Higgs Amplitude Mode in Ferromagnetic Metals

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Dedicated to
Gerry Brown, 7/22/1926 – 5/30/2013

Outline

- Field Theory 101
- Higgs amplitude modes in Condensed Matter
- Stoner Model for ferromagnetic metals
- Ferromagnetic Fermi Liquid Theory for Itinerant Ferromagnetism
- In search of the Higgs in Ferromagnetic Metals
- Conclusion and Future work

Goldstone and Higgs Amplitude Modes in Field Theory

The simplest ordered phase can be characterized by the order parameter, $\Psi(r,t)$:

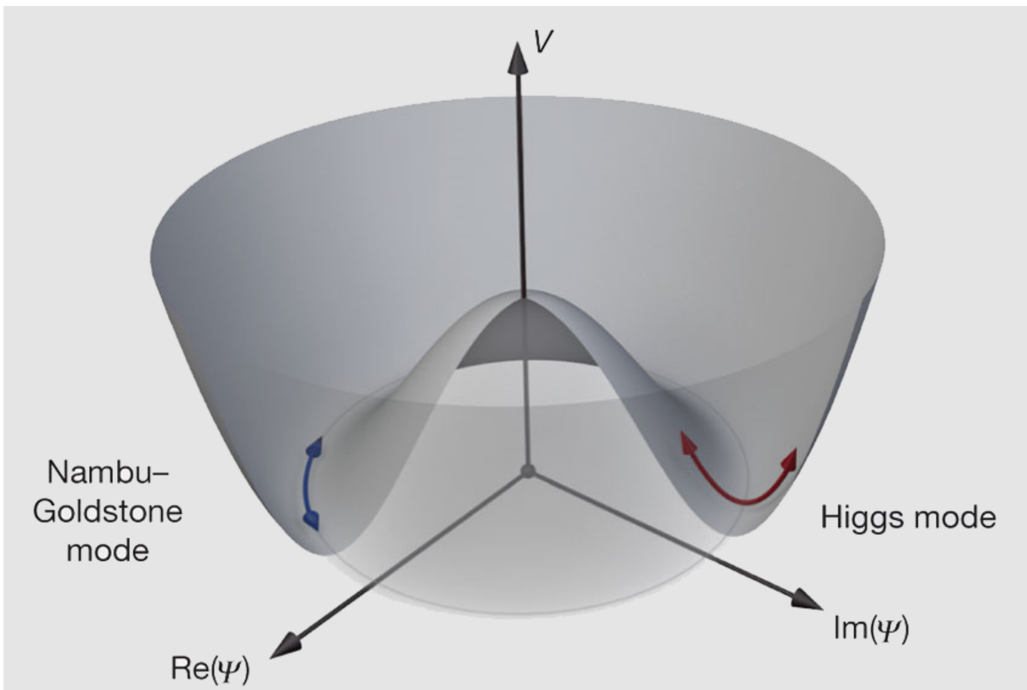
$$\Psi(r,t) = A(r,t)\exp[i\theta(r,t)]$$

where *A(r,t)* is the amplitude and $\theta(r,t)$ is the phase.

Fluctuations in the phase give rise to the gapless Goldstone mode and fluctuations in the amplitude gives rise to the Higgs Amplitude mode

Searching for the Higgs Mode in Itinerant Ferromagnetic Metals

$$\mathcal{L} = \partial_\mu \Psi \partial^\mu \Psi^* - m^2 \Psi^* \Psi - \lambda (\Psi^* \Psi)^2 = \partial_\mu \Psi \partial^\mu \Psi^* - V(\Psi, \Psi^*)$$

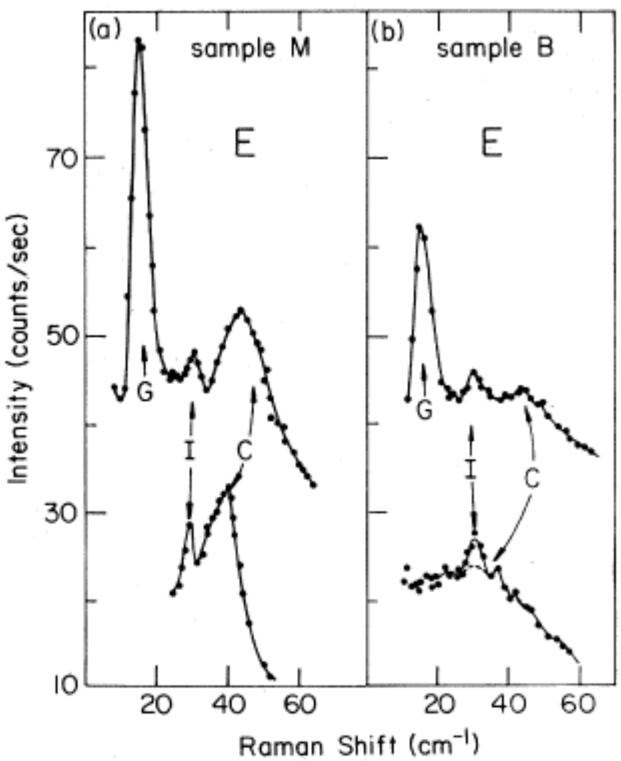


M. Endres *et al.*, *Nature* **487**, 454 (2012)

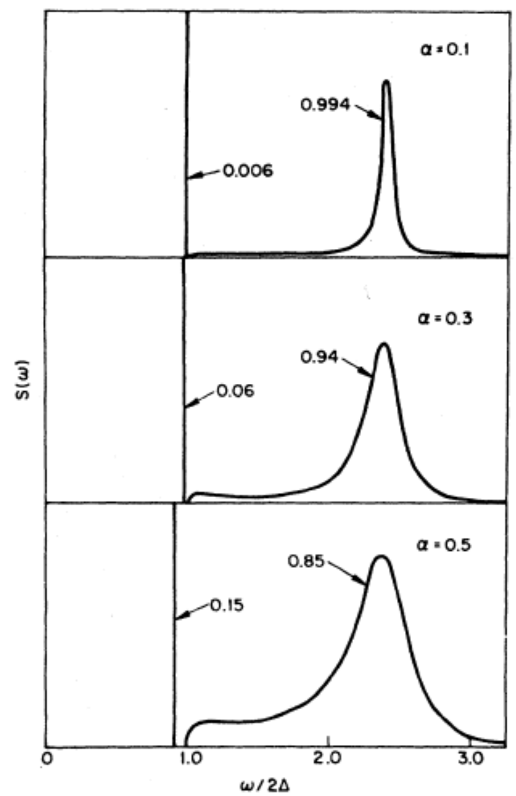
Phase and Amplitude Modes: The New-“Mexican Hat”

Searching for Higgs in Other Condensed Matter Systems

Higgs mode in SC: Raman spectra in 2H-$NbSe_2$ with $T_c^{CDW} = 33K$ and $T_c^{SC} = 7.2K$



R. Sooryakumar *et al.*, *Phys. Rev. B* **23**, 3222 (1981)



Higgs mode is visible only when CDW sets in and it appears as pole in the phonon self energy:

$$\nu \approx 2\Delta[1 - \frac{2\alpha^2}{\pi^2}\frac{\omega_0^2}{\omega_0^2 - 4\Delta^2}]$$

