Yukawa International Seminar 2007
"Interaction and Nanostructural Effects in Low-Dimensional Systems"
November 5-30, 2007, Kyoto

When Landau and Lifshitz meet

— Unconventional Quantum Criticalities —

November 21, 2007
Kyoto

M. Imada
Univ. Tokyo

Collaboration with
T. Misawa, Y. Yamaji, Y.Z. Zhang

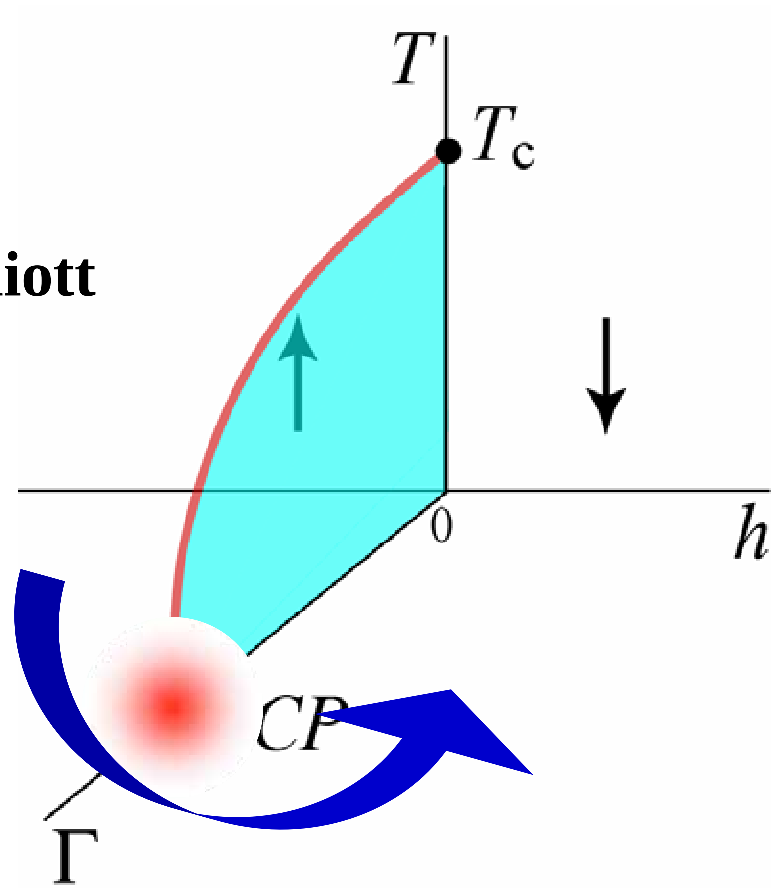
Conventional picture of QCP ; Landau's lineage

transverse Ising

$$H = J\sum_{\langle i,j\rangle} S_i^z \cdot S_j^z - h\sum_i S_i^z$$

QCP: same concept with classical symmetry breaking but in *d* + *z* dim.

Elliott



symmetry breaking

itinerant electrons magnetism

Moriya,Hertz,Millis

low-energy excitation: bosonic fluctuations

⬇

non-Fermi liquid

Standard non-Fermi liquid around QCP

$\rho \sim T^2$ Ferm liquid

↕

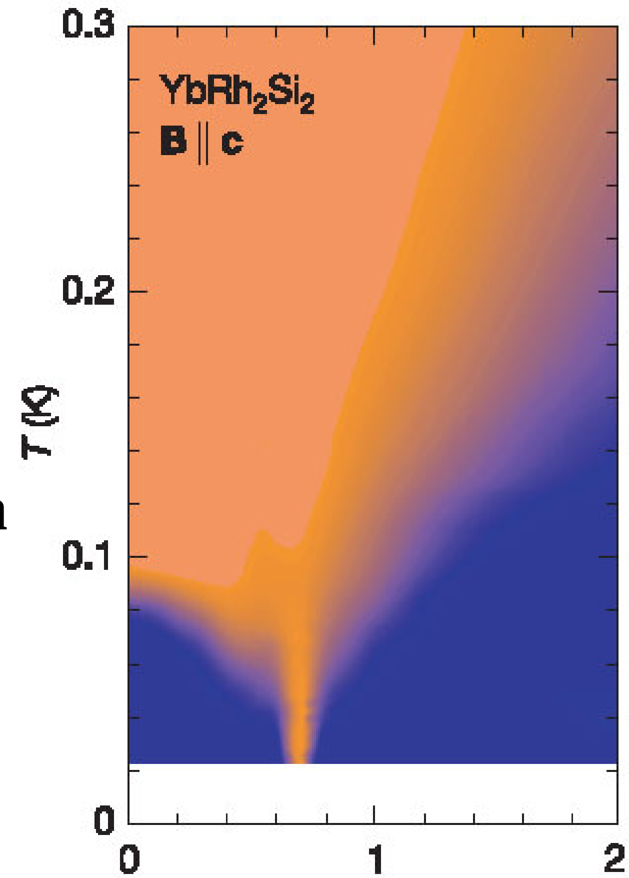
★ $\rho \sim T^{3/2}$ 3D AF

$\sim T^{5/3}$ F

$\sim T$ 2D AF

$\sim T^{4/3}$ F

Ueda, Moriya



Custers, Steglich et al. (2003)

★Quantum criticality expected only around QCP "V" shape structure

All arisie from symmetry breaking QCP

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Quantum Critical Phenomena beyond Standard Picture

4f , 5f

$YbRh_2Si_2$, $CeRu_2Ge_2$, UGe_2, URu_2Si_2, $CeIn_3$, $CeIn_3$, $Ce(Cu,Au)_6$, ….

3d,4d

$ZrZn_2$, MnSi, NiS_2, $Sr_3Ru_2O_7$, YCo5,

…….

$YbRh_2Si_2$; weak antiferromagnet

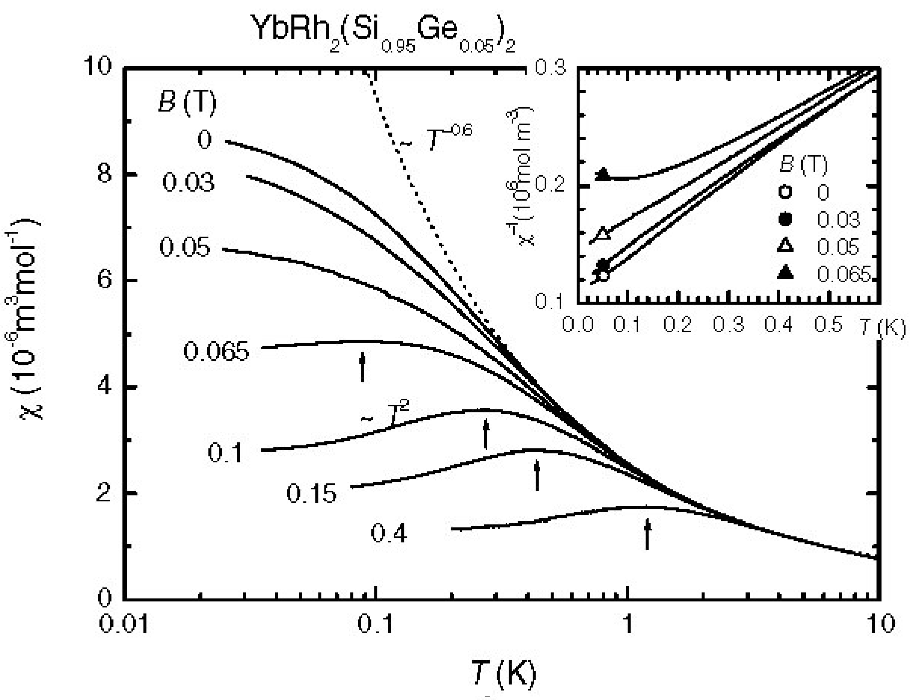
Heavy fermion compound **QCP by magnetic field or pressure**

γ ~2JK^2/mole

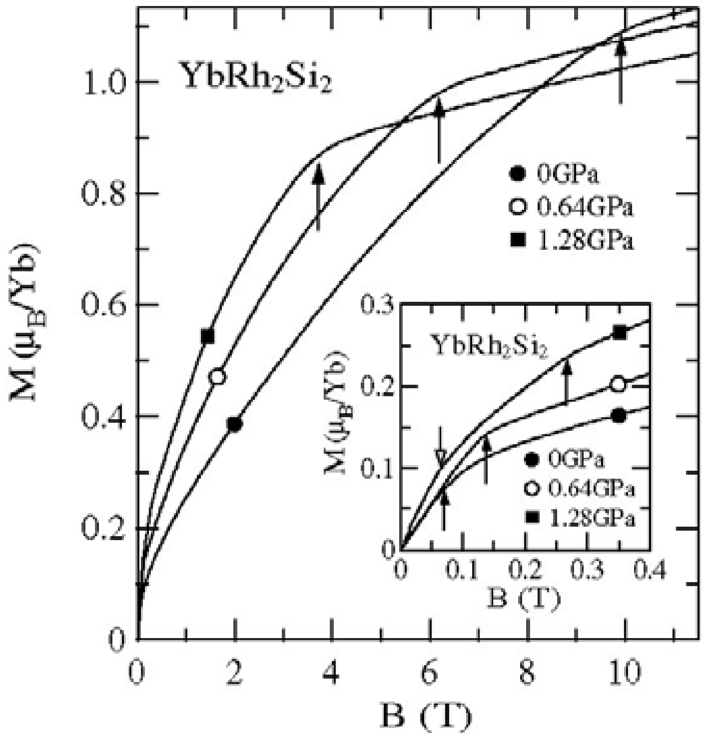
"Ferromagnetic" fluctuation around QCP

$\chi \sim T^{-0.6}$

$M \sim B^{1/2}$



Gegenwart *et al.* PRL(2005)



