Eddie Cohen, long time tails, and FM quantum phase transitions

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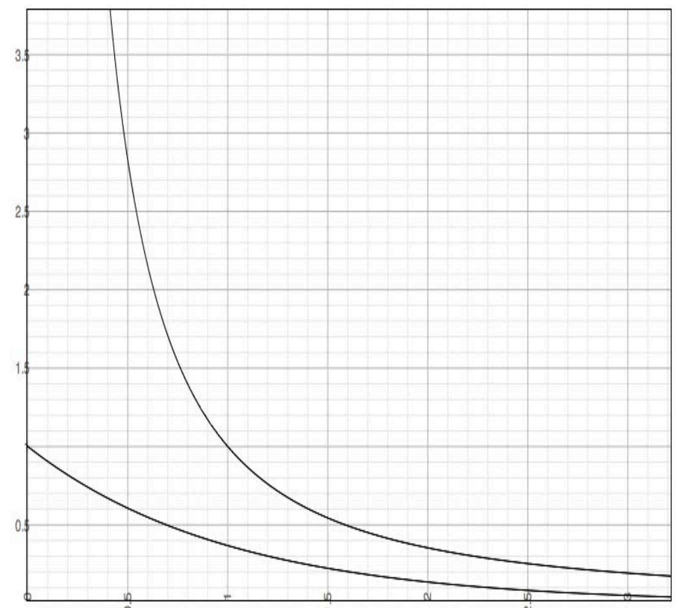

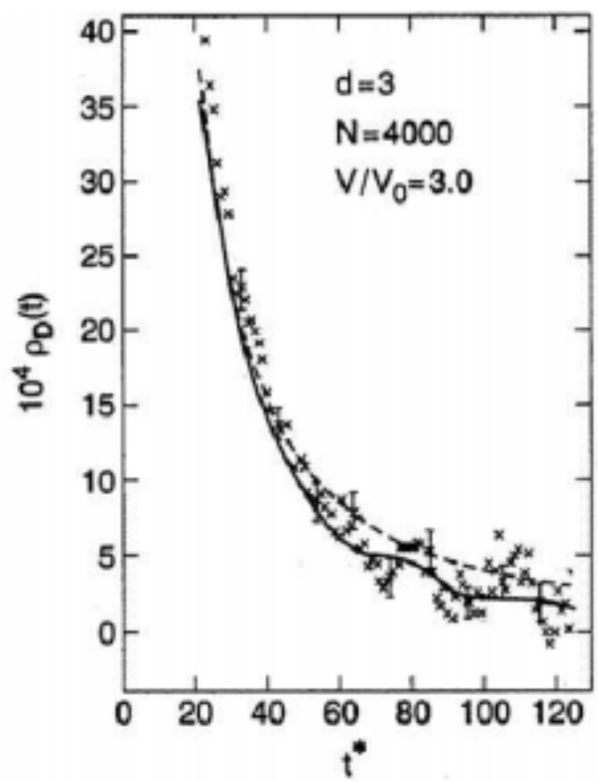

FIG. 3 Normalized velocity autocorrelation function $\rho_{\rm D}(t) = C_D(t)/\langle \boldsymbol{v}^2(0)\rangle$ as a function of the dimensionless time $t^* = t/t_0$, where t_0 is the mean-free time. The crosses indicate computer results obtained by Wood and Erpenbeck (1975) for a system of 4000 hard spheres at a reduced density corresponding to $V/V_0 = 3$, where V is the actual volume and V_0 is the close-packing volume. The dashed curve represents the theoretical curve $\rho_{\rm D}(t) = \alpha_D\,(t^*)^{-3/2}$. The solid curve represents a more complete evaluation of the mode-coupling formula with contributions from all possible hydrodynamic modes and with finite-size corrections included (Dorfman, 1981). From Dorfman *et al.* (1994).

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Universal effects in liquids due to soft or slow modes coupling to……..stuff.

