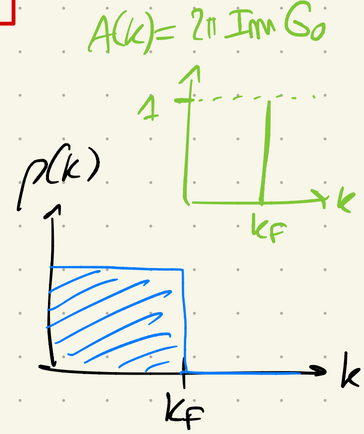
Journal club: Luttinger's theorem

I. Brief reminder: Fermi liquids



- **Free fermions**: $G_0(p, i\omega) = \dfrac{1}{i\omega - \epsilon_p + \mu}$

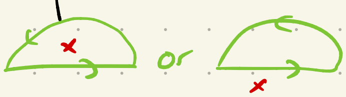
$$N_f = 2 \sum_p \int_{-\infty}^{+\infty} \frac{d\omega}{2\pi} G_0(p, i\omega) e^{i\omega \cdot 0^+}$$

$$= 2 \sum_p \Theta(-\epsilon_p + \mu) = \frac{2 L^d}{(2\pi)^d} \times \mathrm{Vol}(FS).$$

without interactions

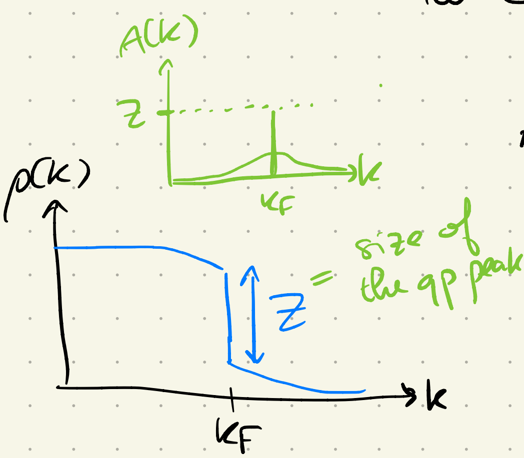
Not a surprise (Pauli exclusion principle).

easy:



- **Interacting fermions**: all the usual stuff with Dyson's equation, etc, and $G(p, i\omega) = \dfrac{1}{i\omega - \epsilon_p^0 + \mu - \Sigma(p, i\omega)}$

self-energy → Re: energy shift; → Im: decay rate.



Assume there is still a FS, i.e.:

long-lived qps.

- $\exists \, E_F$ such that $\mathrm{Im}\, \Sigma(\vec{k}, E_F - \mu) = 0 \quad \forall \vec{k}$
- $\exists \, k_F$ (or more generally a surface) such that $G^{-1}(k_F, E_F - \mu) = 0$ and changes sign between inside/outside the surface.

In particular, $E_F = \varepsilon^0_{k_F} + \mathrm{Re}\, \Sigma(k_F, E_F - \mu)$ defines the surface.

Now, question: what is the size of this FS? I.e: is the k_F with interactions the same as without interactions?

Answer (Luttinger's thm): it remains the same.

↳ $\mathrm{Vol}(FS \text{ without interactions}) = \mathrm{Vol}(FS \text{ with interactions})$.

↳ This looks quite boring.

↳ But actually very interesting sometimes (e.g. HFL).

II. Main idea of the "historical" demonstration

$$G^{-1}(p,i\omega) = i\omega - \epsilon_p^0 + \mu - \Sigma(p,i\omega)$$

$$i\frac{d}{d\omega}\ln G(p,i\omega) = G + iG\frac{d}{d\omega}\Sigma(p,i\omega)$$

$-iG\frac{d}{d\omega}(\text{this})$

<u>Quasiparticles' population:</u>

$$\boxed{\text{NB: by definition, } N_{qp} = N_f}$$

$$N_{qp} = 2\sum_p \int_{-\infty}^{+\infty}\frac{d\omega}{2\pi} G(p,i\omega)e^{i\omega.0^+}$$

$$= 2\sum_p \int_{-\infty}^{+\infty}\frac{d\omega}{2\pi} e^{i\omega.0^+}\Big\{ \underbrace{i\frac{d}{d\omega}\ln G(p,i\omega)}_{\text{"easy"}^{*} \;=\;\Theta(-\epsilon_p^0+\mu-\mathrm{Re}\,\Sigma(p,\epsilon_F))} - \underbrace{iG\frac{d}{d\omega}\Sigma(p,i\omega)}_{\hookrightarrow \text{ goal: show that } \int \text{this} = 0} \Big\}$$