Tokiwa *et al.* PRL (2005)

Puzzling exponents

Moriya, Ueda
RG study; Hertz, Millis

	ρ	C/T	χ_0	χ_Q
Fermi liquid	T^2		constant	
3D AF	$T^{3/2}$	$c-T^{1/2}$	c	$T^{-3/2}\rightarrow$C.W.
F	$T^{5/3}$	$-\ln T$	$T^{-4/3}\rightarrow$C.W.	
2D AF	T	$-\ln T$	c	$-T/\ln T\rightarrow$C.W.
F	$T^{4/3}$	$T^{-1/3}$	$-T\ln T\rightarrow$C.W.	
$YbRh_2Si_2$	T	$-\ln T$	$\sim T^{-0.6}$	

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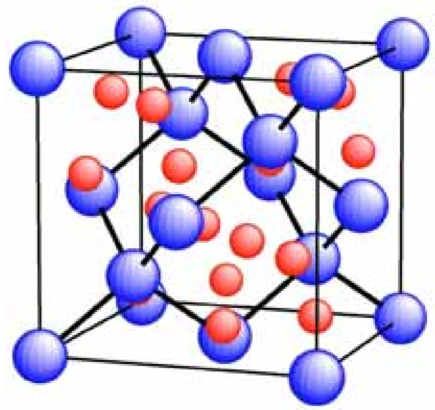
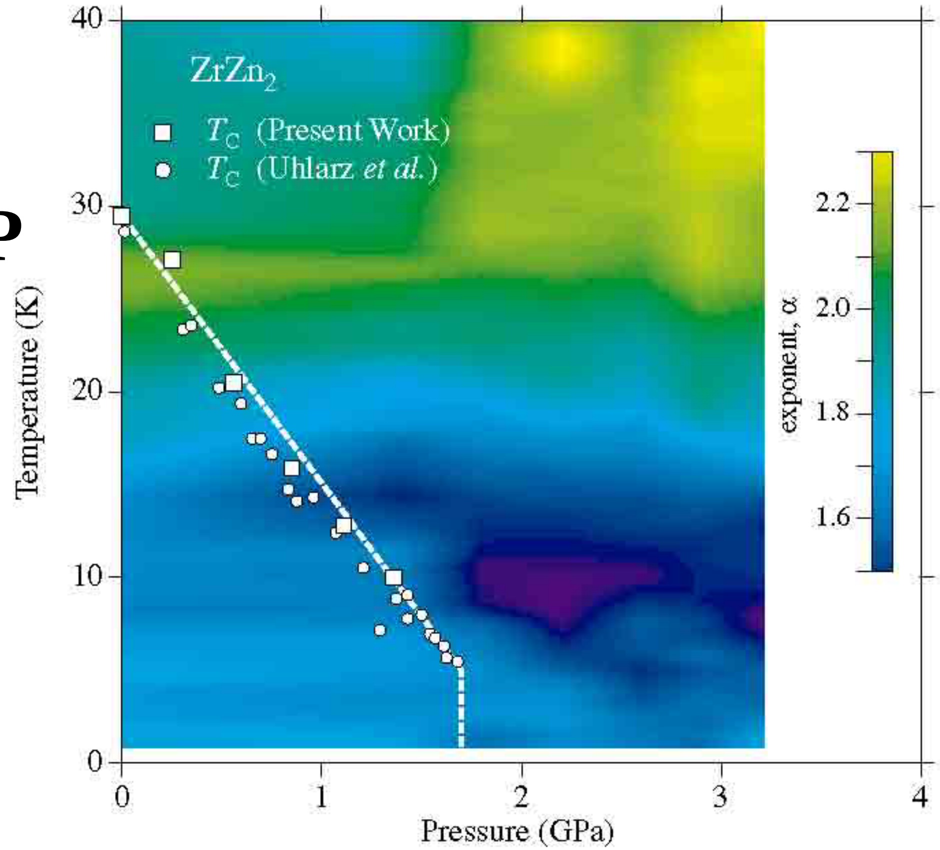
$ZrZn_2$ weak F cubic Laves; Zr 4*d*



continuous
F transition
at ambient P



Yelland et al.

$\rho \sim T^{5/3}$ in ordered region

$\rho \sim T^{3/2}$ in paramagnetic region

too wide region

Takashima,
Takagi et al. (2007)

violation of
standard QCP picture

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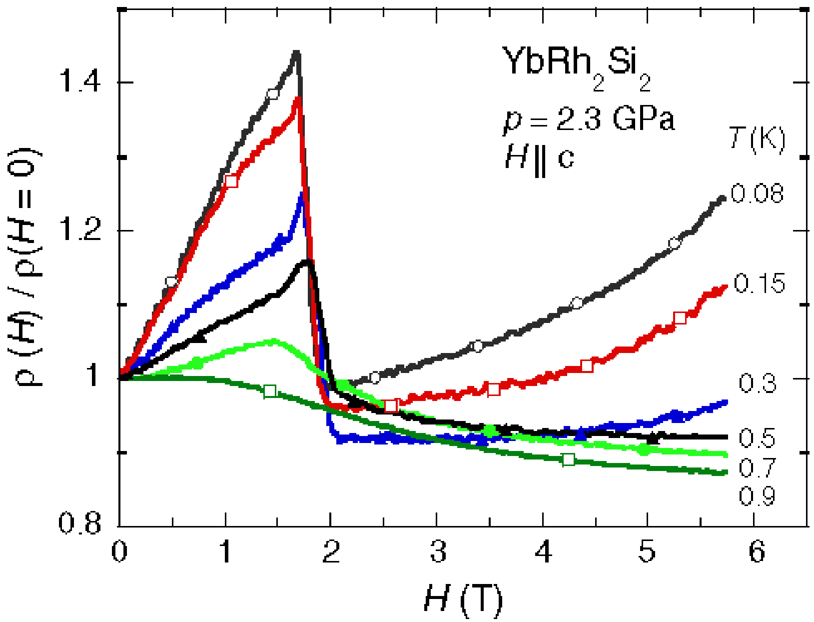
Hint: Near First-Order Transition

$YbRh_2Si_2$

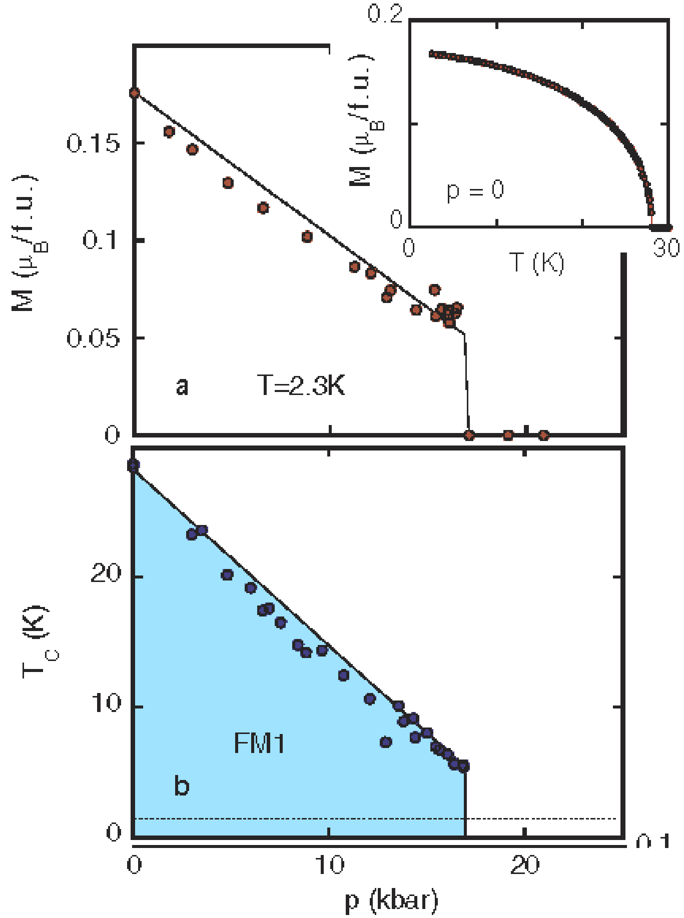
first order transition under pressure at $H \neq 0$



Knebel, Flouquet *et al.*
JPSJ 75 (2006) 14709

$ZrZn_2$

first order above 1.65GPa



Uhlarz, Pfleiderer, Hayden (2004)

Unconventional QCP found in various compounds

proximity of 1st order magnetic transition

4f,5f $YbRh_2Si_2$,
$CeRu_2Ge_2$,Fontes et al,
UGe_2 Huxley et al.
URu_2Si_2, $CeIn_3$,
$Co(S,Se)_2$,YCo_5, $CeIn_3$

3d,4d $ZrZn_2$, MnSi, NiS_2, $Sr_3Ru_2O_7$ …….