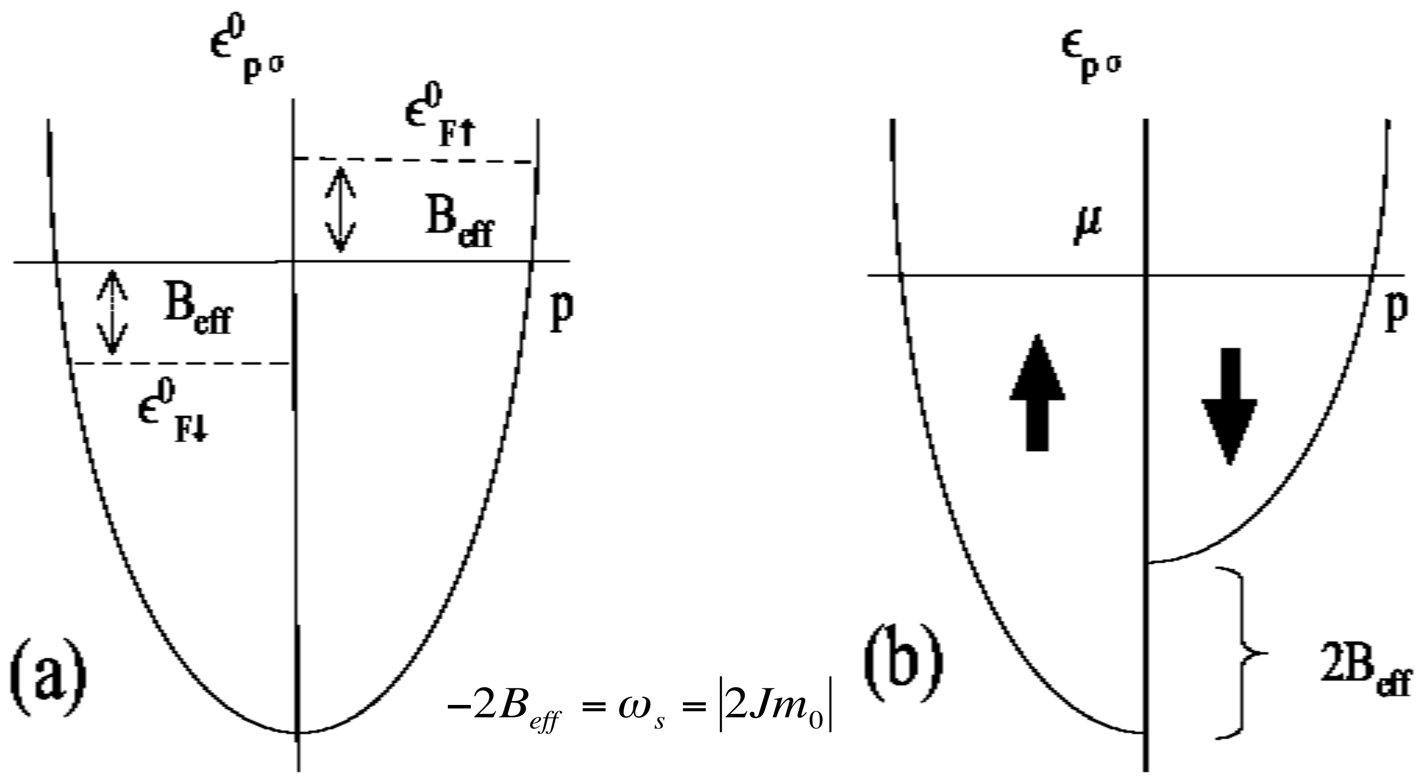
For $\nu > 2\Delta$ one obtains a broad peak near the bare CDW amplitude mode ω_0

P. B. Littlewood and C. M. Varma, *Phys. Rev. B* **26**, 4883 (1982)

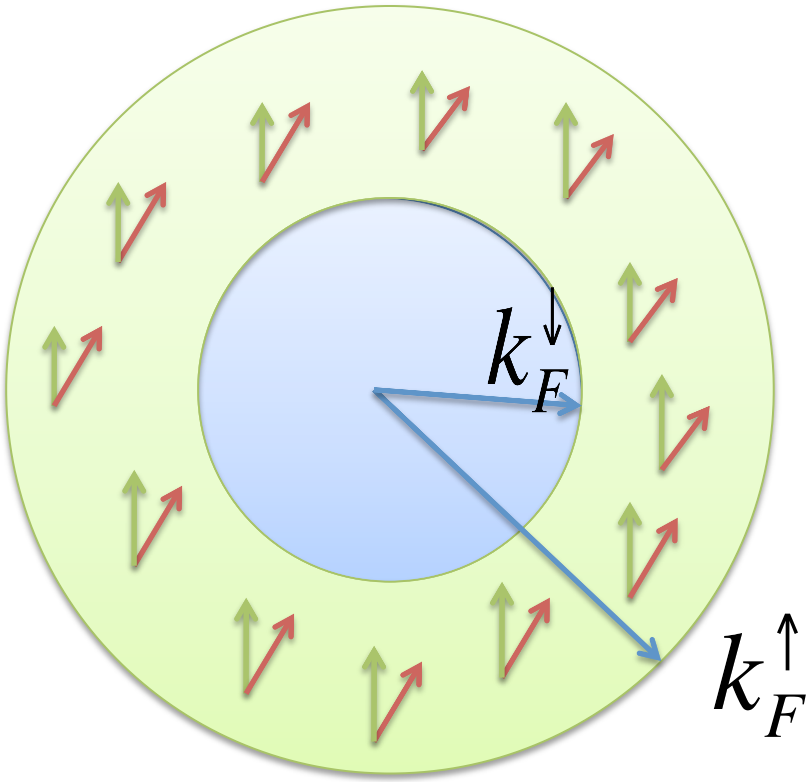
Stoner "Standard-" Model of a Weak Ferromagnet