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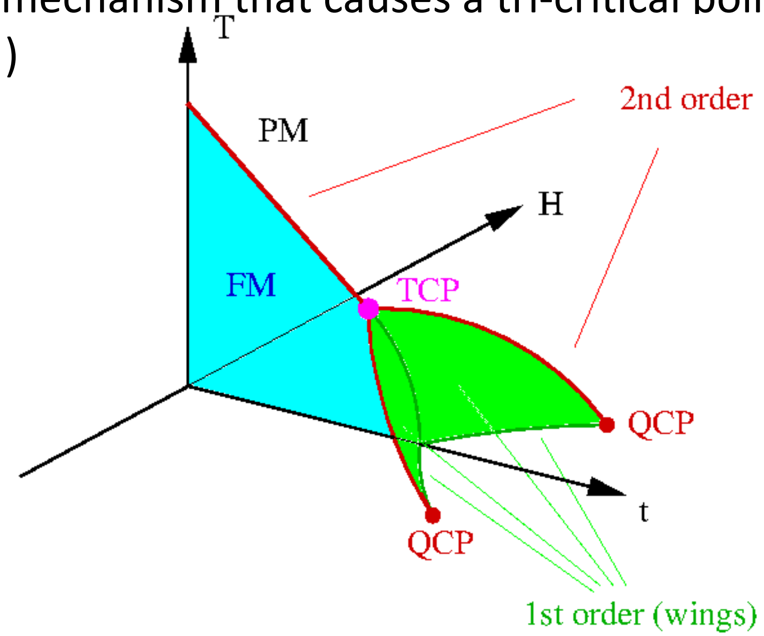

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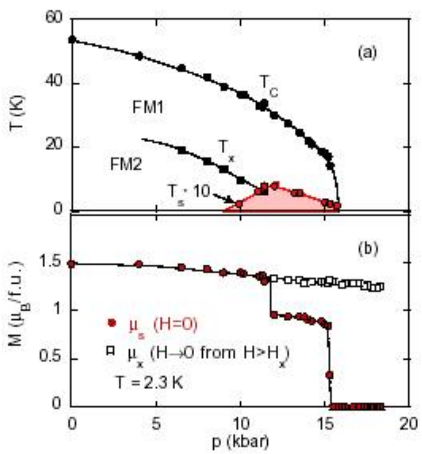

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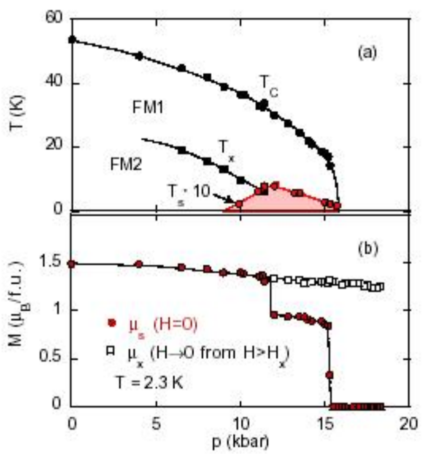

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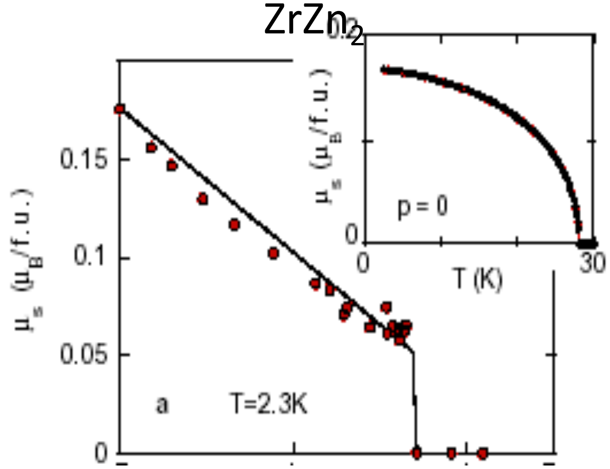