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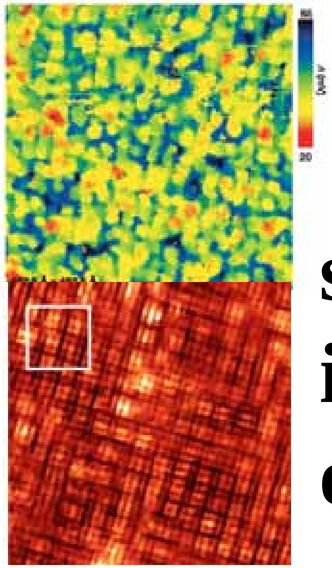
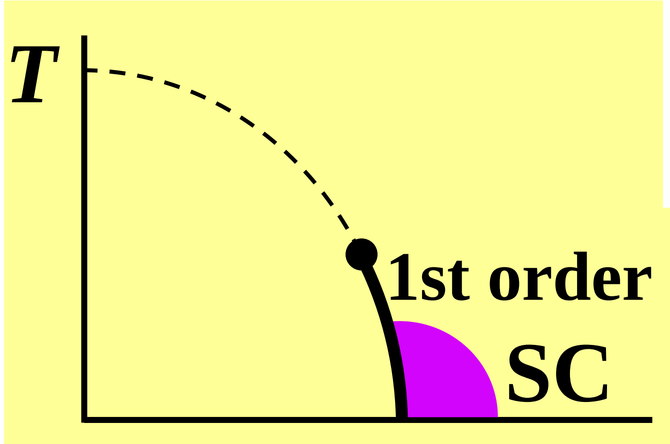
common tendency

1st order MI transitions

cuprates

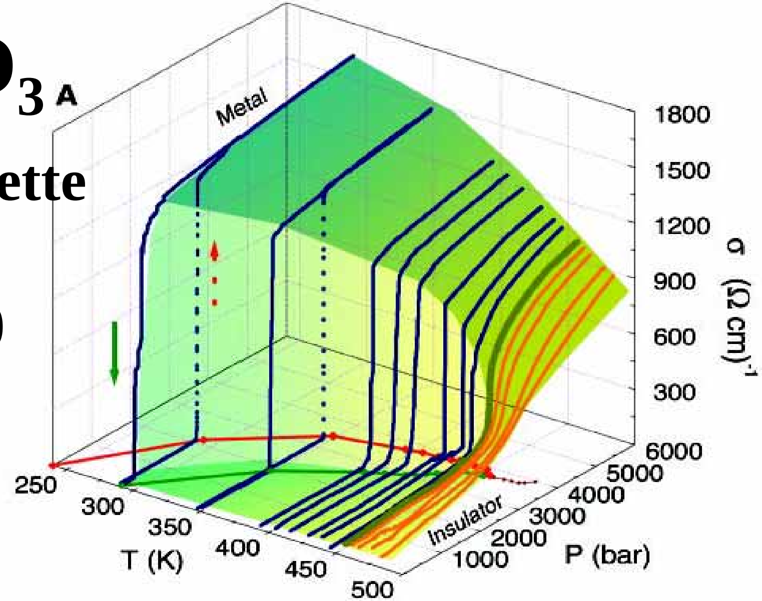
Kohsaka et al.
Hanaguri et al.





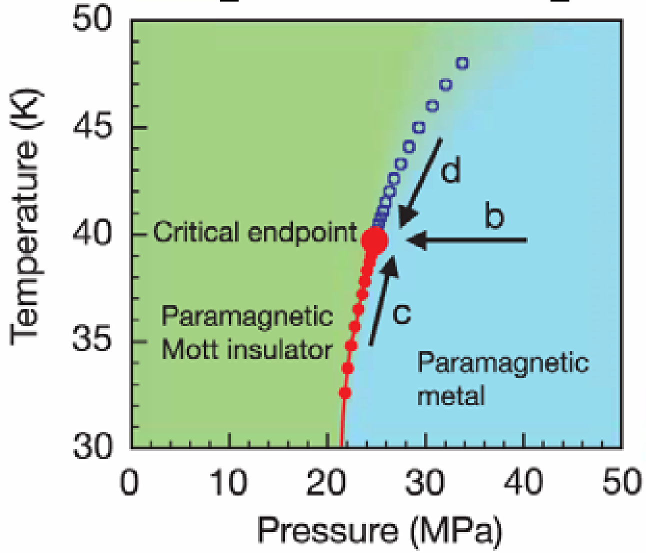
sensitive impurity effect

V_2O_3



Limelette et al. (2003)

κ-$(ET)_2Cu[N(CN)_2]Cl$



Kanoda group

Diverging *charge* fluctuations at T_c

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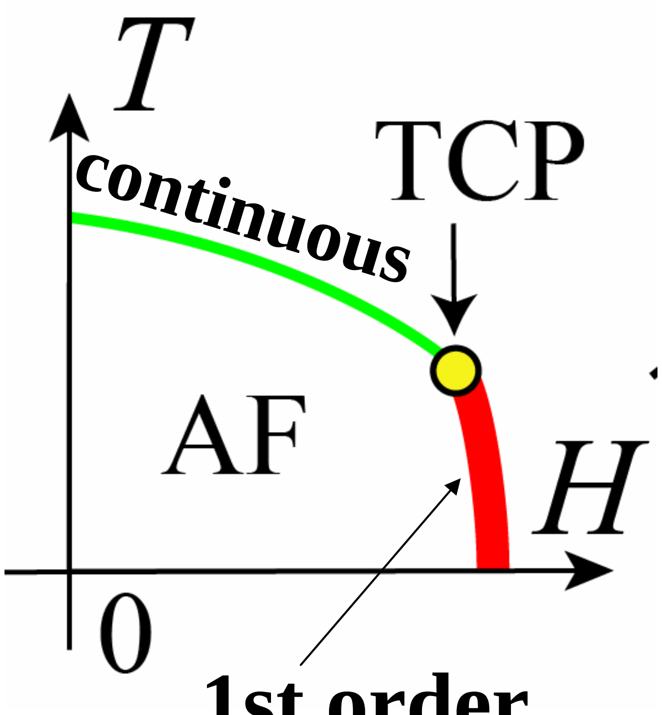
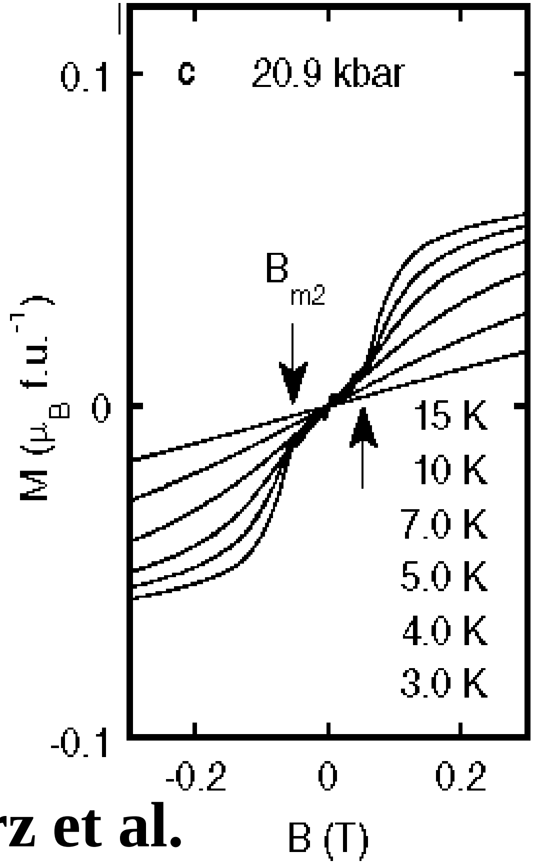
Tricriticality does not solve puzzle

Yamaji

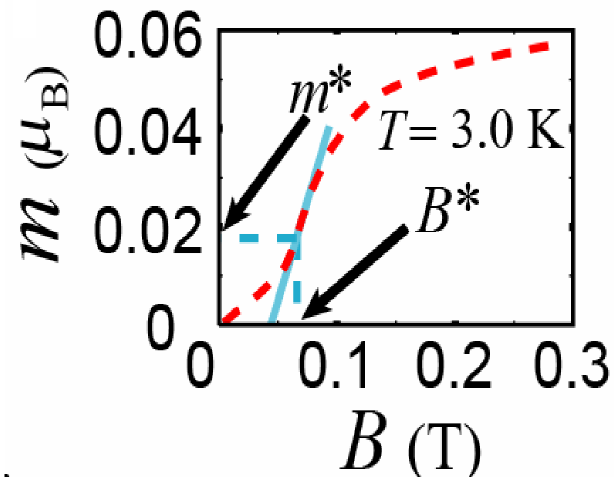
tricriticality?



Metamagnetic transition in $ZrZn_2$



Uhlarz et al.