$$\varepsilon = \varepsilon_0 + \frac{1+J}{2N(0)} m^2 + bm^4 + \ldots$$

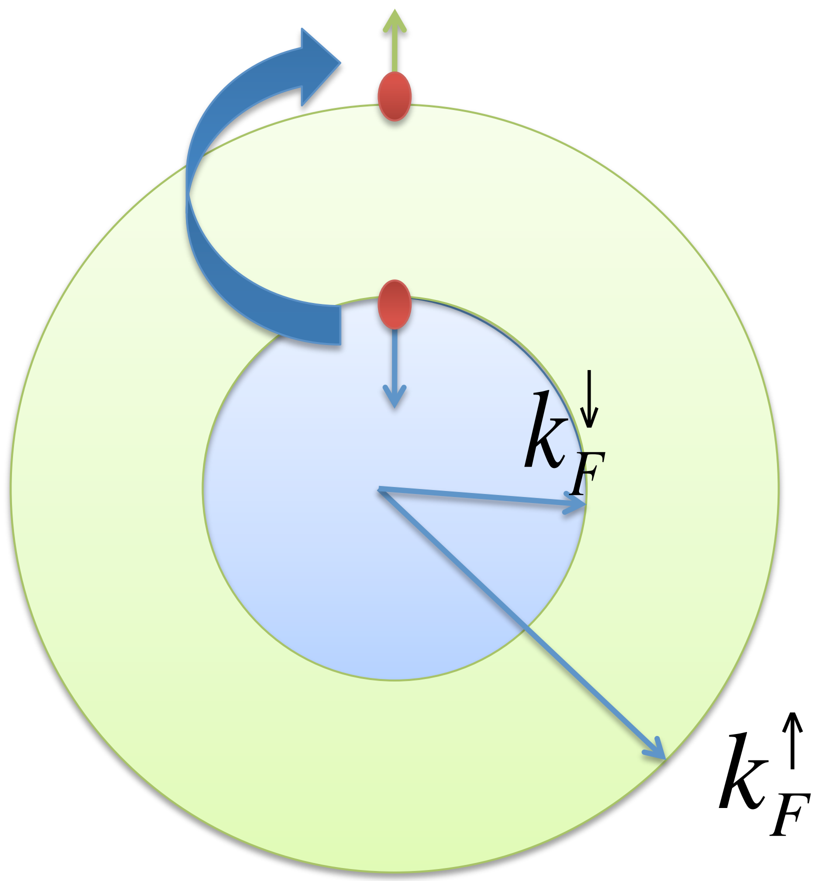
$$m_0^2 \propto |1+J|$$



The Goldstone Mode (Transverse Spin Wave) in the Standard-Model

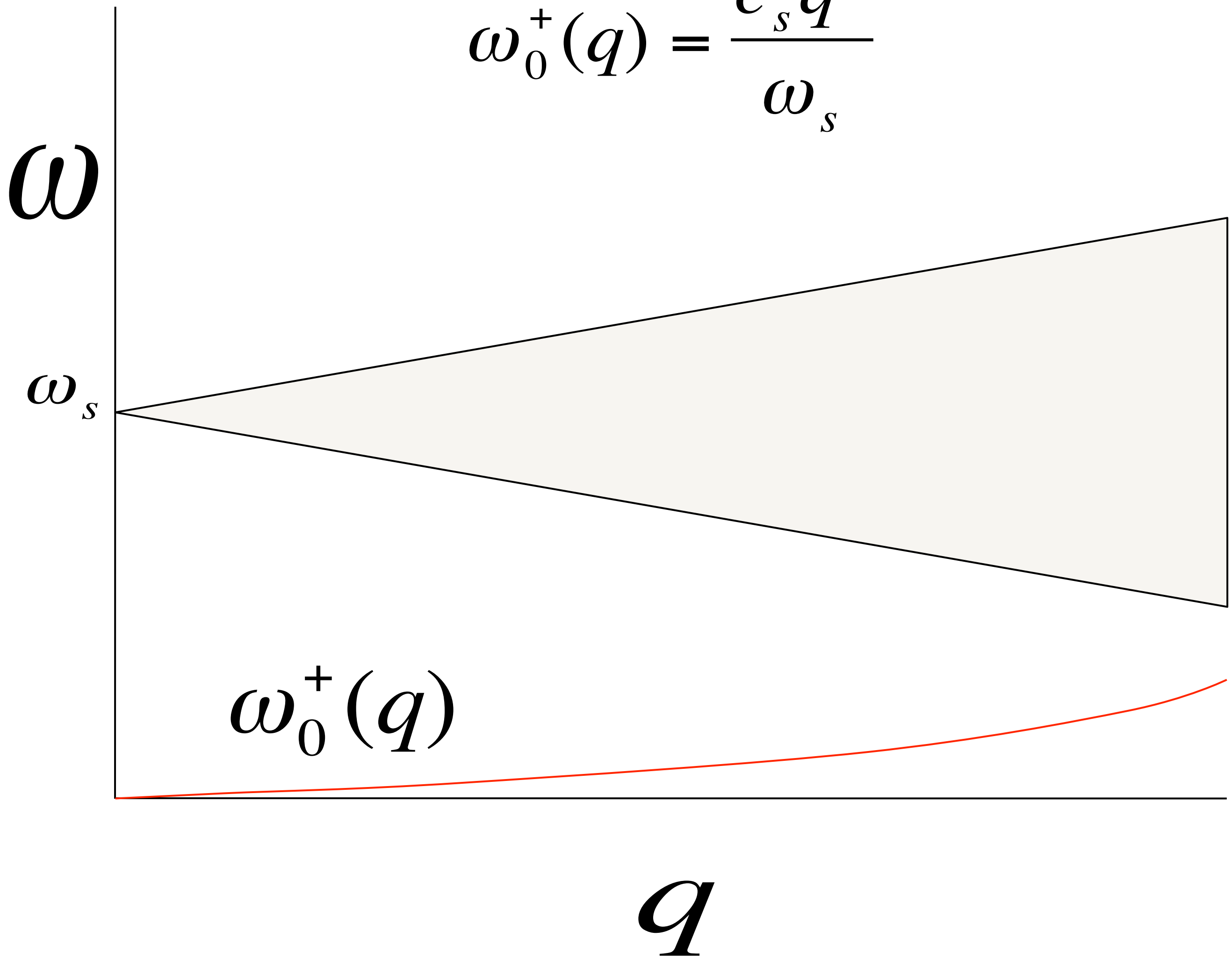


Is this the Higgs Mode?



Goldstone Mode in the Standard Model

$$\omega_0^+(q) = \frac{c_s^2 q^2}{\omega_s}$$



Stoner Gap:

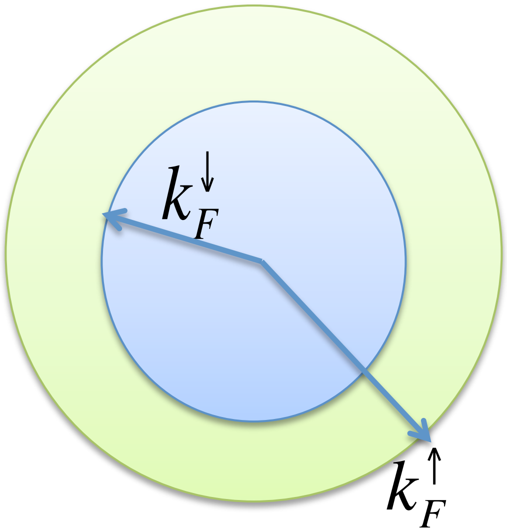
$$\omega_s = |2Jm_0|$$

Ferromagnetic Fermi Liquid Theory (FFLT)

One-To-One Correspondence:

1) The volume of the Fermi sphere is the same for the interacting and non-interacting system:

$$n = \sum_{p\sigma} n_{p\sigma} = \sum_{p\sigma} n^0_{p\sigma} = \frac{k_F^3}{3\pi^2}$$



2) Each energy level in the interacting system corresponds to one and only one energy level in the non-interacting system:

$$\varepsilon^{(0)}_{p\sigma} \rightarrow \varepsilon^{0}_{p\sigma}$$

Landau Fermi Liquid Theory (LFLT)

The fermion like excitations of the interacting system are quasi-particles (qp).

$$E = E_0 + \sum_{p\sigma} \varepsilon^{(0)}_{p\sigma} \delta n_{p\sigma} + \frac{1}{2} \sum_{p\sigma, p'\sigma'} f^{\sigma\sigma'}_{pp'} \delta n_{p\sigma} \delta n_{p'\sigma'} + \ldots$$

$$\varepsilon_{p\sigma} = \varepsilon^{(0)}_{p\sigma} + \sum_{p'\sigma'} f^{\sigma\sigma'}_{pp'} \delta n_{p'\sigma'}$$

