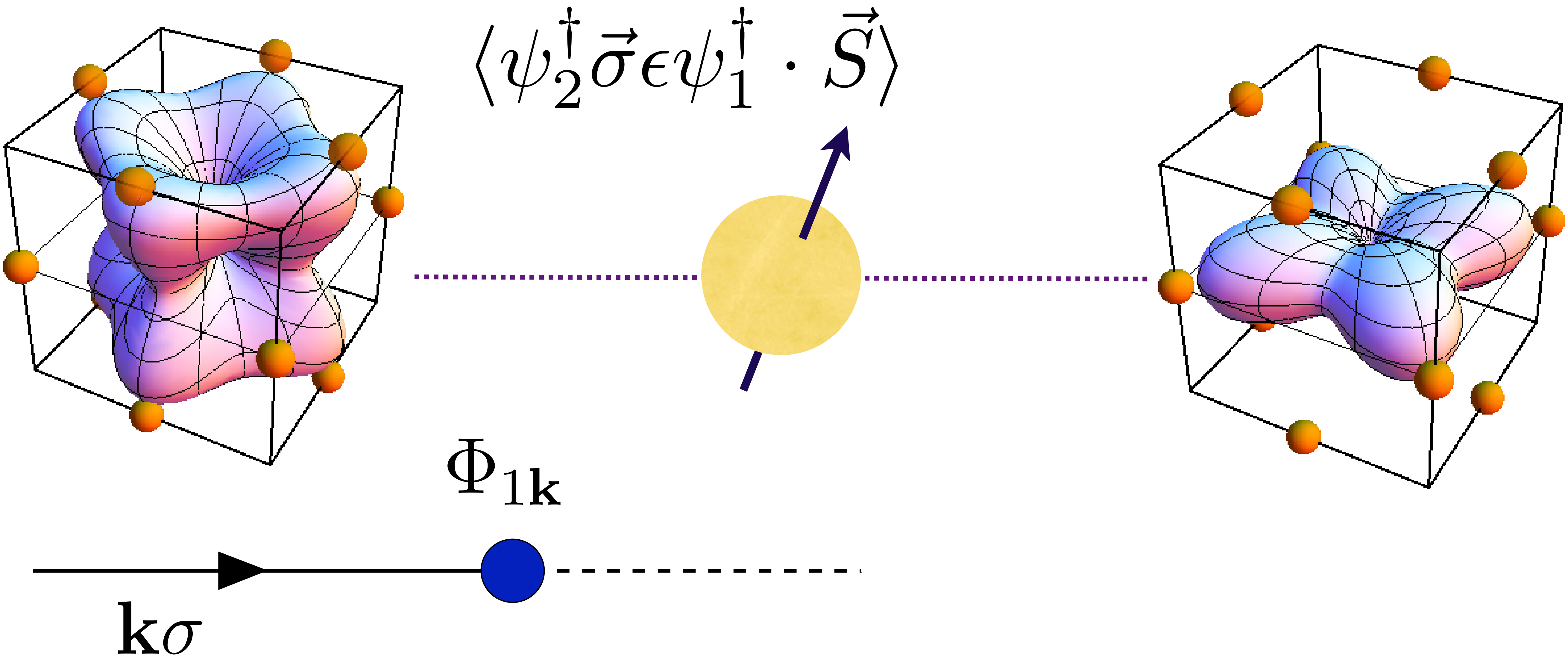


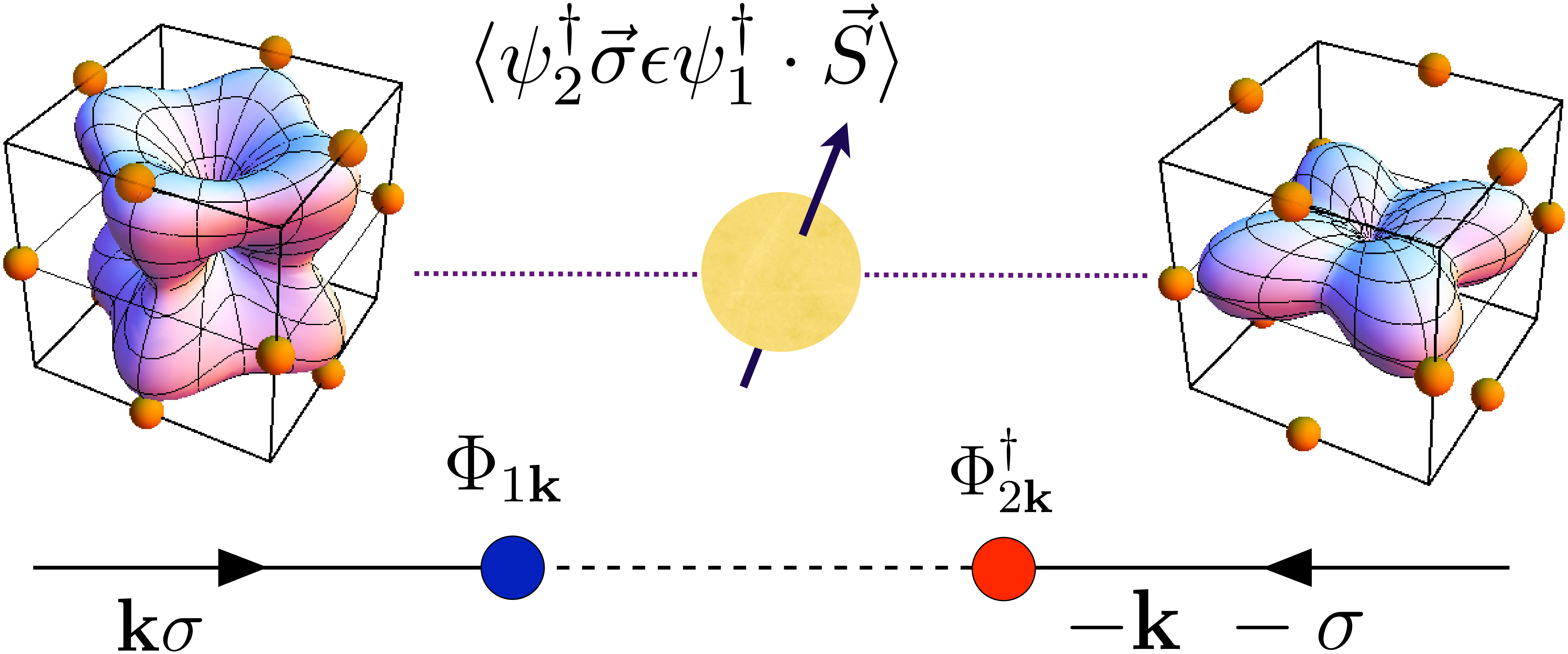