$m - m^* \propto (B - B^*)^{1/\delta}$

$\delta \sim 3/2$

$\delta \geqq 3$ for any GLW

symmetry-breaking transition

Yamaji, Misawa, MI
JPSJ 76 (2007) 063702
75 (2006) 094719

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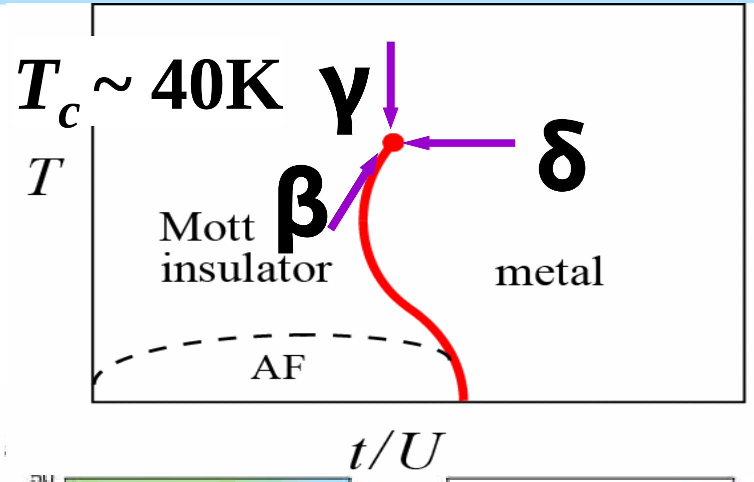
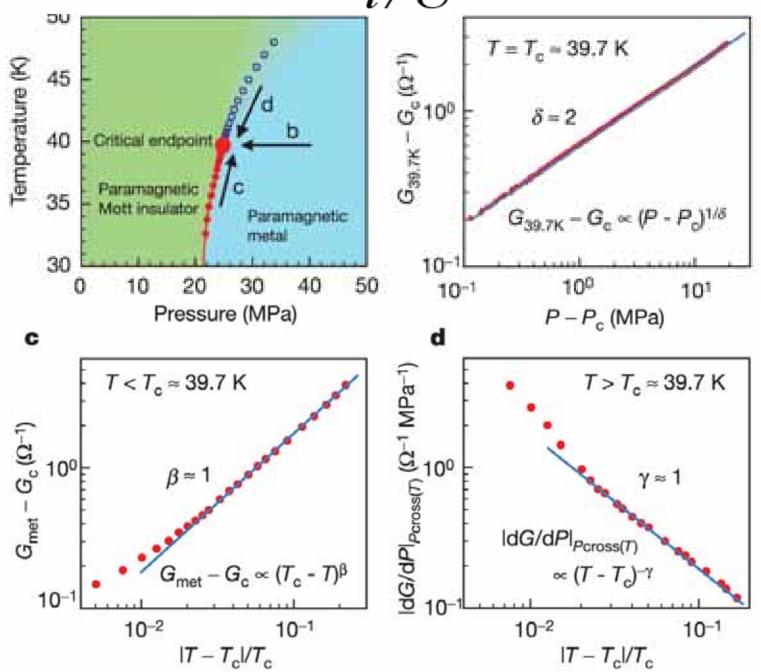
MI transition of κ-$(ET)_2Cu[N(CN)_2]Cl$





Kagawa, Miyagawa, Kanoda Nature, 2005

$$\sigma(P) \sim (P - P_c)^{-1/\delta}$$

$$d\sigma/dP \sim (T - T_c)^{-\gamma}$$

$$\Delta\sigma \sim |T - T_c|^{-\beta}$$

$$\beta \approx 1, \delta \approx 2, \gamma \approx 1$$

$\beta < 1/2$

$\delta > 3$

for symmetry breaking transitions

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Issue

Origin of deviation from standard QCP

Key:

Proximity of first-order transition

Novel concept beyond
conventional GLW framework of QCP

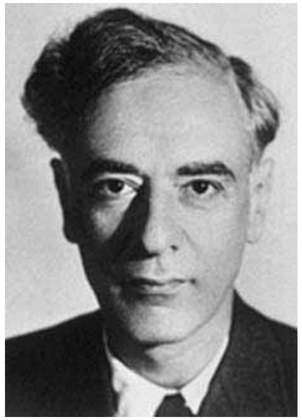
Two categories of quantum phase transitions

—Two major sources of our interest
in condensed matter

★Interaction

★Quantum mechanics

Landau

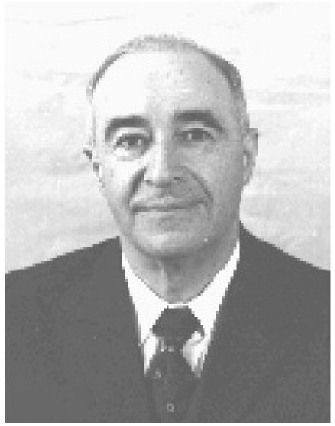


Interaction effect → symmetry-breaking transition

Quantum effect → topological transition

ex. Lifshitz tr. in momentum space

Lifshitz



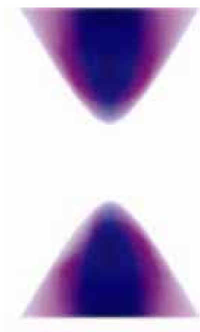
Lineage of Lifshitz: topological transition