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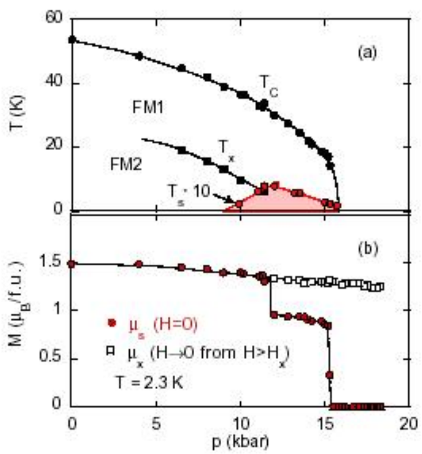

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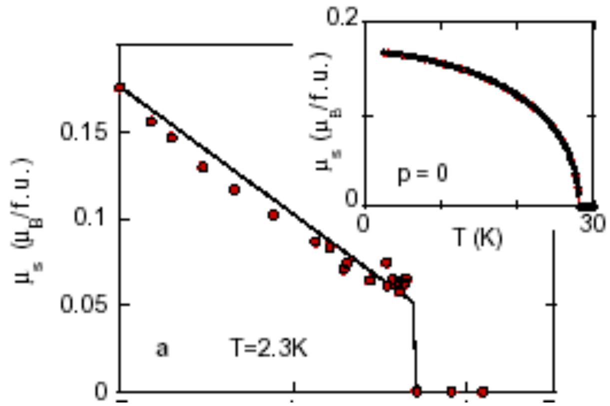

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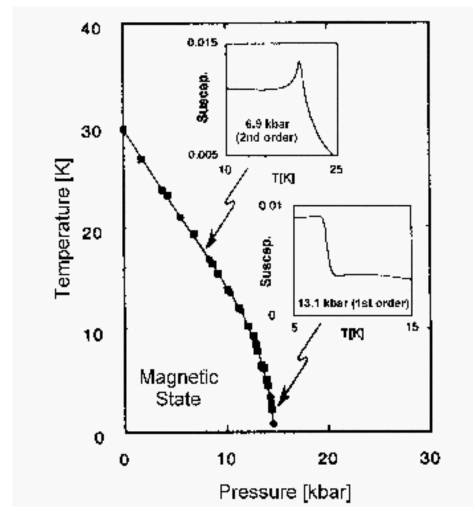

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TABLE I: Systems with low-T ferromagnetic transitions and their properties. T_c = Curie temperature, T_{tc} = tricritical temperature. ρ_0 = residual resistivity. FM = ferromagnet, SC = superconductor. N/A = not applicable; n.a. = not available.

System [a]	Order of Transition [c]	T_c/K [b]	magnetic moment/μ_B [d]	tuning parameter	T_{tc}/K	wings observed	Disorder ($\rho_0/\mu\Omega$cm) [e]	Comments
MnSi [27]	1st [18]	29.5 [28]	0.4 [28]	hydrostatic pressure [18]	≈ 10 [18]	yes [25]	0.33 [25]	weak helimagnet [17] exotic phases [25,26]
$ZrZn_2$ [27]	1st [29]	28.5 [29]	0.17 [29]	hydrostatic pressure [29]	≈ 5 [29]	yes [29]	≥ 0.31 [30]	confusing history, see Ref. 27
$Sr_3Ru_2O_7$	1st [f]	0 [g]	0 [g]	pressure [g]	n.a.	yes [31]	< 0.5 [31]	foliated wing tips, nematic phase [31]
UGe_2 [33]	1st [34]	52 [35]	1.5 [35]	hydrostatic pressure [22,35]	24 [36]	yes [35,36]	0.2 [22]	easy-axis FM coexisting FM+SC [22]
URhGe [33]	1st [37]	9.5 [23]	0.42 [23]	transverse B-field [37,39]	≈ 1 [37]	yes [37]	8 [38]	easy-plane FM coexisting FM+SC [23]
UCoGe [33]	1st [40]	2.5 [40]	0.03 [24]	none	$> 2.5?$ [h]	no	12 [24]	coexisting FM+SC [24]
CoS_2	1st [41]	122 [41]	0.84 [41]	hydrostatic pressure [41]	≈ 120 [41]	no	0.7 [41]	rather high T_c
$La_{1-x}Ce_xIn_2$	1st [42]	$22 - 19.5$ [42, i]	n.a.	composition [42]	$> 22?$ [j]	no	n.a.	third phase between FM and PM? [42]
Ni_3Al [27]	(1st) [k]	$41 - 15$ [l]	0.075 [m]	hydrostatic pressure [43]	n.a.	no	0.84 [44]	order of transition uncertain
$YbIr_2Si_2$ [n]	1st [45]	$1.3 - 2.3$ [o]	n.a.	hydrostatic pressure [45]	n.a.	no	≈ 22 [p]	FM nature of ordered phase suspected [45]
$YbCu_2Si_2$ [n]	n.a.	$4 - 6$ [46, q]	n.a.	hydrostatic pressure [46]	n.a.	no	n.a.	nature of magnetic order unclear
$URu_{2-x}Re_xSi_2$	2nd [47,48]	$25 - 2$ [r]	$0.4 - 0.03$ [48]	composition [47]	N/A	N/A	≈ 100 [s]	strongly disordered
Ni_xPd_{1-x}	2nd [50]	$600 - 7$ [t]	n.a.	composition [50]	N/A	N/A	n.a.	disordered, lowest T_c rather high
$YbNi_4P_2$	2nd [51]	0.17 [51]	≈ 0.05 [51]	none	N/A	N/A	2.6 [51]	quasi-1d, disordered