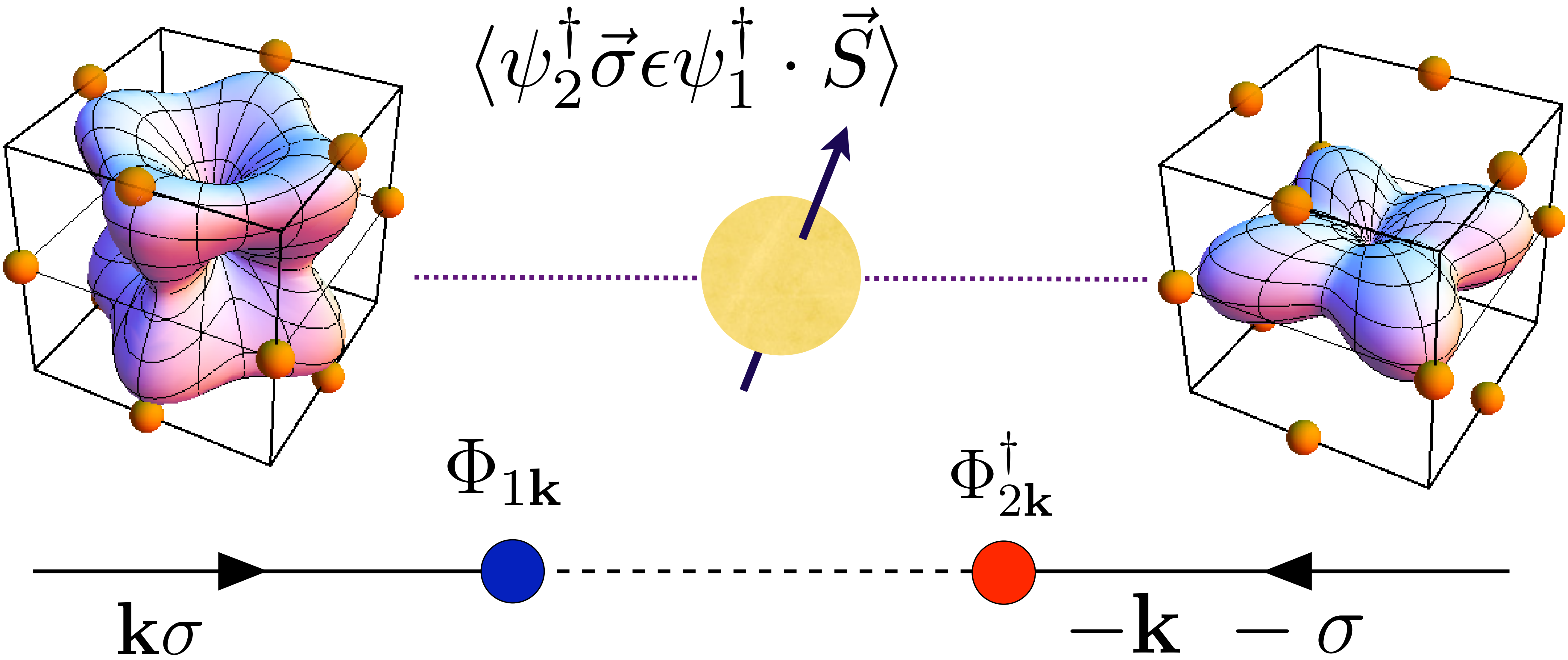
$$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$$