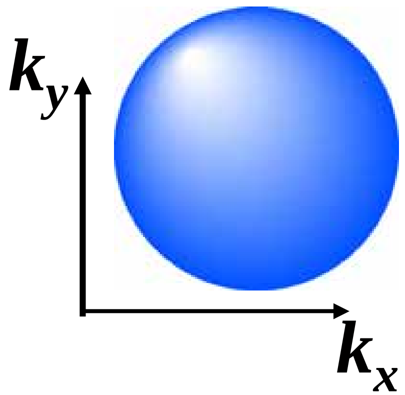
"quantum order": Wen

gapless phase **gapful phase**

topological order

topology change of Fermi surface; Lifshitz transition, MI transition





topological transition

Quantum Hall state

QSH

Noninteracting

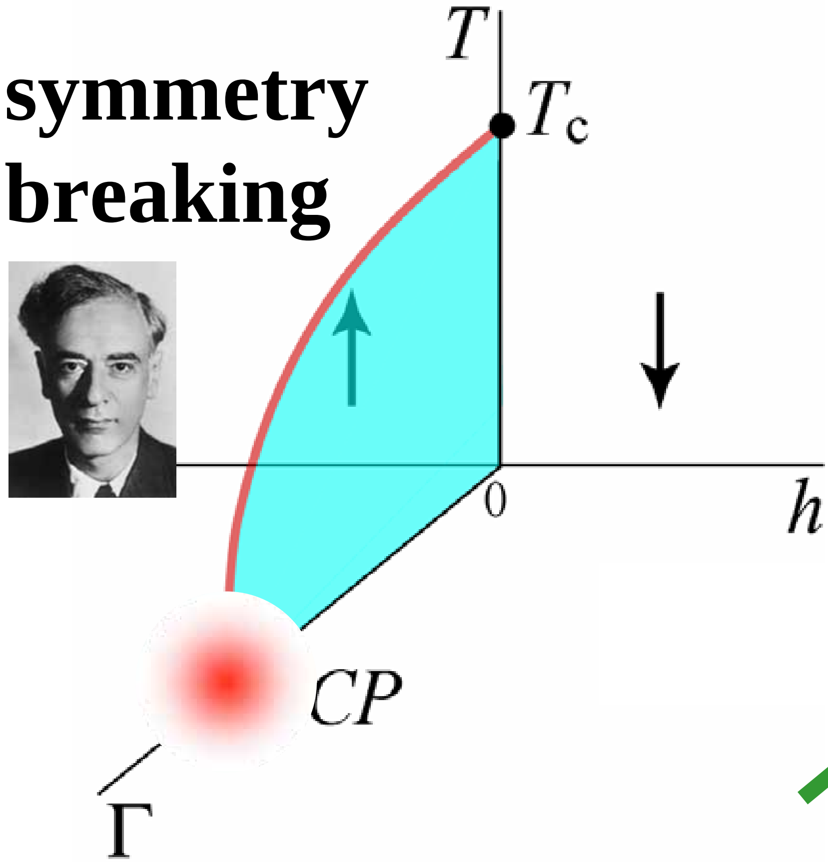
No change in symmetry

continuous transition at $T = 0$

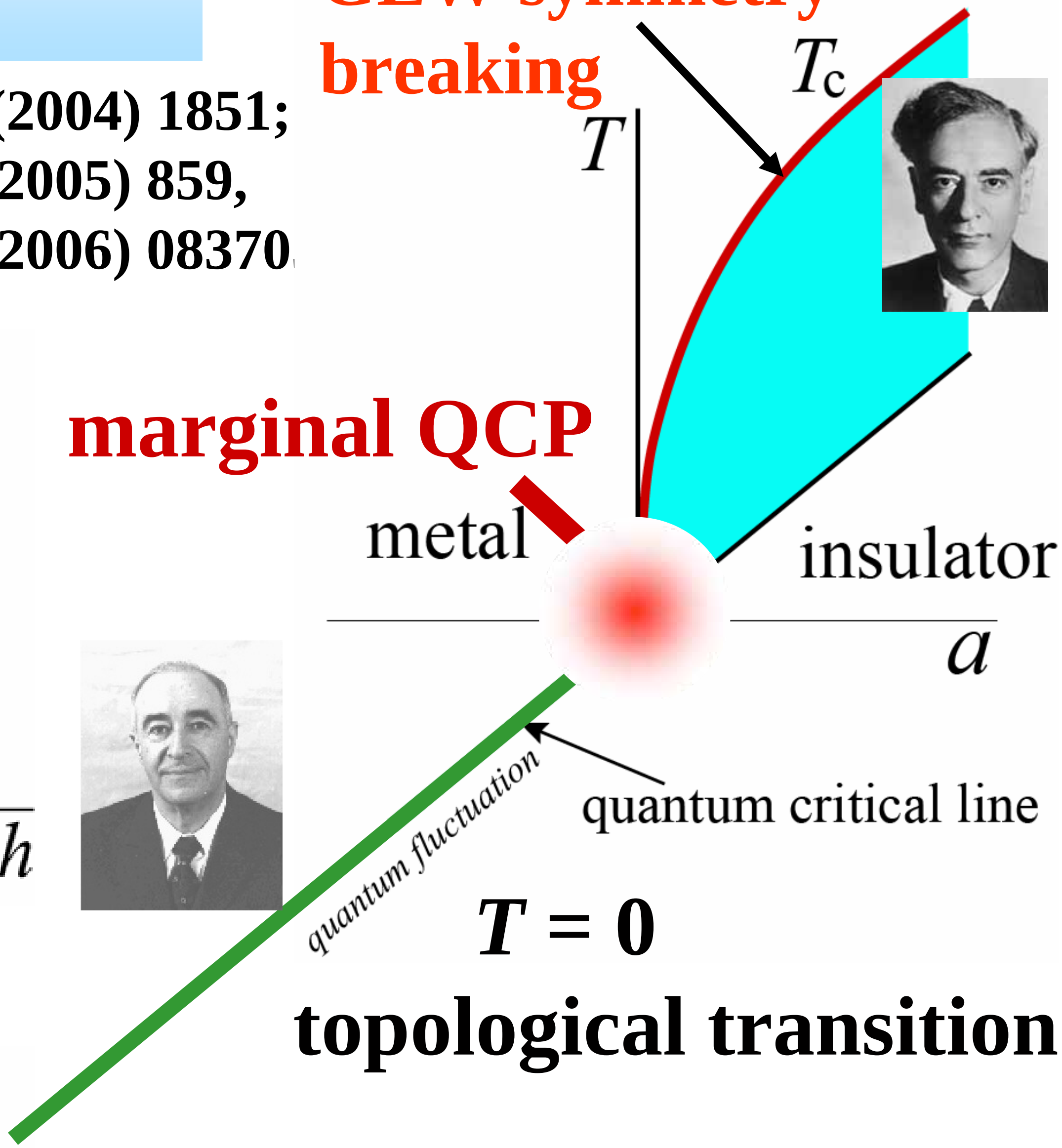
Link between Landau type and Lifshitz type

PRB 72 (2005) 075113; JPSJ 73 (2004) 1851;
74 (2007)115121
74 (2005) 859,
75 (2006) 08370

GLW scheme



Z_2 critical line;
GLW symmetry breaking



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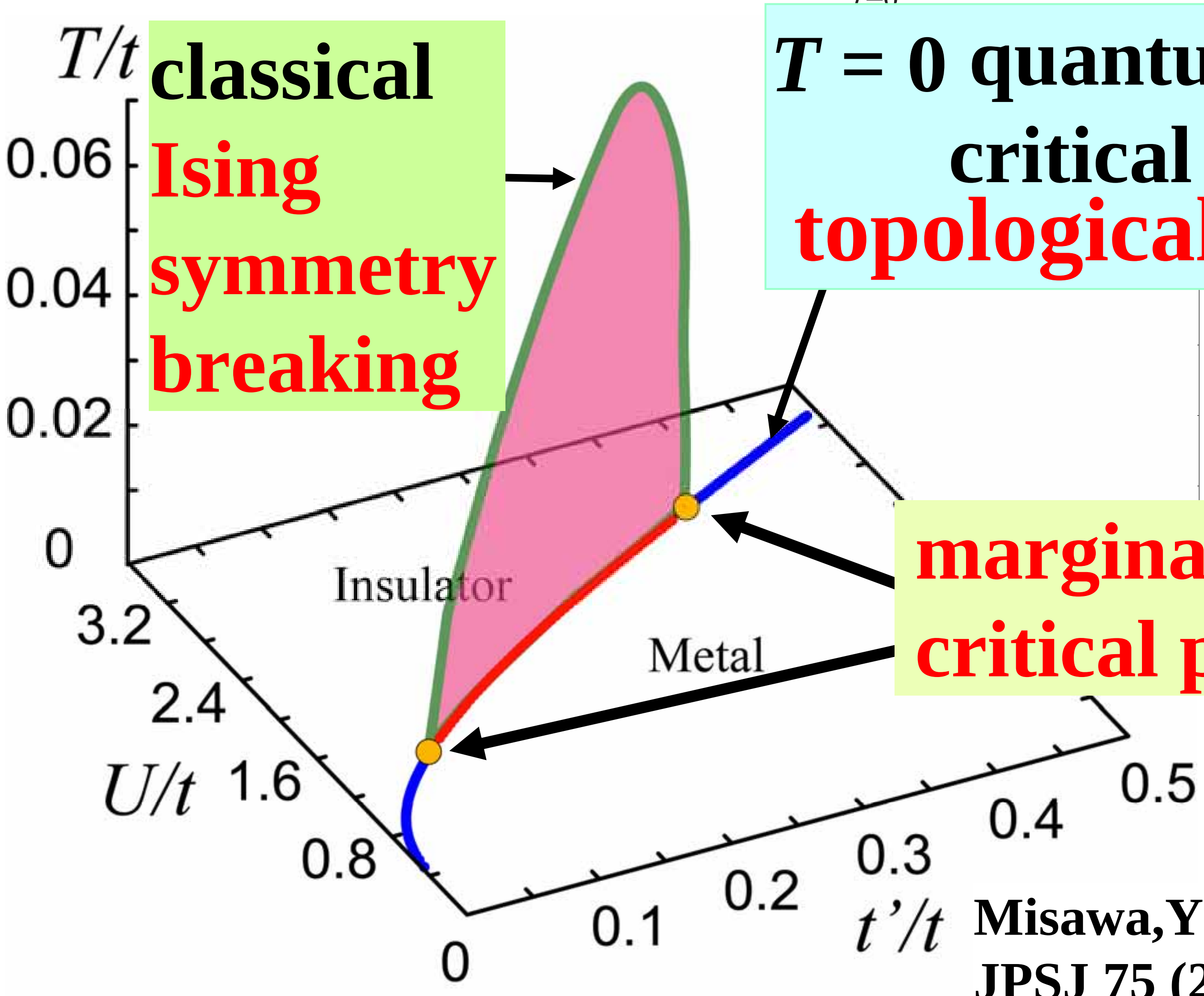
proximity of first-order transition

Physics of
Marginal Quantum Critical Phenomena

Metal-Insulator Transitions

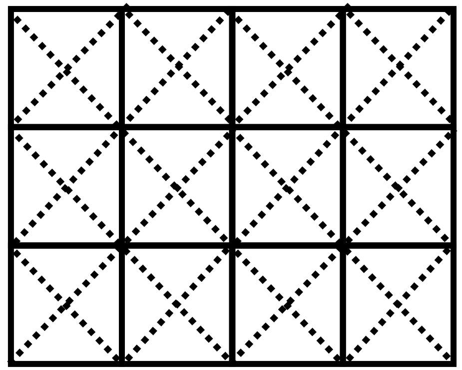
Hartree-Fock Phase Diagram

Metal-Insulator Transition for 2D Hubbard Model



classical
Ising
symmetry
breaking

T = 0 quantum
critical line
topological



marginal quantum
critical point (MQCP)

cf. Ising universality at $T \neq 0$;
DMFT, Kotliar (2000, 2002)

Misawa, Yamaji, Imada
JPSJ 75 (2006) 083705
Misawa, Imada
PRB 75 (2007) 115121

cf.
Hirsch
Hofstetter-Vollhardt
Kondo-Moriya
……..

non-Ginzburg-Landau-Wilson scheme

$$F(Y) - F(Y=0) = AY + \frac{1}{2}BY^2 + \frac{1}{3!}CY^3 + \cdots$$

***Y*: order parameter measured from MI transition**

$Y > 0$; insulator, $Y < 0$; metal

unique expansiotn, but *B*, *C* : jump at Y=0

because of jump of DOS at E_F

non-Ginzburg-Landau-Wilson

⬍

topological nature

$B_m > 0$; continuous ; $A > 0$ → metal, $A < 0$ → insulator

$B_m < 0$; first order $A = B_m = 0$; MQCP

$$\beta = 1, \delta = 2, \gamma = 1$$

new universality class

experimental confirmation: κ-$(ET)_2Cu[N(CN)_2]Cl$

scaling laws at MQCP in 2D

$$\begin{aligned} d &= 2 \\ z &= 4 \\ \alpha &= -1 \\ \beta &= 1 \\ \gamma &= 1 \\ \delta &= 2 \\ \nu &= 1/2 \\ \eta &= 0 \end{aligned}$$

density
$\leftarrow \chi/S \sim \xi^{z}$

unusual universality with large z →

cf.symm. breaking
$\beta \leqq 1/2$, $\delta \geqq 3$

$$\beta(\delta - 1) = \gamma$$
(Widom)

$$\alpha + 2\beta + \gamma = 2$$
(Rushbrooke)

$$2 - \eta = \gamma/\nu$$ **(Fisher)**

$$F \propto \xi^{-(d+z)}$$

$$2\beta + \gamma = (d + z)\nu$$ **: hyperscaling relation**

Ginzburg criterion

$$d + z \geq (2\beta + \gamma)/\nu = d + 4$$

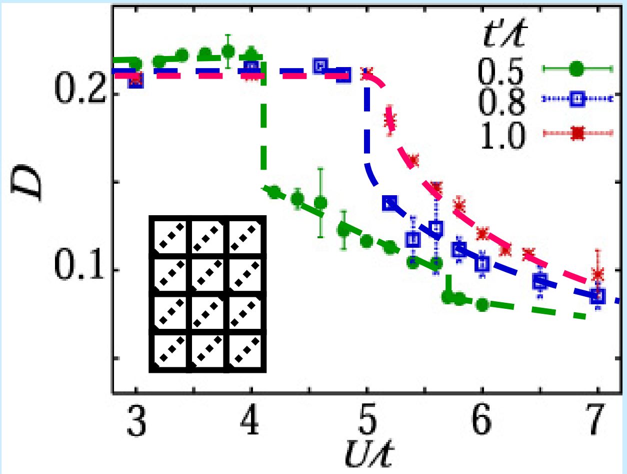
***d* = 2; upper critical dim.**
hyperscaling and mean field compatible

Does MQCP really exist beyond Hartree Fock?