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1. Conventional (= mean-field) theory

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- Conclusion: Conventional theory not viable

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- **Integrate out soft electronic modes to obtain a generalized MFT,**

2. Renormalized mean-field theory.

- In general, conventional theory misses effects of fermion soft modes:

  - Contribution to f_0: $$\int d\mathbf{k} \int d\Omega \, \ln((k+\Omega)^2 + m^2)$$

  - Contribution to eq. of state:

  - Renormalized mean-field equation of state:

$$\frac{d}{dm} \int d\mathbf{k} \int d\Omega \, \ln[(k+\Omega)^2 + m^2] \sim m \begin{cases} \text{const.} - m^{d-1} & (1 < d < 3) \\ \text{const.} + m^2 \ln m & (d = 3) \end{cases}$$

→ $h = tm + vm^3 \ln m + um^3$ (clean, d=3, T=0)

  - v>0

Transition is generically 1st order! (TRK, T Vojta, DB 1999)

Physics?-Free energy gain by making soft fluctuations massive.
→ Coleman-Weinberg mechanism

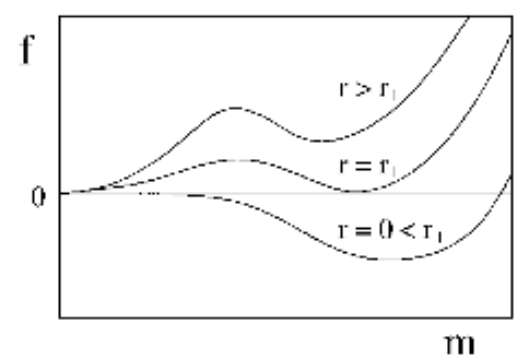
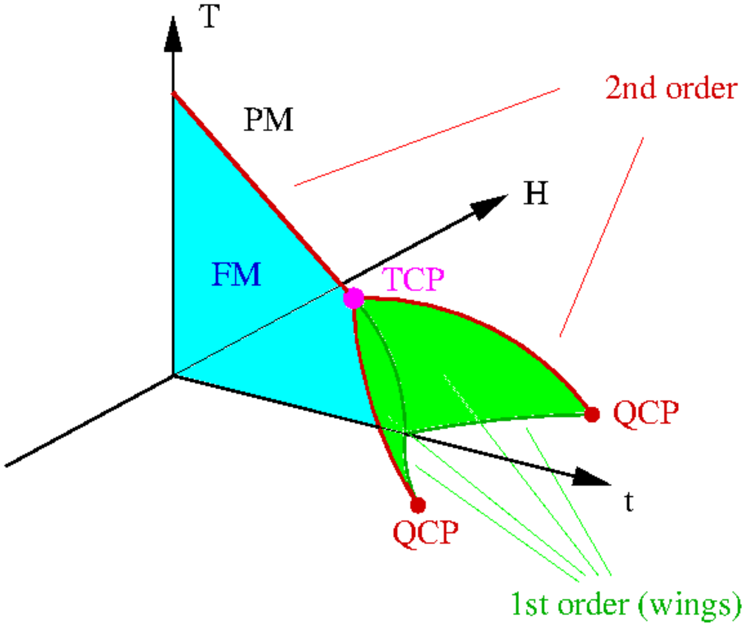