$\langle \psi_2^\dagger \vec{\sigma} \epsilon \psi_1^\dagger \cdot \vec{S} \rangle$
$\Phi_{1\mathbf{k}}$
$\mathbf{k}\sigma$

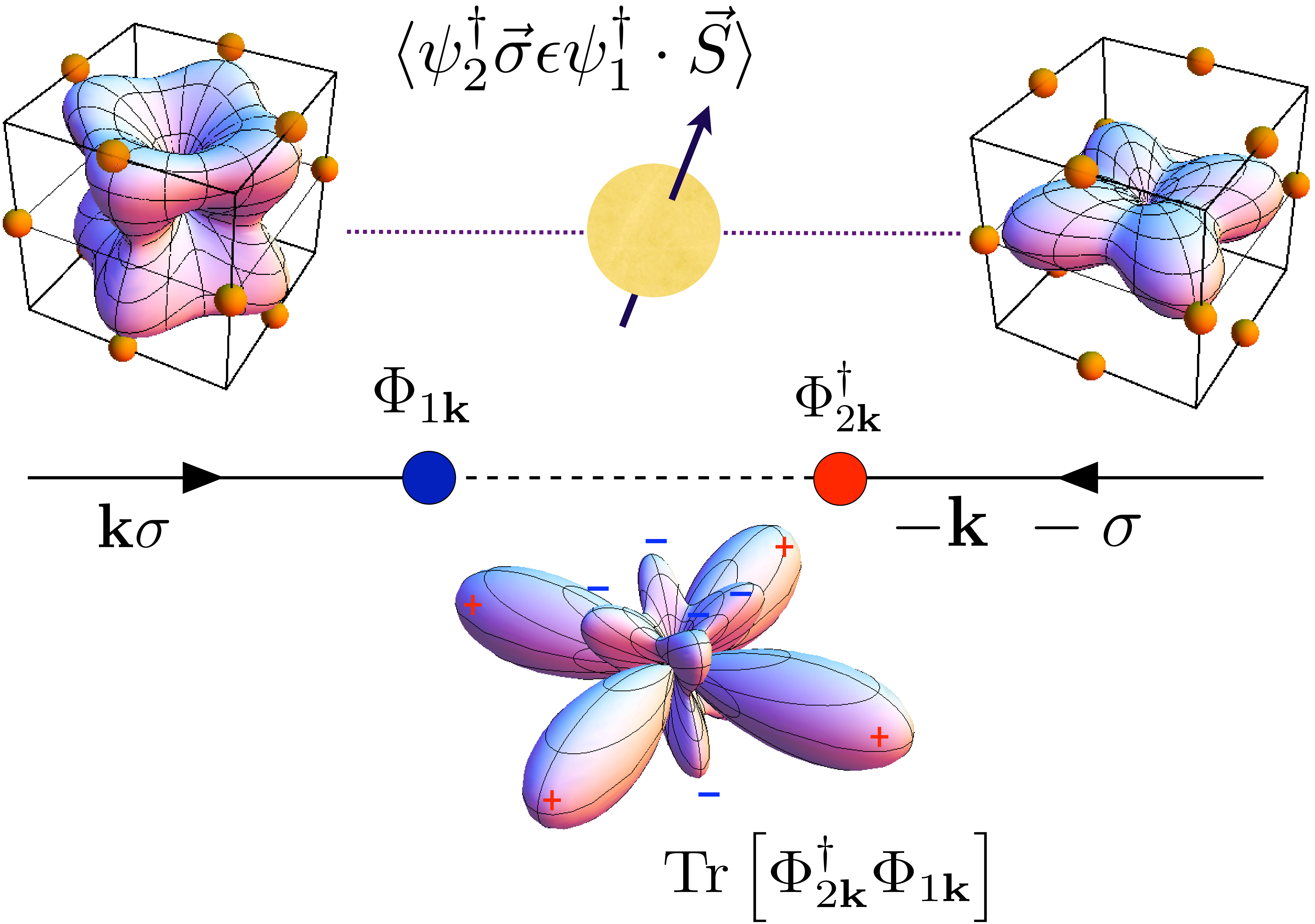


Resonant Andreev Reflection



$$\mathrm{Tr}\left[\Phi_{2\mathbf{k}}^\dagger \Phi_{1\mathbf{k}}\right]$$

Resonant Andreev Reflection



Resonant Andreev Reflection