Exact approach beyond mean-field

PIRG & QMC numerical results

1st order ⇔ continuous
MQCP



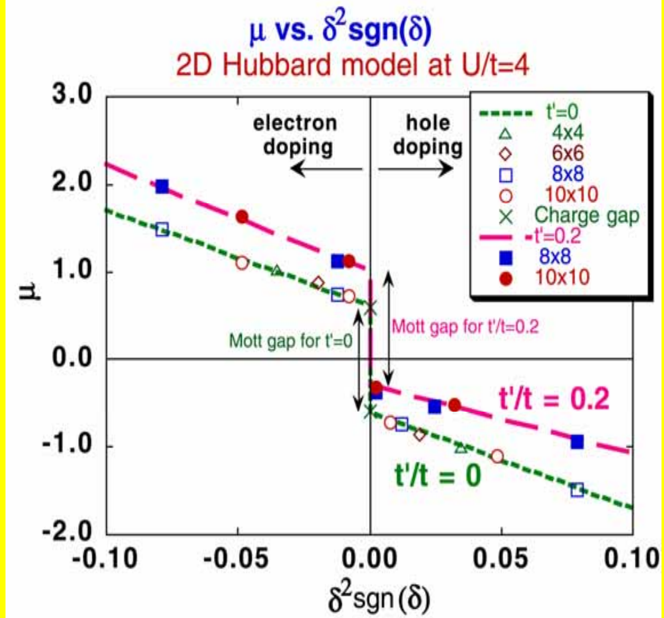
Kashima, Imada (2001)

unconventional universality → $\kappa \propto X^{-1}$, $D_r \propto X^{2}$,
→ $z = 4$, $\delta = 2$

compressibility κ (Furukawa, 1992, Kohno 1997)

Drude weight D_r (Tsunetsugu, 1998, Nakano, 2006)

MI JPSJ 64 (1995) 2954
63 (1994) 4294



Divergence of uniform fluctuations at MQCP

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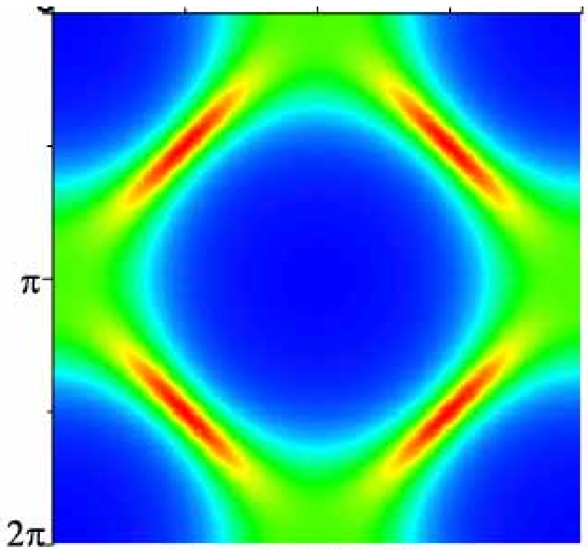
Electron differentiation in momentum space

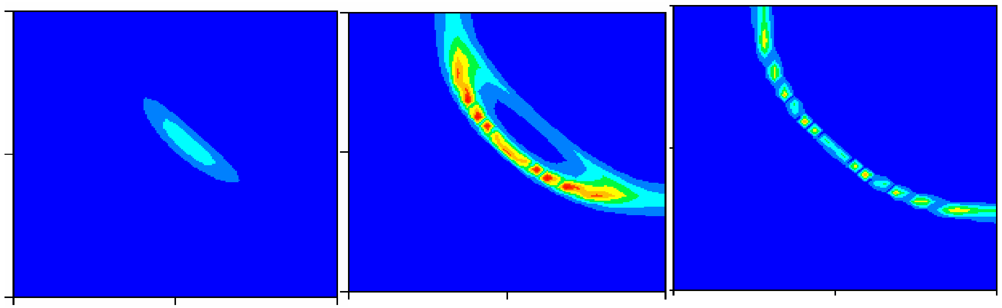
topological character of transition ⇔ differentiation in momentum space

Y. Z. Zhang & Imada Phys.Rev.B (2007)

Extension of DMFT



U=3.5D/8



t-t'Hubbard with t'/t=-0.2

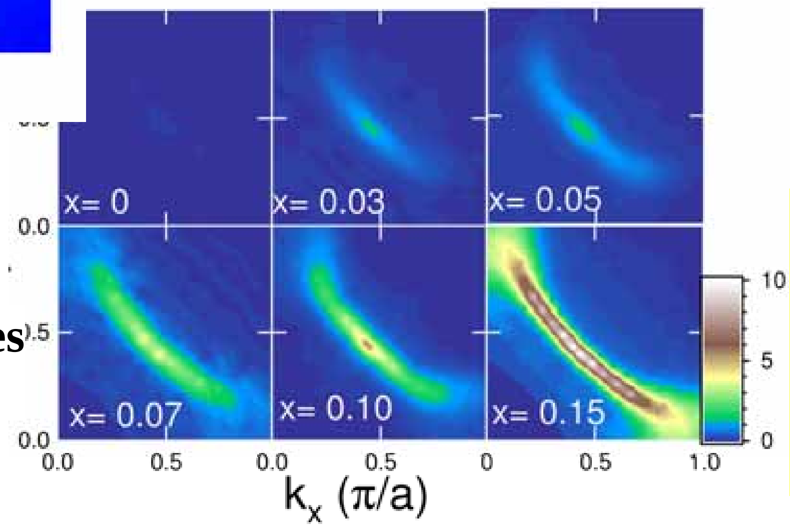
Hanasaki & Imada (2006)

see also
Civelli.Kotliar et al. PRL 95 (2005) 106402
Macridin, Jarrell et al. PRL 97 (2006) 036401

$A(k,\omega)$

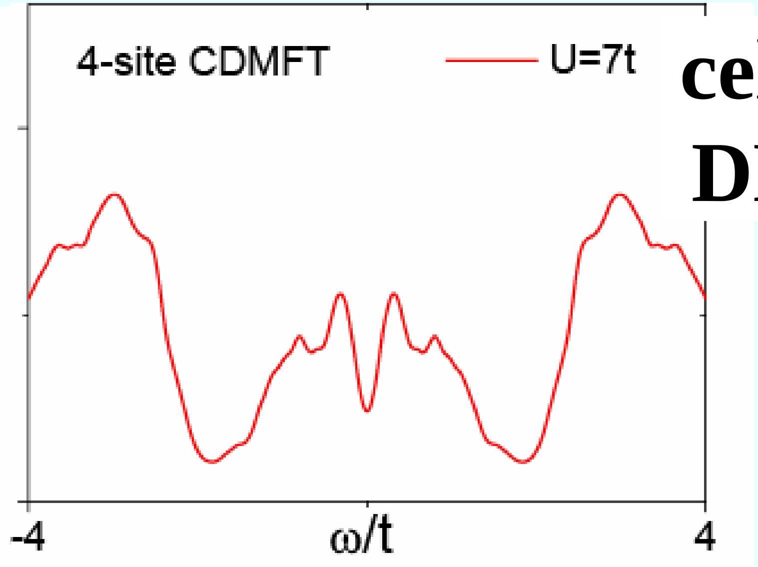
ARPES data for cuprates
Yoshida et al.