$\rightarrow$ Luttinger's thm <u>will be proven</u>, provided that the second term cancels.

since we will have $N_{qp} = \frac{2L^d}{(2\pi)^d}\,\mathrm{Vol}(\text{FS with interactions})$.

<u>Key idea:</u> there exists a functional $\Phi_{LW}[G]$ $\leftarrow$ Luttinger-Ward such that:

(i) $\Sigma(p,i\omega) = \dfrac{\delta\Phi_{LW}[G]}{\delta G(p,i\omega)}$.

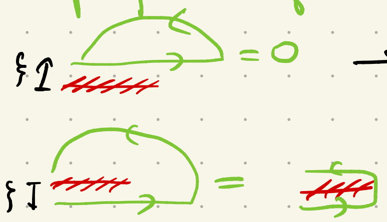
and (ii) $\Phi[G(p,i\omega+i\Omega)] = \Phi[G(p,i\omega)]$: "Ward condition"

$$\text{Then, } \int\frac{d\omega}{2\pi}G(p,i\omega)\frac{\partial}{\partial\omega}\frac{\delta\Phi_{LW}}{\delta G(p,i\omega)} \overset{\text{ibp}}{=} -\int\frac{d\omega}{2\pi}\underbrace{\frac{\partial G(p,i\omega)}{\partial\omega}\frac{\delta\Phi_{LW}}{\delta G(p,i\omega)}}_{=\frac{\partial}{\partial\Omega}\Phi_{LW}[G(p,i\Omega)]\big|_{\Omega=\omega}} = 0$$

<u>Questions that remain:</u>

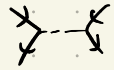
- $\rightarrow$ Does this Φ_{LW} indeed exist?
- $\rightarrow$ What does the "Ward condition" <u>mean</u> physically?

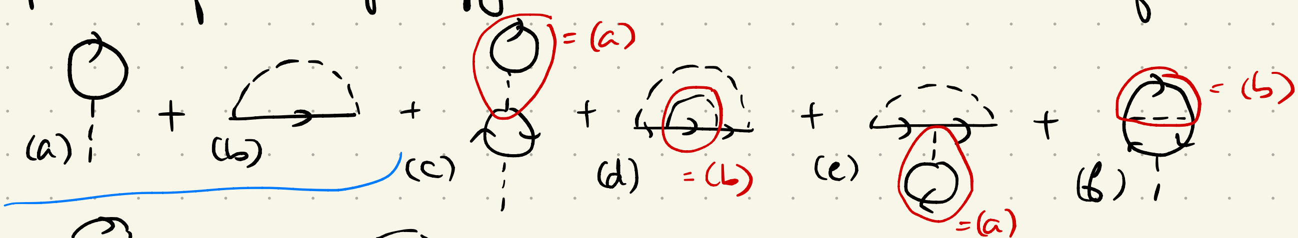
* Only depends upon the analytic properties of $\ln$, actually.

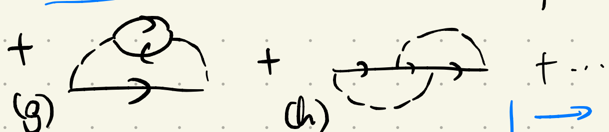


$\rightarrow$ hence $-2i\pi\Theta(-\xi)$

III _ Construction of $\Phi_{LW}[G]$.

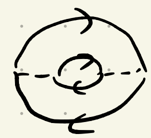
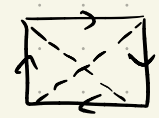
Recall: expansion of the self-energy: consider  interactions for instance.

$\Sigma(p,i\omega) =$ 



→ "skeleton diagrams"

$\Sigma(p,i\omega) =$ sum(skeleton diagrams where $\xrightarrow[G_0]{}$ is replaced by $\xrightarrow[G]{}$).