with the interactions in a spin-rotation invariant system given by,

$$f^{\sigma\sigma'}_{pp'} = f^{s}_{pp'} + f^{a}_{pp'} \sigma \cdot \sigma'$$

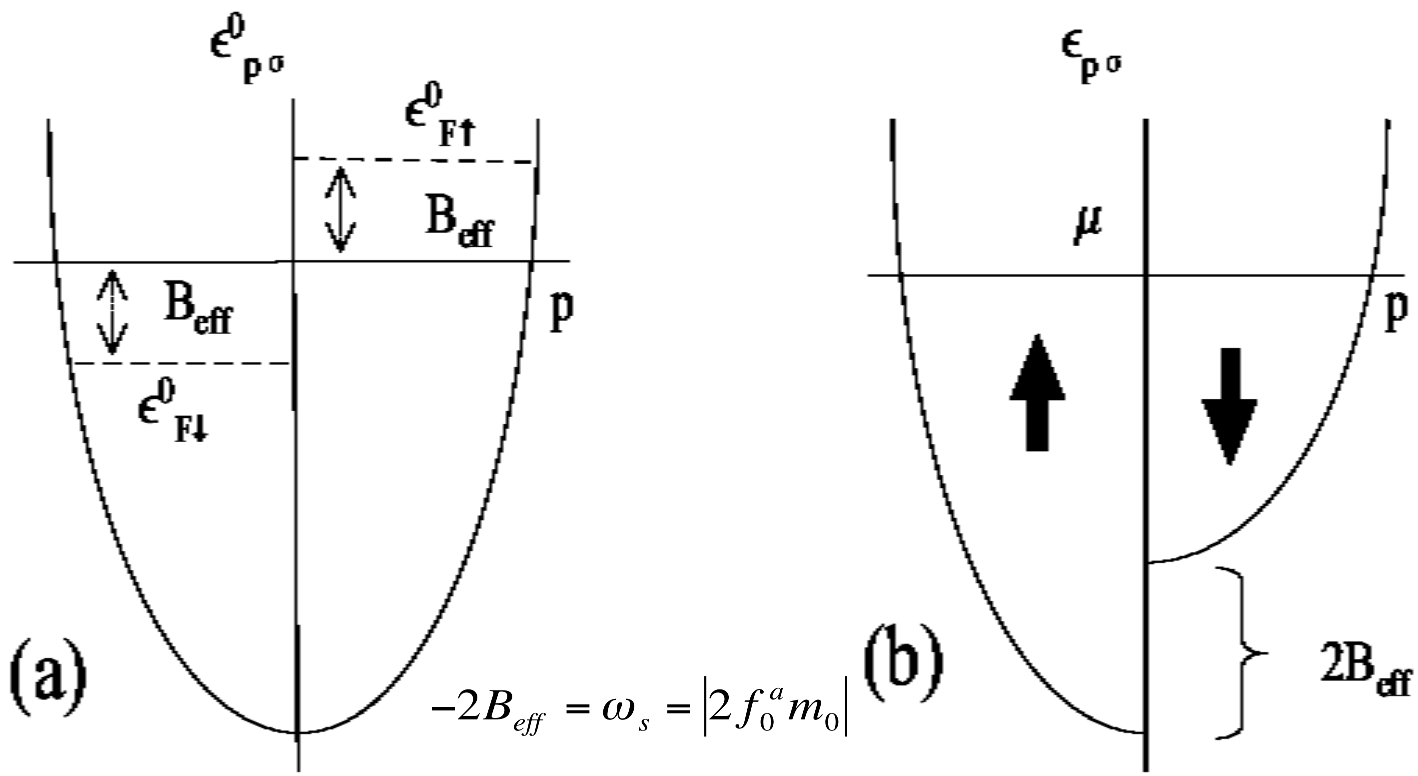
Landau parameters,

$$N(0) f^{s,a}_{pp'} = \sum_{l} F^{s,a}_{l} P_l(\cos\theta)$$

Thermodynamics of a Weak Ferromagnet

$$\varepsilon = \varepsilon_0 + \frac{1+F_0^a}{2N(0)} m^2 + b m^4 + \ldots = E/V$$

$$m_0^2 \propto \left|1+F_0^a\right|$$



$$-2B_{eff} = \omega_s = \left|2 f_0^a m_0\right|$$

Some Consequences of FFLT

For low T properties of strongly interacting Fermi gases/liquids, e.g., ^{3}He, metals, ferromagnetic metals and nuclear matter, are qualitatively the same as a free Fermi gas.

The Entropy, S (or specific heat C_V): $S = \gamma T + \beta T^{3/2}$

where, $\gamma = \frac{\pi^2}{3} N(0)$ **and** $N(0) = \frac{m^* k_F}{\pi^2}$

For $T \ll T_F$,

The spin susceptibility is given by : $\chi = \frac{1}{2} \frac{N(0)}{\left|1 + F_0^a\right|}$

Quasi-Classical/Quantum Kinetic Equation: Dynamics and Transport in a Weak Ferromagnet

The magnetic distribution function for long wavelength and low frequency is quasi-classical:

$$\vec{m}_p(r,t) = \vec{m}_p^0 + \vec{\sigma}_p(r,t)$$

$$\frac{\partial \vec{\sigma}_p}{\partial t} + \vec{v}_p \bullet \vec{\nabla}(\vec{\sigma}_p - \frac{\partial n_p^0}{\partial \varepsilon_p^0}\vec{h}_p)$$

$$= -\frac{2}{\hbar}(\vec{m}_p^0 \times \vec{h}_p + \vec{\sigma}_p \times \vec{h}_p^0) + I(\vec{m}_p)$$

Where, $\vec{h}_p^0 = 2\sum_{p'} f_{pp'}^a \vec{m}_p^0$

and, $I[\vec{m}_p] \propto T^2 \Rightarrow 0$

Spin Waves

In the interacting system the magnetization density is given by,

$$m(r,t) = \sum_p m_p(r,t)$$

and the spin–current is given by,

$$j_{\sigma,i}(r,t) = 2\sum_p \frac{p_i}{m^*}\sigma_p(r,t)(1+\frac{F_1^a}{3})$$

From the Kinetic equation we obtain the equations of motion

for $m(r,t)$ and $j_{\sigma,i}(r,t)$.

Spin Current Equation of Motion

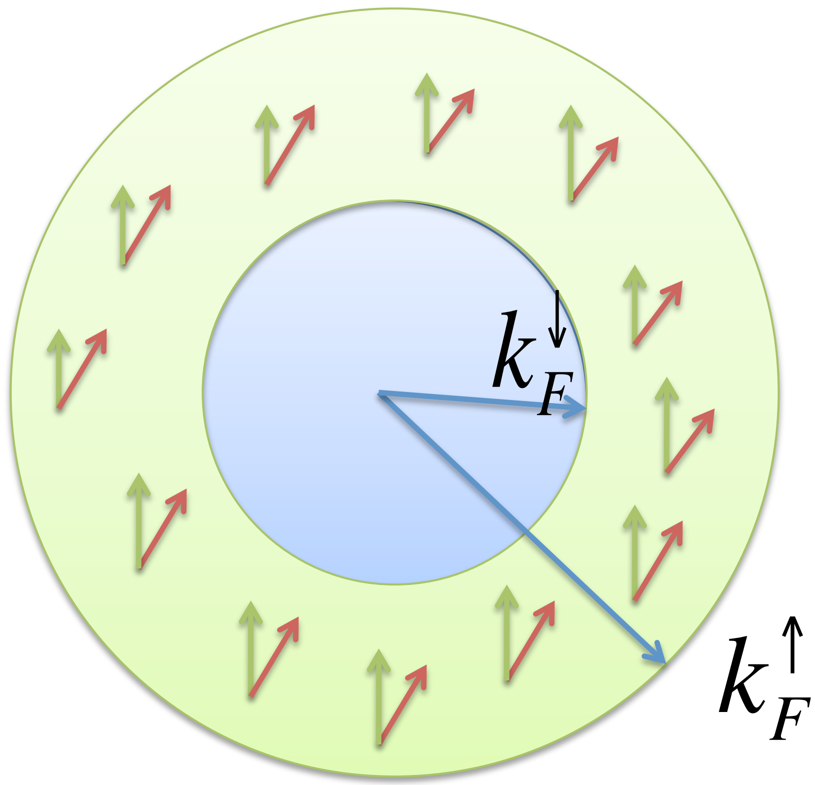
Spin continuity equation for B = 0:

$$\frac{\partial}{\partial t} m(r,t) + \frac{\partial}{\partial x_i} j_{\sigma,i}(r,t) = 0$$