Arc structure



Far from picture of local criticality

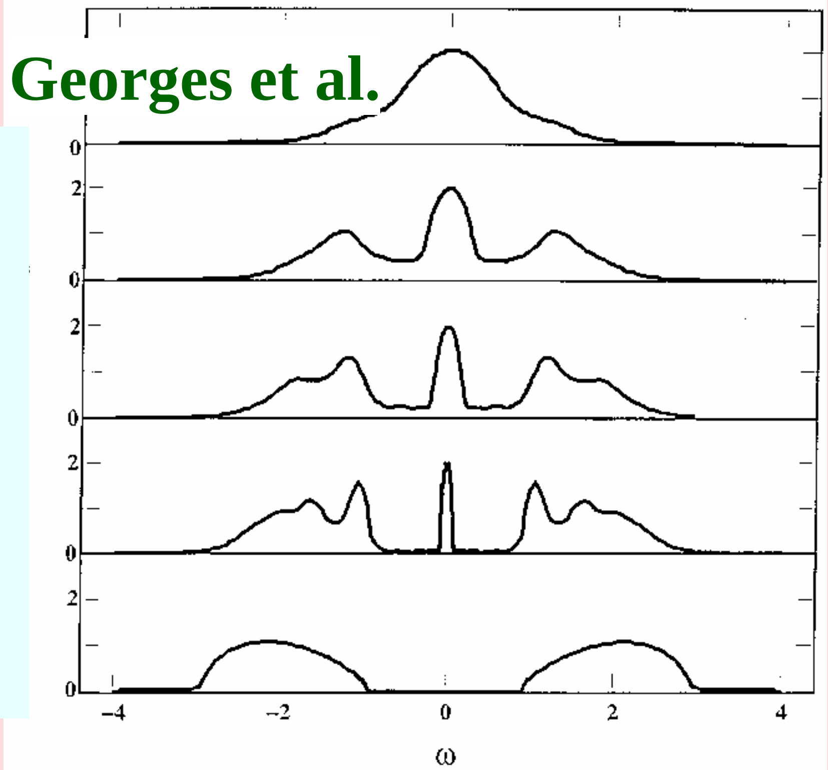
Coherent peak?



cellular DMFT

pseudogap

absence of coherent peak



single-site DMFT

quasiparticle weight $Z \to 0$

Y. Z. Zhang & Imada Phys.Rev.B (2007)

→Shin's group $SrVO_3$

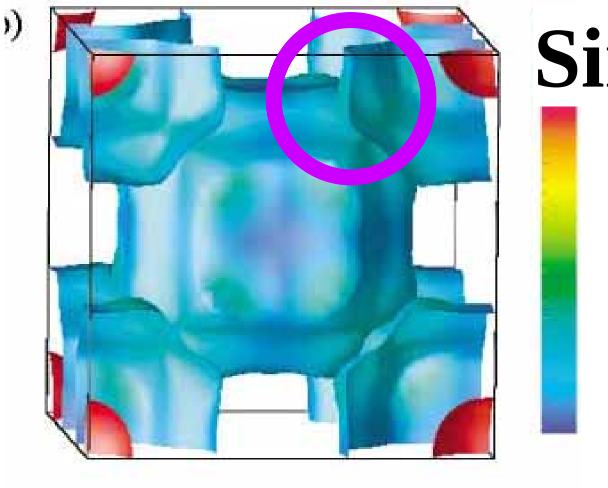
Dramatically different from single-site DMFT

Unconventional Lifshitz transition in $ZrZn_2$

Another proximity of first-order transition

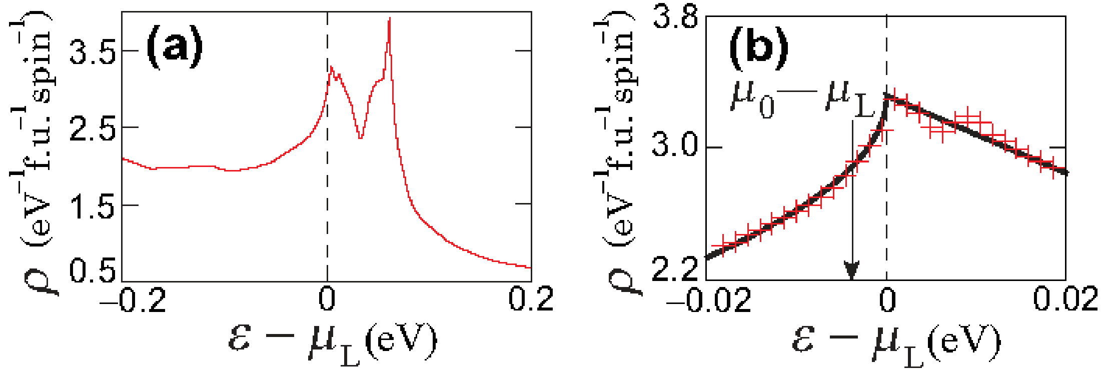
Yamaji:
Poster PS28

Lifshitz transition of $ZrZn_2$



Singh (2002) Harima (2007) de Haas

Harima Freeman (1988) Yates et al. (2003)



neck-collapsing Lifshitz transition → MQCP

Density of states from LDA

$$\rho = \rho_0 + \rho_{1/2}(\varepsilon - \mu_L)^{1/2} + \dots$$

ε ⇔ *Y* magnetization

$$F(Y) - F(Y=0) = aY + \frac{1}{2}bY^2 + c'Y^{5/2} + \frac{1}{3!}cY^3 + \cdots$$

beyond Wohlfarth-Rhodes-Shimizu ϕ^6 description

Comparison with experiment

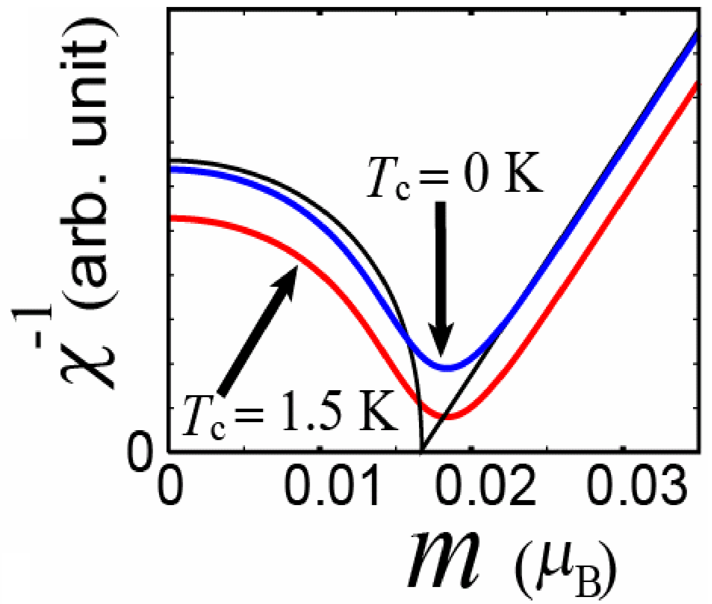
$$F(Y) - F(Y=0) = aY + \frac{1}{2}bY^2 + c'Y^{5/2} + \frac{1}{3!}cY^3 + \cdots$$

$a \rightarrow 0$, $b \rightarrow 0$; Marginal Quantum Critical Point

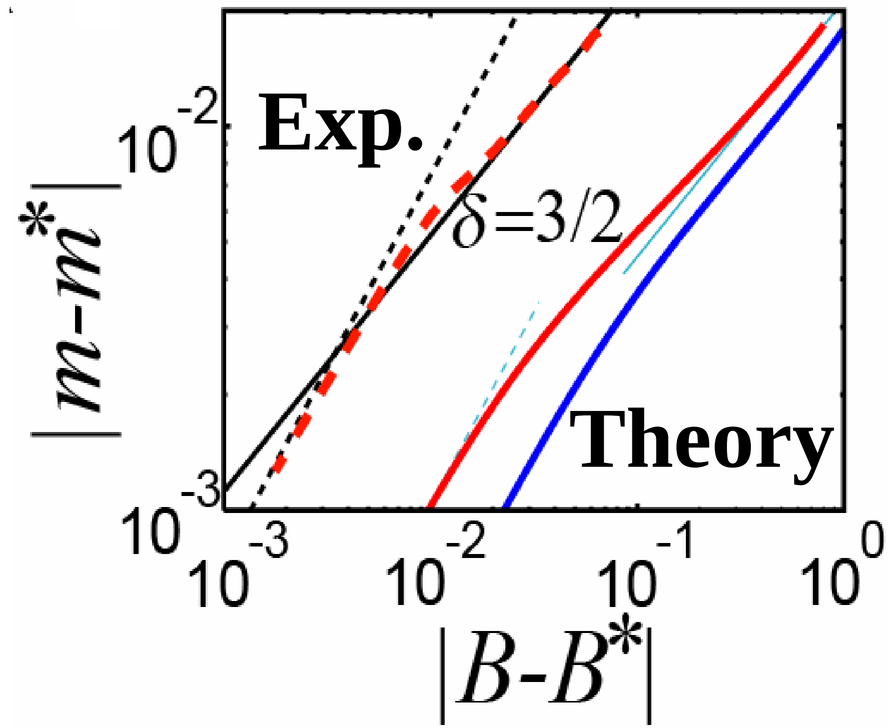
$dF/dY = 0 \rightarrow Y \propto |B-B^*|^{2/3}$