Define: $\Phi[G] = \frac{1}{2}$  $+ \frac{1}{2}$  $+ \frac{1}{4}$  $+ \frac{1}{4}$  $+ \dots$

(Hartree) (Fock)

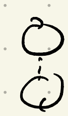
where $\rightarrow = G$, not G_0.

(NB there is a close relationship between $\Phi[G]$ and the energy functional of the electron liquid - see e.g. Giuliani, Vignale).

And one can check that, by construction, $\Sigma(p,i\omega) = \dfrac{\delta\Phi[G]}{\delta G(p,i\omega)}$.

<u>As for the Ward condition</u>:

Physically, actually quite obvious, $i\omega \to i\omega + i\Omega$ just shifts the origin of energies, so $\Phi[G]$, which is very much like the total energy of the liquid, is conserved up to a cst.

Mathematically, even more obvious: in $\Phi[G] =$  +  + ...,
all the fermion loops are closed, which means that one integrates over $\int_{-\infty}^{+\infty} d\omega$, so obviously $\Phi[G]$ is invariant under a shift of ω.

IV. About $U(1)$ symmetry and the Ward condition

→ Starting point: $L = \sum_p c^\dagger_{p\sigma}\left(\frac{\partial}{\partial\tau} + \varepsilon^0_p - \mu\right)c_{p\sigma}$ + Interactions.

One "implicit" assumption of the FL theory is the conservation of particle number by the interactions (cf adiabatic concept).

I.e. global $U(1)$ symmetry: $\begin{cases} c_{p\sigma} \mapsto c_{p\sigma}e^{i\theta} \\ c^\dagger_{p\sigma} \mapsto c^\dagger_{p\sigma}e^{-i\theta} \end{cases}$ leaves L invariant (including the Interactions).

→ Consequence: time-dependent $U(1)$ sym $\begin{cases} c_{p\sigma}(\tau) \mapsto c_{p\sigma}(\tau)e^{i\Omega\tau} \\ c^\dagger_{p\sigma}(\tau) \mapsto c^\dagger_{p\sigma}(\tau)e^{-i\Omega\tau} \end{cases}$

leaves L invariant up to a shift of μ "gauge transfo."

Thus $G(p,i\omega) = \int e^{i\omega\tau}\langle T c_p(\tau)c^\dagger_p(0)\rangle$

with the new $\int d\tau\, L$ and new measure (also invar.)

$$\mapsto \int e^{i\omega\tau}\langle T c_p(\tau)e^{i\Omega\tau}c^\dagger_p(0)\rangle = G(p, i\omega + i\Omega).$$

→ There is a set of correlation functions which are conserved by this transformation (basically all the "gauge-invar. quantities" indep. of μ).

The conservation laws are the Ward identities.

There is one such law for $\Phi[G]$.

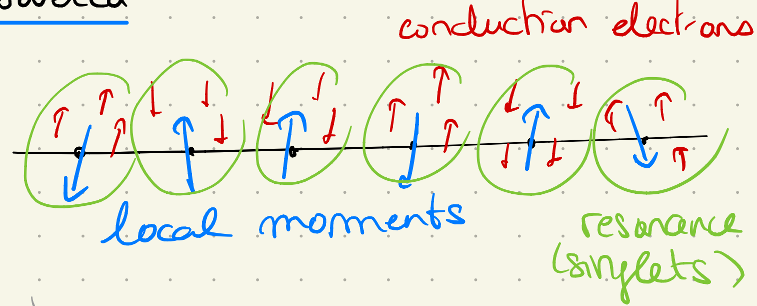
$\Rightarrow$ $\Phi[G(p,i\omega)] = \Phi[G(p,i\omega+i\Omega)]$ is thus understood as a Ward identity for the global $U(1)$ symmetry of the FL lagrangian.