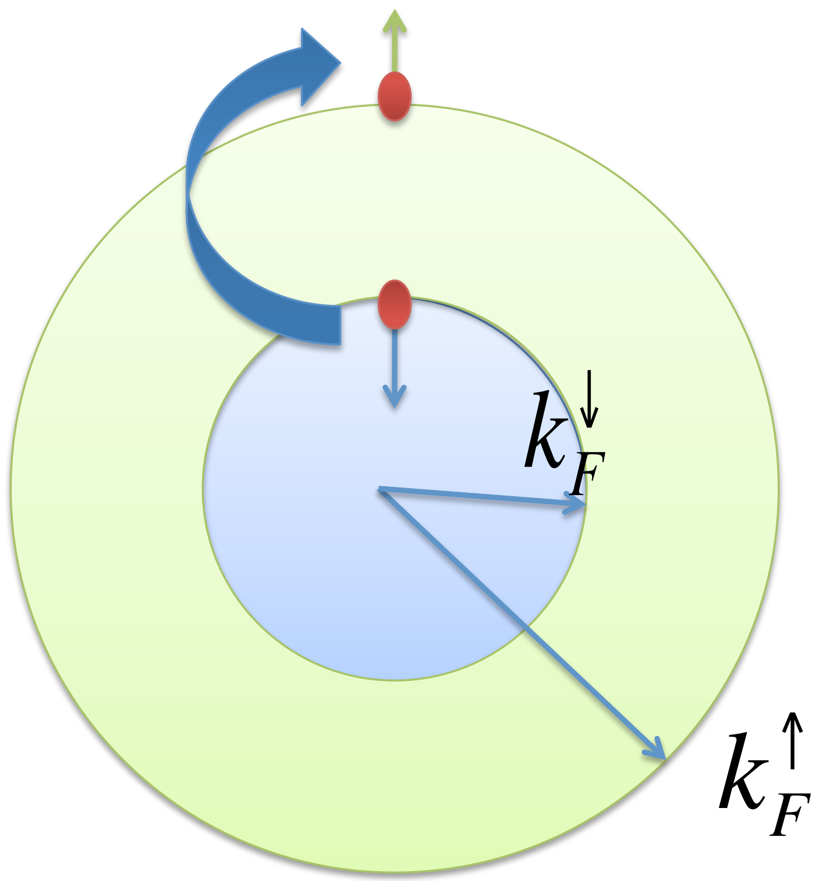
Spin current equation of motion:

$$\frac{\partial}{\partial t} j_{\sigma,i}(r,t) + c_s^2 \frac{\partial}{\partial x_i} m(r,t) = \frac{-2}{N(0)} (F_0^a - F_1^a/3) j_{\sigma,i}(r,t) \times m^0$$

The Goldstone Mode (Transverse Spin Wave) in FFLT

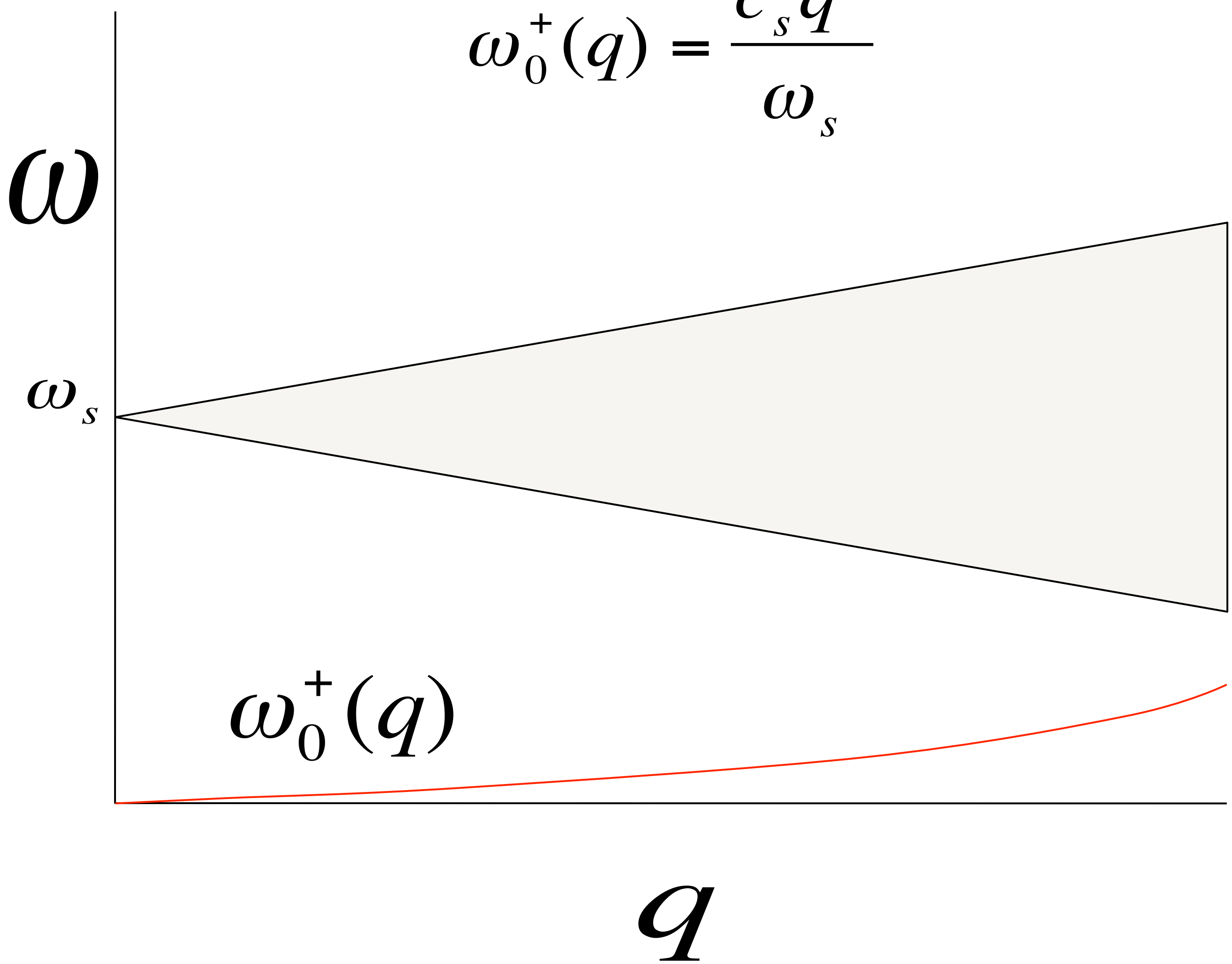


Higgs Amplitude Mode in FFLT?