FIG. 2: Schematic sketch of the free energy for three values of the parameter r. The first-order transition occurs at $r = r_1 > 0$. It pre-empts the second-order transition of Landau theory which would occur at $r = 0$.

2. Renormalized mean-field theory

- External field h produces tricritical wings:
  (DB, TRK, J. Rollbühler 2005)



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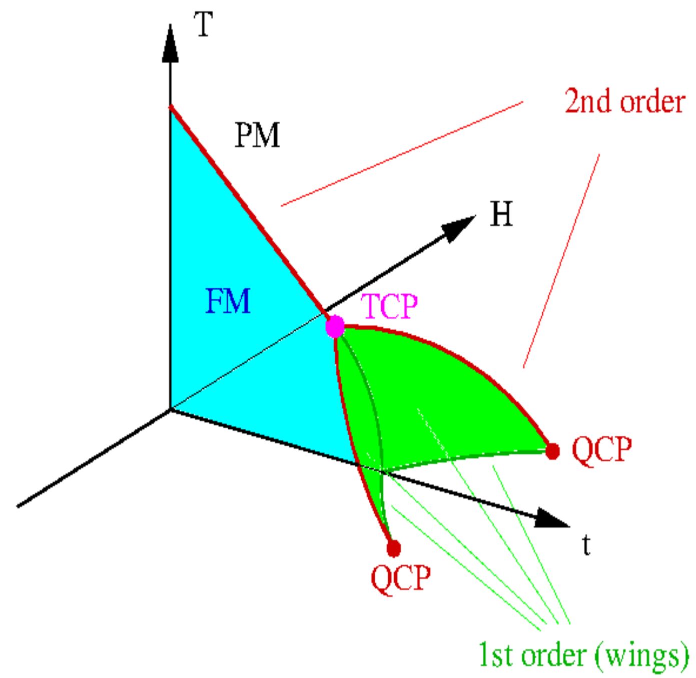
- h>0 gives soft modes a mass, ln m -> ln (m+h)
  ☞Hertz theory works (at T=0)!



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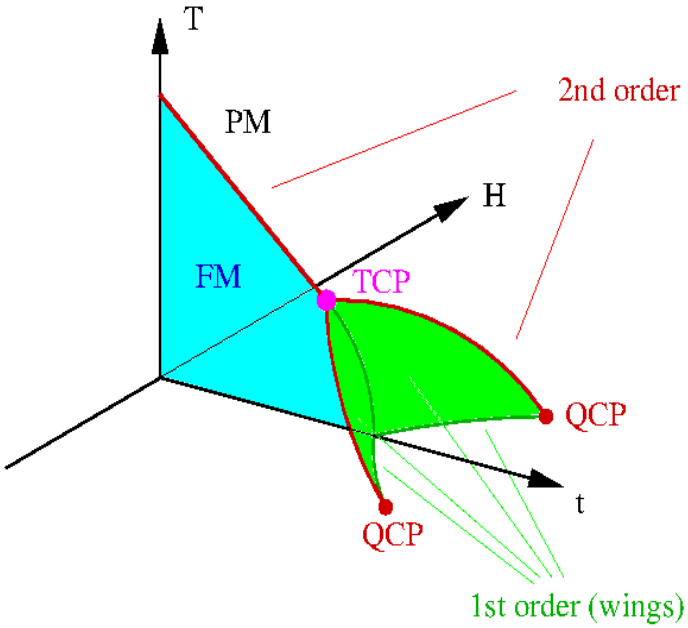