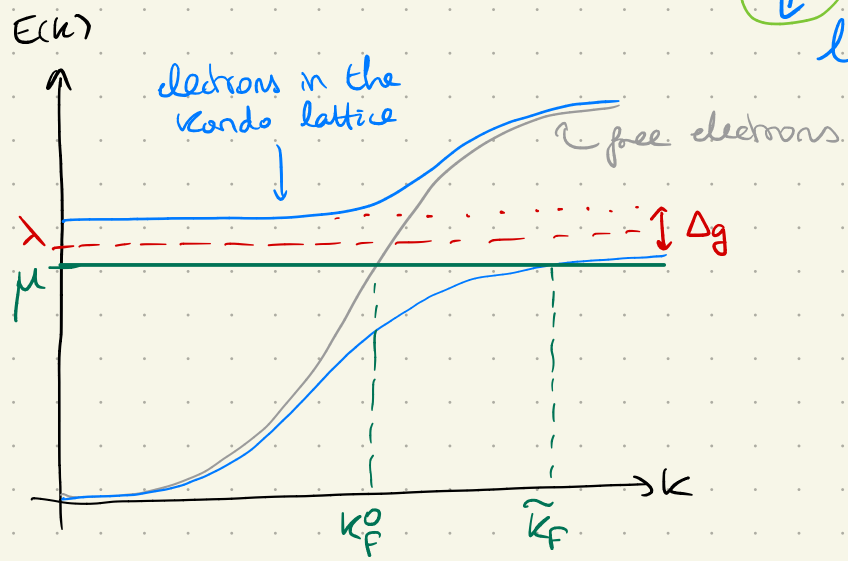
Luttinger's theorem

$$\boxed{\begin{array}{ccc} \text{Number conservation} & \longleftrightarrow & \text{Volume conservation} \\ \uparrow & \text{Ward identity} & \uparrow \\ \text{Sym. of the Lagrangian} & & \text{Sym. of the correlations} \end{array}}$$

V – Questions that remained unanswered

Physics of the Kondo lattice:





$\lambda \sim$ chemical potential for the local moments

$\Delta_g =$ gap opened by the resonance

$\mu =$ chemical potential of the conduction electrons.

- k_F^0 : "small" FS of the free electrons; $m_* \propto \left|\frac{d^2 E_F}{dk^2}\right|^{-1}$ light
- $\tilde{k}_F$: "large" FS of the renormalized fermions. m_* large : heavy fermions.

But Luttinger's thm tells us that the FS volume should be conserved!
→ is this a breakdown of Luttinger's thm?

The Kondo effect is known to be nonperturbative (e.g. $T_K = D e^{-\frac{1}{J\rho}}$)

Kondo temperature; conduction bandwidth; coupling; e^- density

→ is Luttinger's thm true perturbatively but fails nonperturbatively?

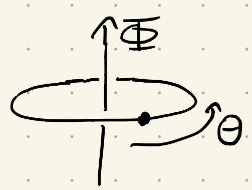
→ or is there a nonperturbative proof of the theorem?

Note about LSM: "equivalent" to Luttinger in 1D (see other paper by M.O.) cf Jordan-Wigner and the XXZ chain.

Mapping to fermions (interacting as soon as $J_z \neq 0$) with filling $\nu = m_z + \frac{1}{2}$ shows the equivalence.

(And LSM actually generalize this to $S \in \mathbb{N} + \frac{1}{2}$, with $\nu = m_z + S$).

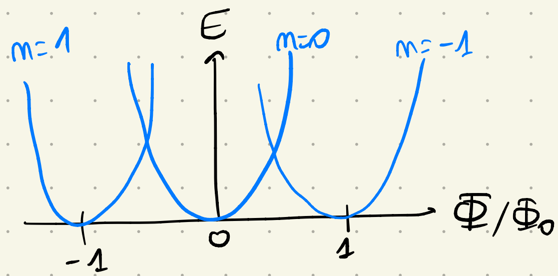
VI. A (very) brief reminder: Aharonov-Bohm effect



Particle constrained to move along a ring.

$$H = \frac{1}{2m}(p+eA)^2 = \frac{1}{2m}\left(-i\hbar\frac{\partial}{\partial\theta} + \frac{e\Phi}{2\pi}\right)^2 .$$ $\left(\Phi_0 = \frac{h}{e}\right)$

Eigenfunctions: $\psi_m = \frac{1}{\sqrt{2\pi}} e^{im\theta}$, $m \in \mathbb{Z}$; eigenvalues: $E_m = \frac{1}{2m}\left(m + \frac{\Phi}{\Phi_0}\right)^2$



<u>Spectral flow</u>: take $\Phi \to \Phi_0$.