$|m-m^*| \propto |B-B^*|^{1/\delta}$

$Y \propto B^{2/3} \rightarrow \delta = 3/2$



experiments: at 3K



Quantum Tricritical Phenomena

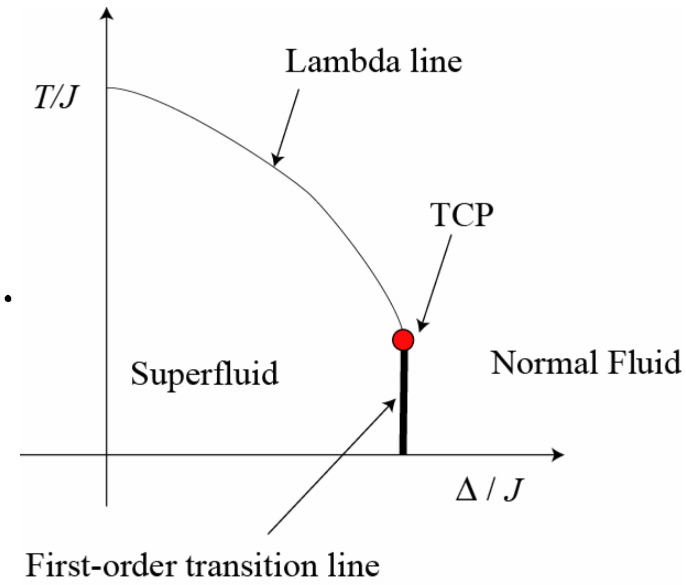
Proximity of 1st order transition within GLW scheme

Case of $YbRh_2Si_2$

Misawa: poster PS27

Physics of tricritical point

$$F(M^\dagger) = \frac{1}{2} r M^{\dagger 2} + \frac{1}{4} u M^{\dagger 4} + \frac{1}{6} v M^{\dagger 6} + \cdot$$



classical tricritical point: $r = 0$, $u = 0$

concomitant divergence of
$S(Q)$ at ordering wavenumber Q (AF)
and
$S(q=0)$ at uniform mode $q=0$ (F)

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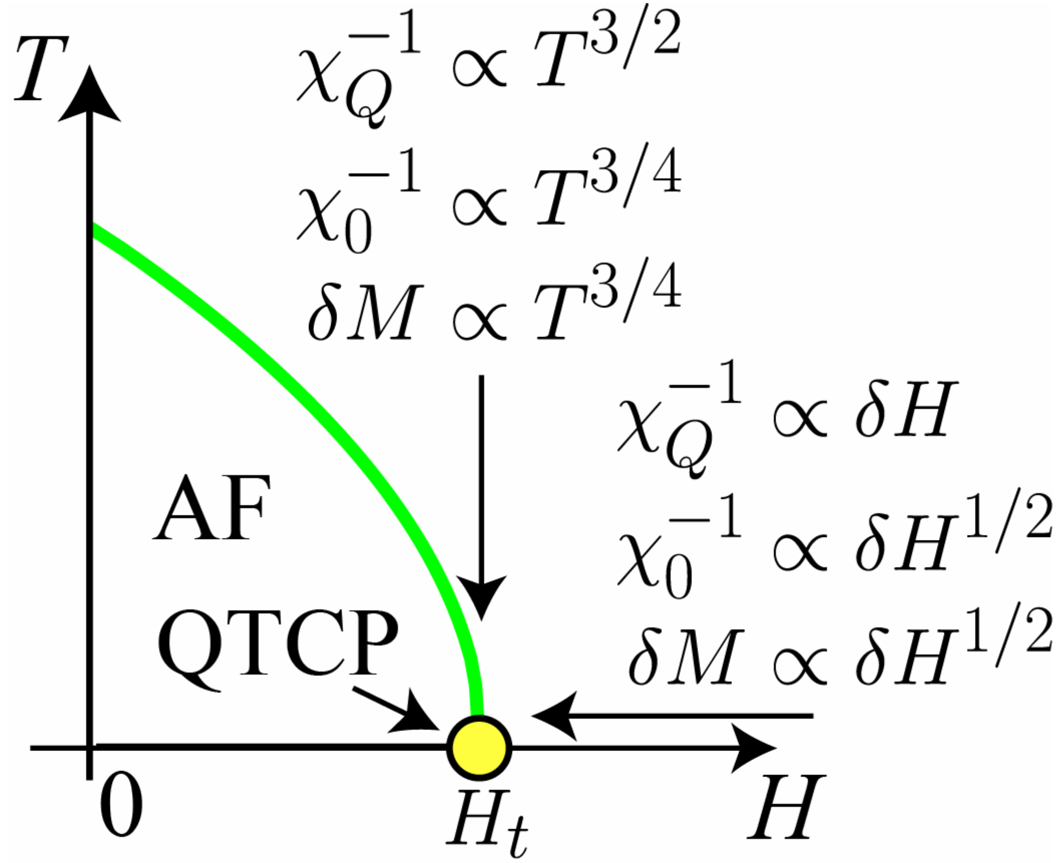
Spin Fluctuation Theory of Quantum Tricriticality

Misawa
arXiv:0710.3260
poster PS27

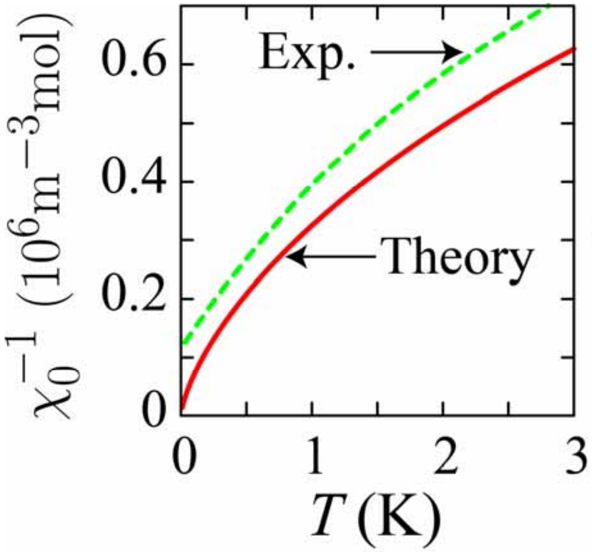


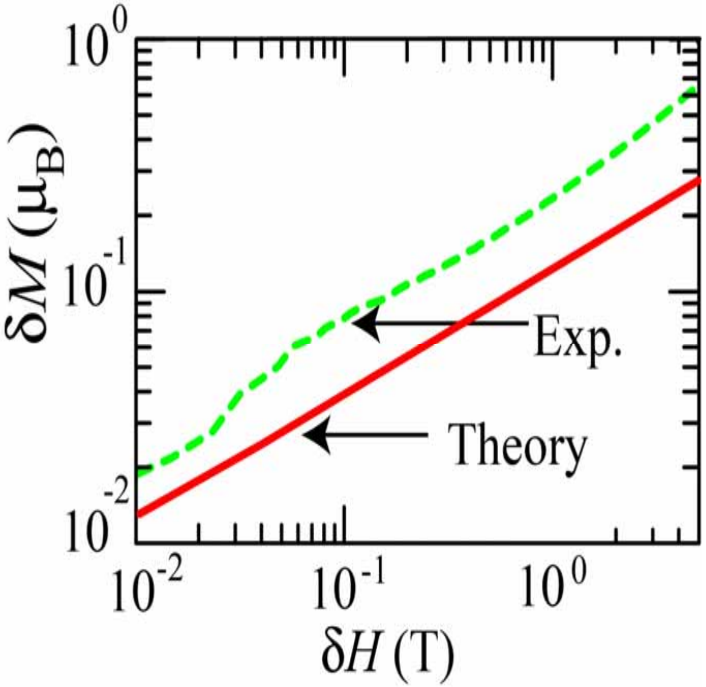
SCR theory with mode coupling of spin fluctuations

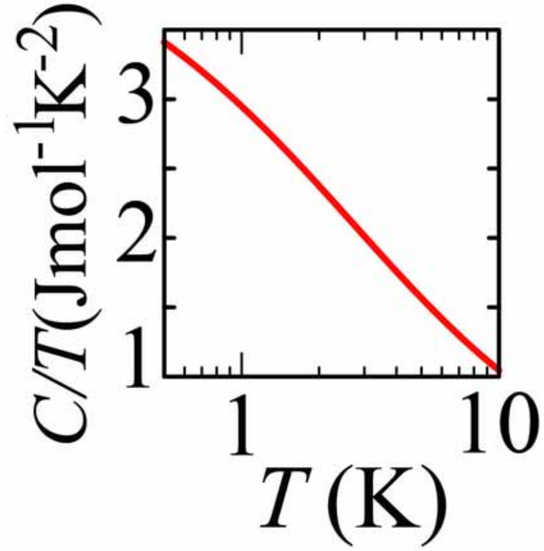
Coexistence of ferromagnetic fluctuations with AF
Stronger non Fermi liquid

Quantum tricriticality vs. experiments

$YbRh_2Si_2$







$\chi_0 \sim T^{-0.75}$

$\sim T^{-0.6}$

$\delta M \sim \delta H^{1/2}$

$\gamma \sim -\ln T$

at $T > 0.5$K

quantum tricriticality with new universality class:

agreement with $YbRh_2Si_2$

proximity of 1st order transition

Summary

Unconventional quantum critical phenomena arising from proximity of 1st order transitions

Interaction drives topological transition to
1st order & symmetry breaking

Internal structure of MIT: QCL, MQCP, Z_2 line

MQCP

new universality class : diverging $k = 0$ mode

electron differentiation

Mott transitions κ-ET, V_2O_3, …

Lifshitz transitions $ZrZn_2$

Quantum tricriticality

unconventional non-Fermi liquid

Diverging fluctuations at $k = 0$ $YbRh_2Si_2$

Outlook

Low-energy excitation around MQCP

Quasiparticle survives or fractionalization?

Detailed structure of electron differentiation

MQCP structure for nontrivial topological order

QH QSH

Effects of MQCP on superconductivity