Goldstone Mode in a Weak FFLT: The Standard Model $F_1^a = 0$ (Stoner Model)

$$\omega_0^+(q) = \frac{c_s^2 q^2}{\omega_s}$$



Stoner Gap:

$$\omega_s = \left|2 f_0^a m_0\right|$$

Higgs Amplitude Mode in Weak FFLT, with F_1^a
(Bedell & Blagoev, 2001)

$$\omega_0^+(q) = \frac{c_s^2 q^2}{\Omega_1^+}$$

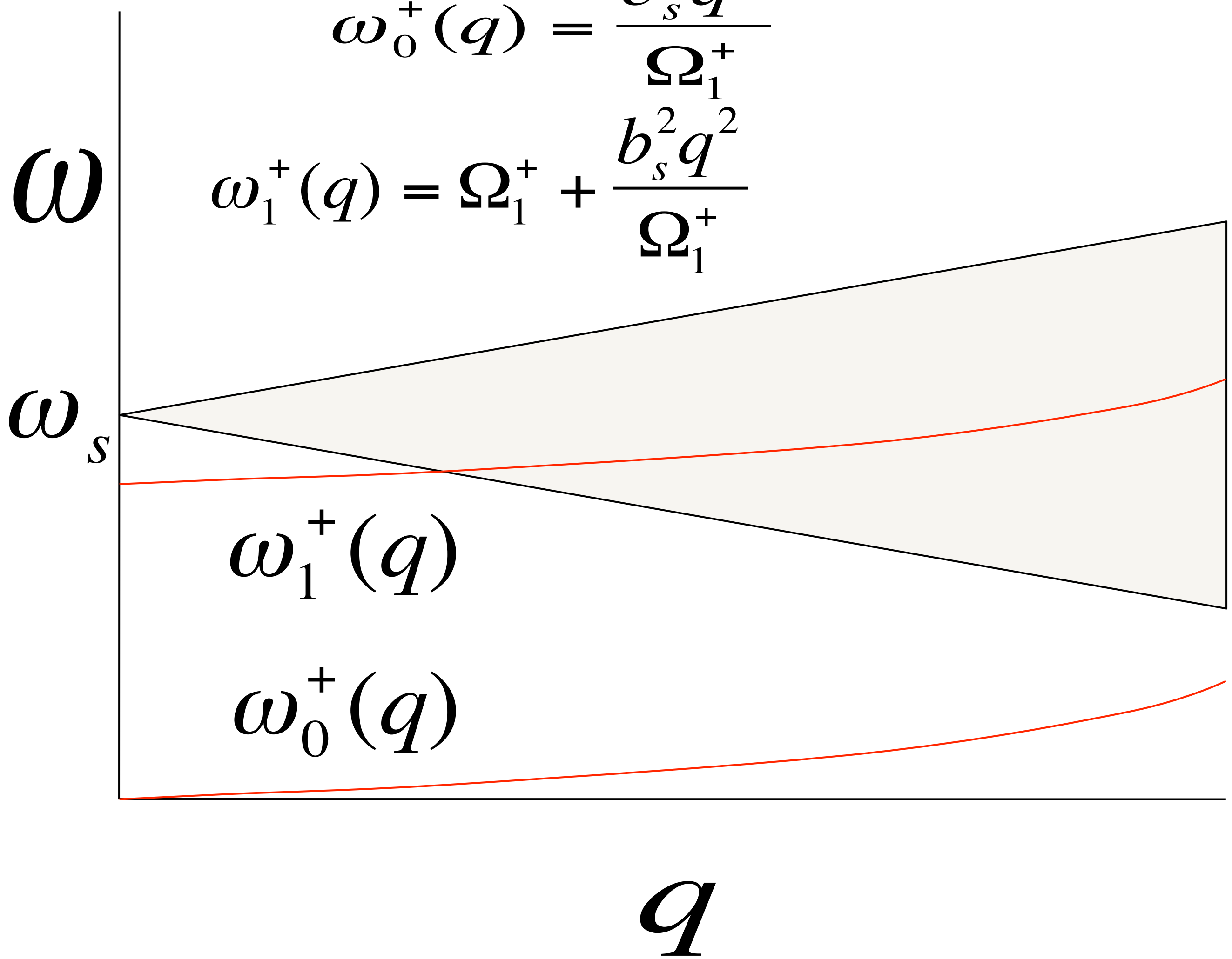
$$\omega_1^+(q) = \Omega_1^+ + \frac{b_s^2 q^2}{\Omega_1^+}$$

$$F_0^a < -1$$

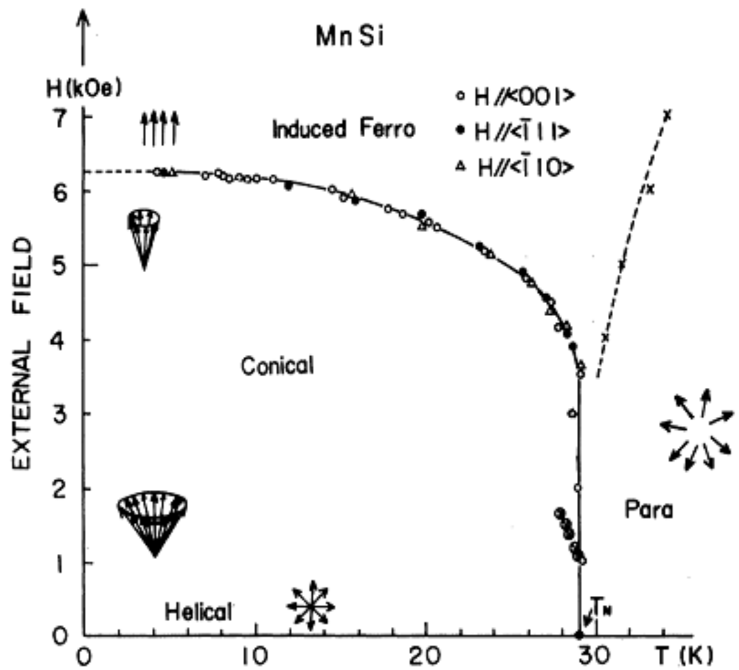
$$F_1^a < 0$$

$$\Omega_1^+ = \frac{2m_0}{N(0)}\left|(F_0^a - \frac{F_1^a}{3})\right|$$

$$\omega_s = \left|2 f_0^a m_0\right|$$



Search for the Higgs in a weak ferromagnetic metal: MnSi



Y. Ishikawa et al., Phys. Rev. B **16** 4956(1977)

T_{Cu}= 29.5K, with a saturated moment $\mu = 0.4\mu_B$/Mn, which is small compared with the effective moment $2.2\mu_B$/Mn

Dynamical structure function

$$S^{\pm}(q,\omega) = \mathrm{Im}[\chi^{\pm}(q,\omega)]$$

$S^{\pm}(q,\omega)$ can be measured by neutron scattering:

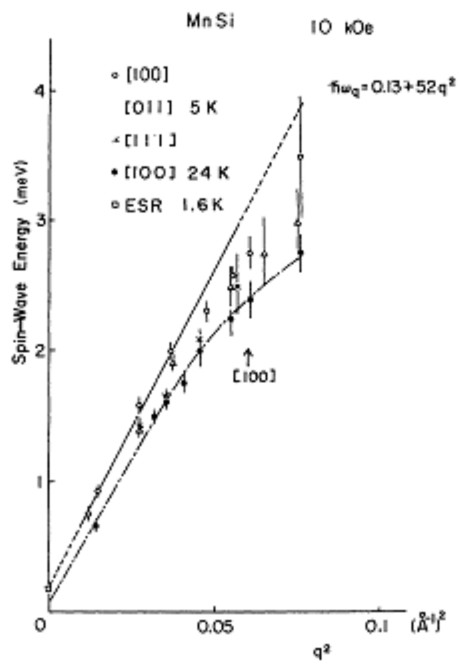
$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_0 S^{\pm}(q,\omega)$$

$$\int \omega S^{\pm}(q,\omega) d\omega = (1+\frac{F_1^a}{3})\frac{nq^2}{2m^*}$$

Experiment results (MnSi)