This takes $H \mapsto H' = \frac{1}{2m}\left(-i\hbar\frac{\partial}{\partial\theta} + e\frac{\Phi}{2\pi} + 1\right)$

and $\psi_m \mapsto \psi_m' = \psi_m e^{-i\int_0^\theta \vec{A}\cdot d\vec{r}} = e^{-\frac{ie}{\hbar}\frac{\Phi_0}{2\pi}\theta}\psi_m$

$= e^{-i\theta}\psi_m = \psi_{m-1}$

such that $H'\psi_m' = E_m \psi_m'$. *

VII. The proof by Oshikawa

- <u>Main idea</u>: recycle an argument about the LSM theorem in dimension D.

Take a system of size $L_1 \times \cdots \times L_D$ with periodic b.c. ("D-dim tore").

Then insert a flux along axis x_1, in the gauge $A_1 = \Phi / L_1$, adiabatically from $\Phi = 0$ to $\Phi = \Phi_0$. $H(0)|\psi_0\rangle = E_0|\psi_0\rangle$

This evolves $H(\Phi=0) \mapsto H(\Phi_0)$, and the g.s. $|\psi_0\rangle \mapsto |\psi_0'\rangle$

and the reminder hereabove tells us that $H(\Phi_0)|\psi_0'\rangle = E_0|\psi_0'\rangle$. *

Now imagine there is a unitary $\hat{U}$ such that $UH(\Phi_0)U^{-1} = H(0)$.

Then, $H(0)\hat{U}|\psi_0'\rangle = \hat{U}H(\Phi_0)|\psi_0'\rangle = E_0\hat{U}|\psi_0'\rangle$. ↳ in VI, $U(\theta) = e^{i\theta}$

So we've shown that in the gauge choice where H is fixed, insertion of a flux Φ_0 sends $\boxed{|\psi_0\rangle \to U|\psi_0'\rangle}$. ⤳ in the case of VI, $U\psi_m' = \psi_m$ quite boring*

* Indeed, LT for (VI) states "$2\pi \times 1 \in 2\pi\mathbb{Z}$" not wow.
[1 particle on the ring]

- <u>How does one build $\hat{U}$?</u>

Action of the flux insertion upon particles: $\begin{cases} c_{r,\sigma} \mapsto e^{i2\pi x_1/L_1} c_{r,\sigma} \\ c^\dagger_{r,\sigma} \mapsto e^{-i2\pi x_1/L_1} c^\dagger_{r,\sigma} \end{cases}$.

$\Rightarrow$ Choose $\hat{U} = \exp\left(i\frac{2\pi}{L_1}\sum_{\vec{r},\sigma} x_1 n_{\vec{r},\sigma}\right)$.

One can check it takes $U c_{r\sigma} U^{-1} \mapsto c_{r,\sigma}$ and $U c^\dagger_{r,\sigma} U^{-1} \mapsto c^\dagger_{r,\sigma}$ independently.

As long as $H(0)$ is built out of $c^\dagger_s$ and c_s, it ensures $U H(\Phi_0) U^{-1} = H(0)$.

- <u>Momentum transformation:</u> one had $\hat{P}_x|\Psi_0\rangle = P_x^0|\Psi_0\rangle$ $\quad$ generator of transl.; $T_x = e^{iP_x}$ $\quad$ $(x \equiv x_1)$

(assumption of the FL: translation sym. is not broken).