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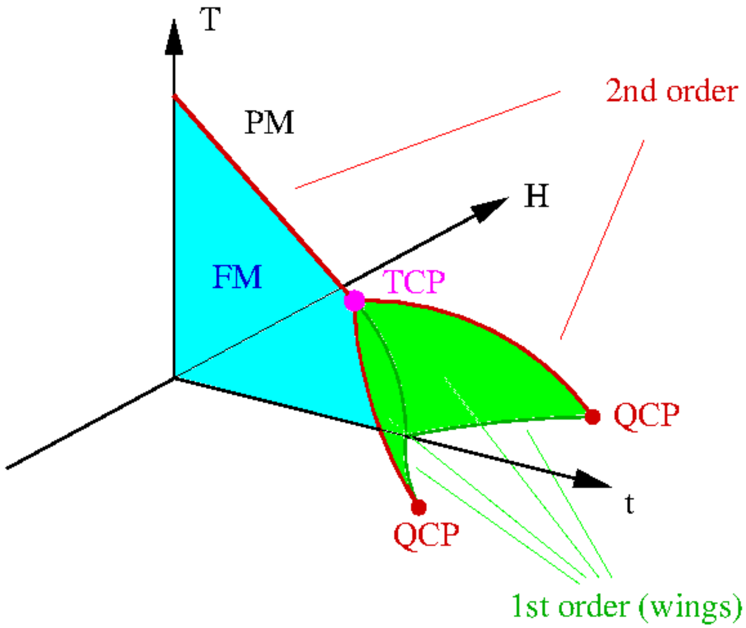

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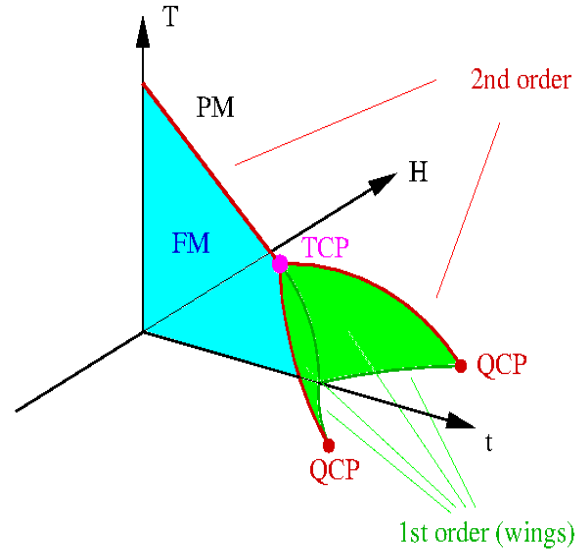

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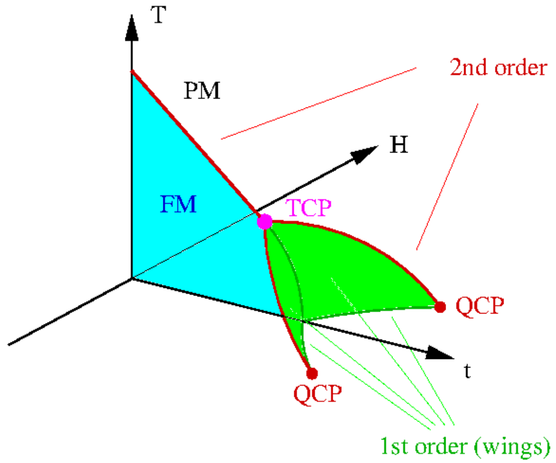