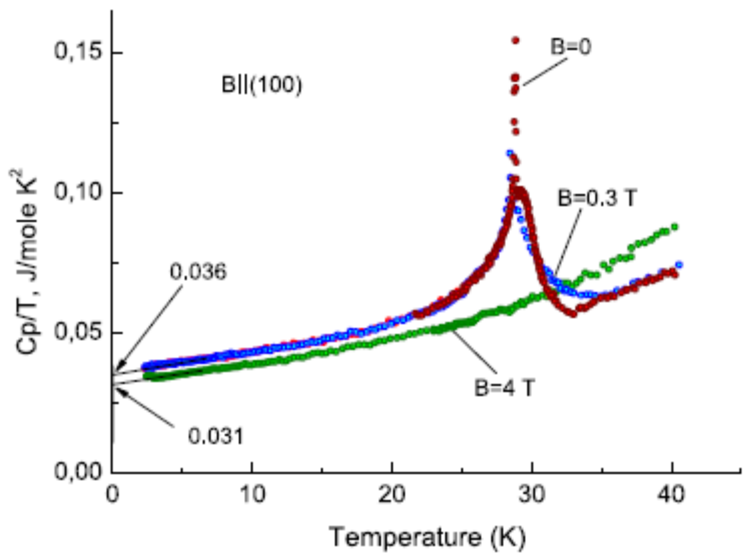
Neutron scattering gives the magnon dispersion:

$$\omega(meV) = 0.13 + 52q(\mathring{A})^2$$



Specific heat measurement gives

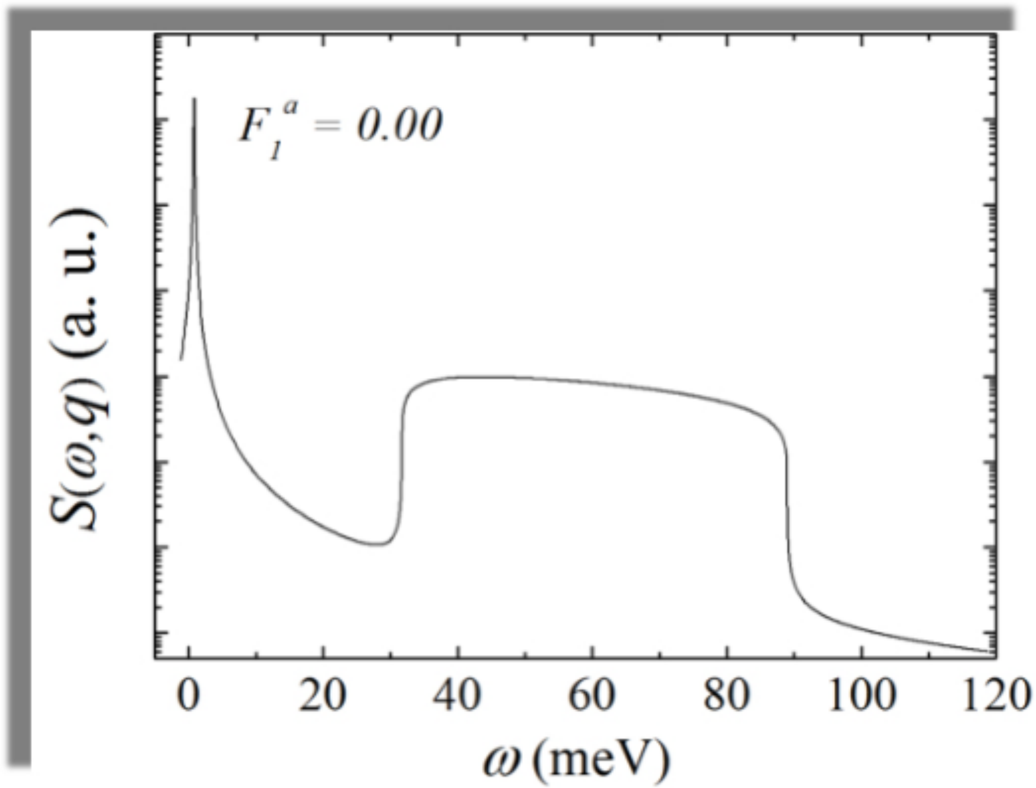
$$\gamma = (C/T)_0 = 36mJmole^{-1}K^{-2}$$



Y. Ishikawa et al., Phys. Rev. B **16** 4956(1977)

S.M. Stishov et al., J. Phys.: Condens. Matter **20** 235222 (2008)

Emerging Higgs Amplitude Mode



Higgs mode emerging in a weak ferromagnet

Summary

- We use Landau Fermi liquid theory to study the collective modes in the weak FM system, and find a Higgs Amplitude mode in addition to the Goldstone Mode.

- We use this model to describe the itinerant FM material MnSi, and by fitting the available data, we calculate the dynamic structure function which can be verified in neutron scattering experiments.

- In the future, we are interested in making the connection between FFLT and field theory to further the understanding the Higgs amplitude mode. We will also study the finite T and B effects on the collective modes.

Dynamics and Response Functions

$$\chi^{\pm}(q,w) = \frac{2\sum_{\mathbf{p}} \delta m_p^{\pm}}{\delta B^{\pm}} = \frac{\nu_0^{\pm}(q,w)}{\delta B^{\pm}}$$

From the Landau kinetic equation and keeping δ**B** in the equation:

$\chi^{\pm}$ are related to each other through: $\chi^{-}(q,w) = {\chi^{+}}^{*}(q,-w)$

Solving the equation, we can get:

$$\chi^{+}(q,\omega) = \frac{-\chi_0^{+} + \frac{2m_0 f_1^a}{qv_F(1+F_1^a/3)}\chi_1^{+}}{1 - f_0^a \chi_0^{+} - \frac{\omega}{qv_F}\frac{f_1^a}{1+F_1^a/3}\chi_1^{+}}$$

where,

$$\chi_0^{+}(q,\omega) = -N(0)\{1 - \frac{1}{2qv_F}[\omega + \frac{2m_0}{N(0)}(1+F_0^a)]ln(\frac{\omega+2m_0 f_0^a + qv_F}{\omega+2m_0 f_0^a - qv_F})\}$$

$$\chi_1^{+}(q,\omega) = -\frac{N(0)}{qv_F}[\omega + \frac{2m_0}{N(0)}(1+F_0^a)][1 - \frac{1}{2qv_F}(\omega + 2m_0 f_0^a)ln(\frac{\omega+2m_0 f_0^a + qv_F}{\omega+2m_0 f_0^a - qv_F})]$$

For small momentum transfer, the dynamical structure function can be expanded as:

$$S^+(q,\omega) = -\frac{1}{\pi} Im(\chi^+(q,\omega))$$

$$= 2m_0\delta(\omega-\omega_1^+) + \frac{(1+F_1^a/3)^2}{6m_0(f_0^a-f_1^a/3)^2}(qv_F)^2\delta(\omega-\omega_2^+)$$

Goldstone mode (magnon)

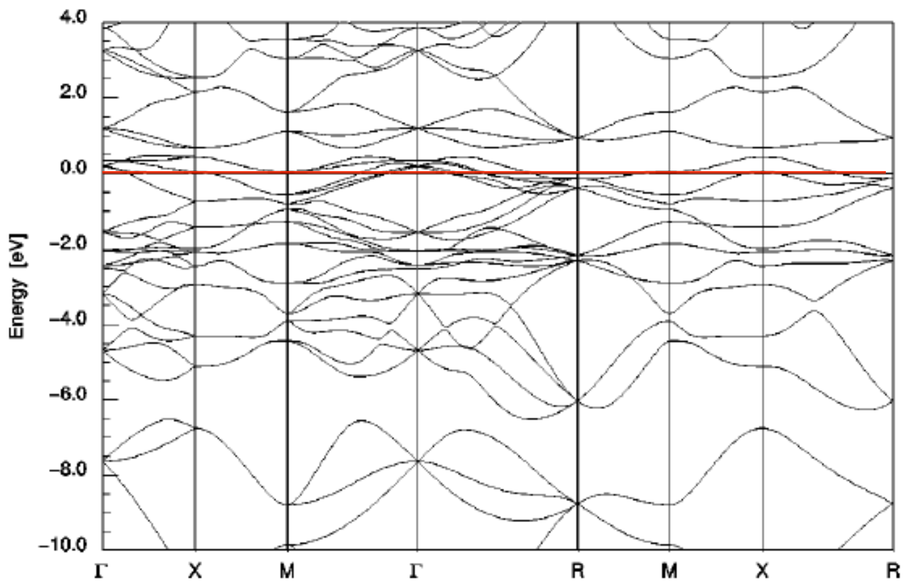
Gapped mode (Higgs mode)

$$\omega_1^+(q) = \frac{c_s^2}{\omega^+}q^2$$

$$\omega_2^+ = \omega^+ - \frac{c_s^2}{\omega^+}q^2 + \frac{2N(0)v_F^2}{15m_0}(\frac{3}{F_a^a}+1)q^2$$

Two well-defined peaks described by the two delta functions.