Since $[H(\Phi), P_x] = 0 \ \forall \Phi$, $\hat{P}_x|\Psi_0'\rangle = P_x^0|\Psi_0'\rangle$ as well. $\rightsquigarrow$ ⚠ Very different* from VI: that's because $P_x^0 + 2\pi \equiv P_x^0$. *(at first sight)

But one can check $\hat{U}^{-1} e^{i\hat{P}_x}\hat{U} = e^{iP_x}\exp\left(i\frac{2\pi}{L_1}\sum_{\vec{r},\sigma} n_{\vec{r},\sigma}\right)$

Thus $e^{iP_x} U|\Psi_0'\rangle = \hat{U} e^{i\hat{P}_x}|\Psi_0'\rangle e^{i\frac{2\pi}{L_1}\sum n_{r\sigma}} = \exp\left(iP_x^0 + i\frac{2\pi}{L_1}\sum_{r\sigma} n_{r\sigma}\right) U|\Psi_0'\rangle$

$$\Rightarrow \hat{P}_x(U|\Psi_0'\rangle) = P_x^0 + 2\pi \nu L_2 L_3 \cdots L_D$$

particle number per unit cell.

- <u>FL hypothesis:</u> there are $N_F^{(L)}$ quasiparticles occupying $V_F^{(L)} = \frac{(2\pi)^D N_F^{(L)}}{L_1 \cdots L_D}$

NB this is very different from the "historical proof": we do not use the adiabatic concept leading to $\rho_{qp} = \rho_e$, but instead we define a qp as the "unit of matter" occupying a unit volume of the FS.

Put more clearly: $\begin{cases} \text{Luttinger: we know } N_F^{(L)} = N_F^0\text{; now show } \frac{V_F^{(L)}}{N_F^{(L)}} = \frac{V_F^0}{N_F^0}. \\ \text{Oshikawa: we know } \frac{V_F^{(L)}}{N_F^{(L)}} = \frac{V_L^0}{N_F^0}\text{; now show } N_F^{(L)} = N_F^0. \end{cases}$

And minimal coupling tells us that $k_1 \to k_1 + eA_1 = k_1 + 2\pi/L_1$ $\quad$ now this is similar to VI.

Thus $\Delta P_x = N_F^{(L)} \cdot \frac{2\pi}{L_1}$. And recall this is also $2\pi\nu L_2 \cdots L_D$.

- <u>Identification:</u> $\frac{2\pi}{L_1}(\underbrace{N_F^{(L)}}_{= N_F^0} - \nu L_1 \cdots L_D) = 2\pi \times \text{integer}$ $\quad$ (since momentum is defined mod 2π.)

Provided the L_i are incommensurate, $N_F^{(L)} - \nu L_1 \cdots L_D = L_1 L_2 \cdots L_D \times \text{integer}$.

$$\longrightarrow \boxed{\frac{V_F^{(L)}}{(2\pi)^D} - \nu = m \in \mathbb{Z}}$$

Luttinger's thm

m = number of filled bands.

VIII. The Kondo lattice: Oshikawa's bold move

$= c^\dagger_{j\alpha} \vec{\sigma}_{\alpha\beta} c_{j\beta}$

local qubit

Now take $H_{KL} = -\sum_{ij} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_j n_{j\uparrow} n_{j\downarrow} + \sum_j J^K_j \vec{s}_j \cdot \vec{S}_j$

and a fictitious, spin-dependent, flux insertion $c^{(\dagger)}_{j\uparrow} \to c^{(\dagger)}_{j\uparrow} \exp[(-) i 2\pi x_1 / L_1]$.

And Oshikawa writes "we must now use $U_\uparrow = \exp\left(i \frac{2\pi}{L_1} \sum_r x_1 (n_{r,\uparrow} + S^z_r) \right)$".

(The result being $\frac{2V_F}{(2\pi)^D} - \nu = 2 N_s S$ consistent with the HFL theory).

But this means that implicitly, he consider that the flux insertion must also take $S^\pm_r \to S^\pm_r e^{\mp i 2\pi x_1 / L_1}$; i.e. that somehow, the local qubits $\vec{S}_j$ are charged under the same $U(1)$ as the electrons. Why?

IX. Why should spins become fermions?

How come that localized spins can "put more fermions into the FS"?

(1) Back to Anderson's model.