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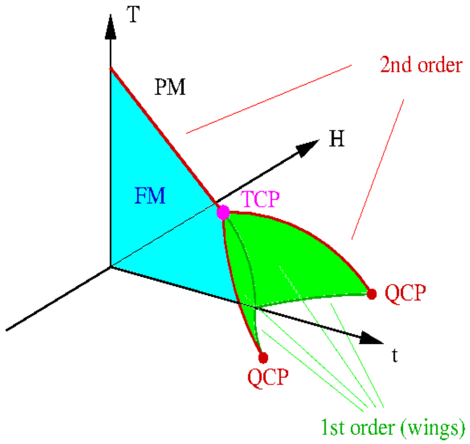

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  - More generally, Hertz theory works if field conjugate the OP does not change the soft-mode spectrum (DB, TRK, T Vojta 2002)

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•Sufficiently strong non-magnetic disorder drives transition 2^{nd} order. Also understood.

TABLE I: Systems with low-T ferromagnetic transitions and their properties. T_c = Curie temperature, T_{tc} = tricritical temperature. ρ_0 = residual resistivity. FM = ferromagnet, SC = superconductor. N/A = not applicable; n.a. = not available.

System [a]	Order of Transition [c]	T_c/K [b]	magnetic moment/μ_B [d]	tuning parameter	T_{tc}/K	wings observed	Disorder ($\rho_0/\mu\Omega$cm) [e]	Comments
MnSi [27]	1st [18]	29.5 [28]	0.4 [28]	hydrostatic pressure [18]	≈ 10 [18]	yes [25]	0.33 [25]	weak helimagnet [17] exotic phases [25,26]
$ZrZn_2$ [27]	1st [29]	28.5 [29]	0.17 [29]	hydrostatic pressure [29]	≈ 5 [29]	yes [29]	≥ 0.31 [30]	confusing history, see Ref. 27
$Sr_3Ru_2O_7$	1st [f]	0 [g]	0 [g]	pressure [g]	n.a.	yes [31]	< 0.5 [31]	foliated wing tips, nematic phase [31]
UGe_2 [33]	1st [34]	52 [35]	1.5 [35]	hydrostatic pressure [22,35]	24 [36]	yes [35,36]	0.2 [22]	easy-axis FM coexisting FM+SC [22]
URhGe [33]	1st [37]	9.5 [23]	0.42 [23]	transverse B-field [37,39]	≈ 1 [37]	yes [37]	8 [38]	easy-plane FM coexisting FM+SC [23]
UCoGe [33]	1st [40]	2.5 [40]	0.03 [24]	none	$> 2.5?$ [h]	no	12 [24]	coexisting FM+SC [24]
CoS_2	1st [41]	122 [41]	0.84 [41]	hydrostatic pressure [41]	≈ 120 [41]	no	0.7 [41]	rather high T_c
$La_{1-x}Ce_xIn_2$	1st [42]	$22 - 19.5$ [42] [i]	n.a.	composition [42]	$> 22?$ [j]	no	n.a.	third phase between FM and PM? [42]
Ni_3Al [27]	(1st) [k]	$41 - 15$ [l]	0.075 [m]	hydrostatic pressure [43]	n.a.	no	0.84 [44]	order of transition uncertain
$YbIr_2Si_2$ [n]	1st [45]	$1.3 - 2.3$ [o]	n.a.	hydrostatic pressure [45]	n.a.	no	≈ 22 [p]	FM nature of ordered phase suspected [45]
$YbCu_2Si_2$ [n]	n.a.	$4 - 6$ [46] [q]	n.a.	hydrostatic pressure [46]	n.a.	no	n.a.	nature of magnetic order unclear
$URu_{2-x}Re_xSi_2$	2nd [47,48]	$25 - 2$ [r]	$0.4 - 0.03$ [48]	composition [47]	N/A	N/A	≈ 100 [s]	strongly disordered
Ni_xPd_{1-x}	2nd [50]	$600 - 7$ [t]	n.a.	composition [50]	N/A	N/A	n.a.	disordered, lowest T_c rather high
$YbNi_4P_2$	2nd [51]	0.17 [51]	≈ 0.05 [51]	none	N/A	N/A	2.6 [51]	quasi-1d, disordered

Many More BDs Eddie!!!

Helena and Ted