Band structure calculation shows that there are 5 bands(3d) around Fermi level filled with 6/cell electrons.



T. Jeong et al., Phys. Rev. B **70** 075114(2004)

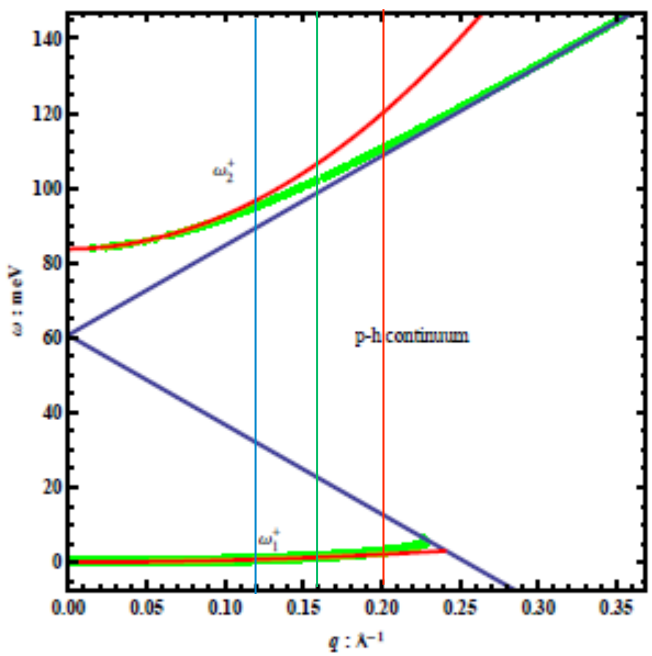
In our model, we approximate the 6 electrons/cell filled in one band with quadratic dispersion:

$$E = \frac{\hbar^2 k^2}{2m^*}$$

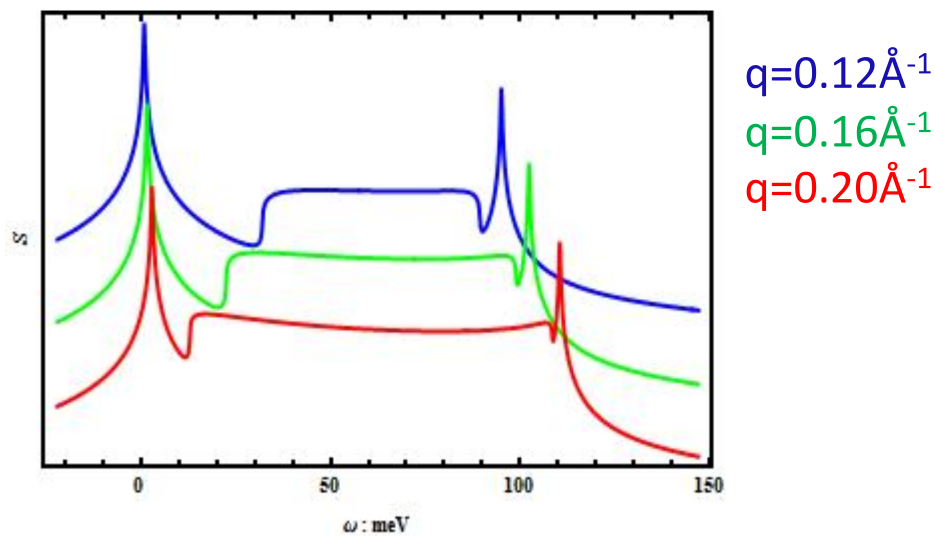
By fitting theory to experimental data, we get:

$$N(0) = 6.4 \times 10^{29} eV^{-1} m^{-3}$$
$$m^* = 39.3 m_e$$
$$E_F = 0.147 eV$$
$$v_F = 3.63 \times 10^4 m s^{-1}$$
$$F_1^a = -\frac{375 + 321 F_0^a}{143 + 125 F_0^a}$$

For $F_0^a = -1.16,\ F_1^a = 1.32$

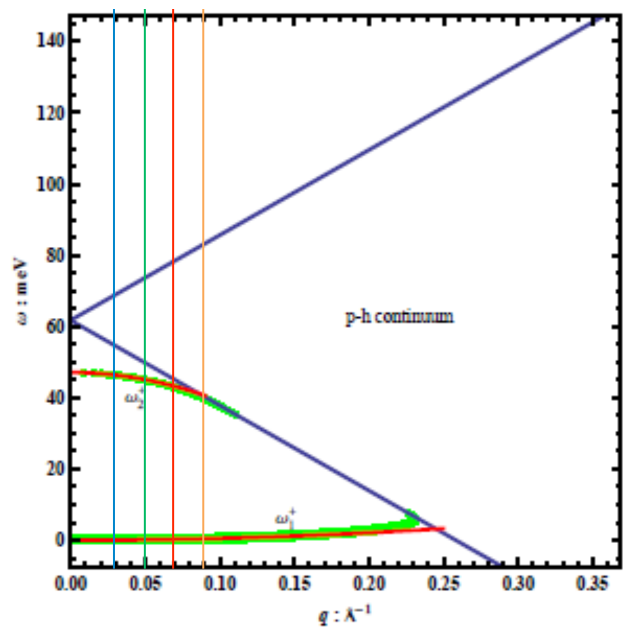


Dispersion of the collective modes

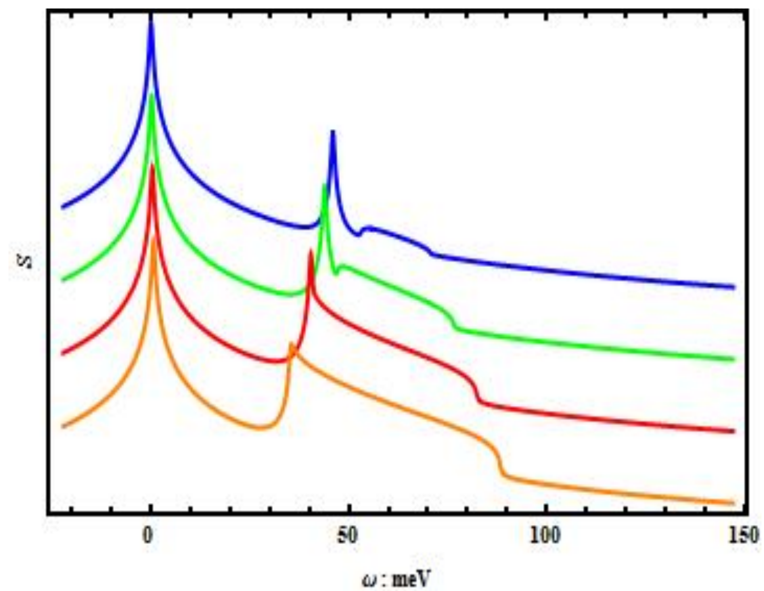


Dynamical structure function

For $F_0^a = -1.18,\ F_1^a = -0.84$



Dispersion of the collective modes



Dynamical structure function