Conduction electrons $c^\dagger_{k\sigma}$ coupled to a localized orbital d_σ.

$$\hat{H}_{c\text{-}d} = \sum_{k\sigma} \left(\epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + (V_k d^\dagger_\sigma c_{k\sigma} + h.c.) \right) + \sum_\sigma \epsilon_\sigma n_{d\sigma} + U n_{d\uparrow} n_{d\downarrow}$$

and recall that 2nd-order perturbation theory: $\hat{H}_{c\text{-}d} \mapsto \hat{H}_K$

where $\hat{H}_K = \sum_{k\sigma} \epsilon_{k\sigma} c^\dagger_{k\sigma} c_{k\sigma} + 2 J_K \hat{\vec{S}}_d \cdot \hat{\vec{s}}_c(\vec{r} = \vec{0})$

$\vec{0}$ = position of d

$$\vec{S}_d = \sum_{\alpha\beta} d^\dagger_\alpha \vec{\sigma}_{\alpha\beta} d_\beta$$

$\hat{S}^+_d \equiv \hat{d}^\dagger$, $\hat{S}^-_d \equiv \hat{d}$

→ The fact that $\hat{S}^\pm_d$ are charged like the conduction electrons is inherited from their being the spin of the d-electron.

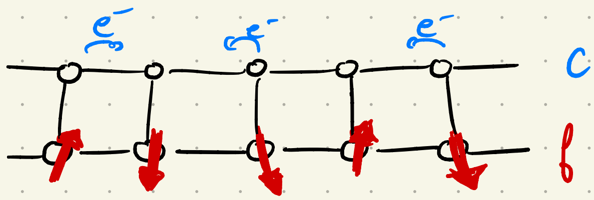
feeling

(2) Fractionalize the spin

There's something fishy in the previous argument: we are not supposed to know that our spins $\vec{S}_j$ are those of hidden d-electrons.
"Oshikawa's theorem" should hold for any qubit $\vec{S}_j$, even a nuclear spin!

Solution: assume that the qubit $\vec{S}_j$, regardless of its physical nature, is fractionalized into fermions, i.e. write $\vec{S}_j = f^\dagger_{j\alpha} \vec{\sigma}_{\alpha\beta} f_{j\beta}$ "fictitious" fermions
and the constraint $f^\dagger_{i\sigma} f_{i\sigma} = 1 \ \forall i \longrightarrow U(1)_{gauge}$.

Back to the Kondo lattice: $c^\dagger$ with density p, $f^\dagger$ with density 1.



$$\boxed{\mathcal{H}_{KL} = \sum_p \epsilon_p c^\dagger_{p\sigma} c_{p\sigma} + J_k \sum_i c^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} c_{i\beta} \vec{S}_i}$$

→ Hybridization $c^\dagger_{i\alpha} c_{i\beta} f^\dagger_{i\beta} f_{i\alpha}$ with group $U(1) \times U(1)_{gauge}$.

→ Now our $f^\dagger$ fermions are either localized d-electrons, or some kind of localized fictitious fermions, and in both cases they are charged under a $U(1)_{gauge}$ ensuring there is one fermion per site.

→ Question: only the $c^\dagger$ fermions are mobile, and they have density p → where does the large heavy FS come from?
↳ of density $1+p$.

X – When does the FS actually become large?

$$H_{hyb} = (c^\dagger_{j\beta} f_{j\beta})(f^\dagger_{j\alpha} c_{j\alpha}) \quad \text{with gauge group } U(1)_c \times U(1)_f .$$

- First case: $V_{j\beta} = \langle c^\dagger_{j\beta} f_{j\beta} \rangle \neq 0$ spontaneous sym. breaking.
  $\rightarrow U(1)_c \times U(1)_f$ broken down to $U(1)$.

(Note $c^\dagger_{j\beta} f_{j\beta}$ corresponds to a singlet formation, $\downarrow\uparrow$.)

Both $c^\dagger$ and $f^\dagger$ are charged under the remaining $U(1)$.
The GS is a Slater determinant of (c, f), with density $p+1$.
This is the Kondo physics i.e. what Oshikawa wanted to achieve.

- Second case: $V_{j\beta} = 0$ and $U(1)_c \times U(1)_f$ remains unbroken.

Then $\vec{S}_j$ is not charged like the conduction electrons, the GS is (Slater(c))$\times$(Slater(f)) and the FS density is p.
It seems boring at first sight, maybe that's why Oshikawa did not mention this case.
NB actually there is some interesting physics there (FL* criticality, ...)

That's all folks!