科研費特定領域
「スーパークリーン物質で実現する新しい量子相の物理
キックオフ研究会　2005.12.15 −16

量子臨界点近傍に現われる新奇量子現象の解明

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班の研究課題

新概念の追求

量子臨界点近傍の物理

新しい量子臨界現象

モット転移　^{3}He単原子層、有機伝導体、遷移金属化合物

電荷秩序転移　有機伝導体、遷移金属酸化物

価数転移　希土類化合物

giant density fluctuation

新奇量子相

ギャップレス量子スピン液体

^{3}He単原子層、有機伝導体、遷移金属化合物

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Novel Quantum Phase and Criticality

Takahiro Mizusaki
Shinji Watanabe
Kota Hanasaki
Takahiro Misawa
Yohei Yamaji

Masatoshi Imada

Quantum Spin Liquid

Compounds with Geometrical frustration

Suppression of magnetic order,
Large residual entropy

Spin liquid

	$S>1/2$	$S=1/2$
Triangular	$LiCrO_2$ $NiGa_2S_4$ Nambu, Nakatsuji, Maeno	β'-$X[Pd(dmit)_2]_2$ Tamura, Kato κ–$(ET)_2Cu_2(CN)_3$ Kanoda ($NaTiO_2$, $LiNiO_2$)
J_1-J_2		$Li_2VO(Si,Ge)O_4$ Melzi et al.
Kagomè	$Sr(Cr,Ga)_{12}O_{19}$ Obradors et al. Broholm et al.	^3He on graphite Greywall, Elser, Fukuyama Volborthite Hiroi
Spinel	$(Zn,Li)V_2O_4$ $ZrCr_2O_4$	($LiTi_2O_4$)
Pyrochlore	$R_2Mo_2O_7$ Greedan et al. Taguchi, Tokura et al.	$Y_2Ir_2O_7$ Fukazawa, Maeno
fcc	Sato et al.	Sr_2CaReO_6 Wiebe et al.

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Gapless spin liquid

triangular lattice

S=1/2

κ–(ET)$_2$Cu$_2$(CN)$_3$ T_1, χ

^{3}He monolayer χ , C

S=1

NiGa$_2$S$_4$ χ, C, **neutron**

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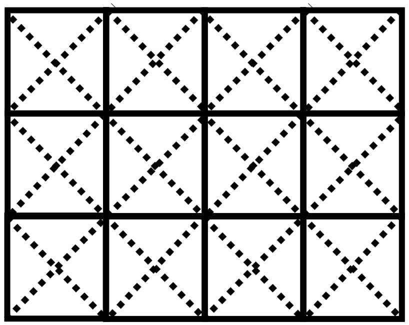
Phase Diagram of Frustrated Hubbard Model at ½ Filling

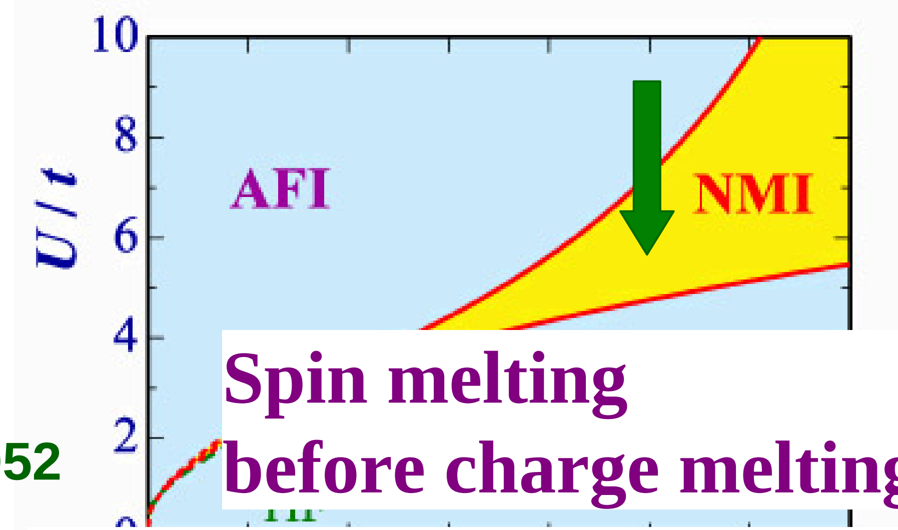


Frustrated square lattice

Kashima et al.

JPSJ 70 (2001) 3052

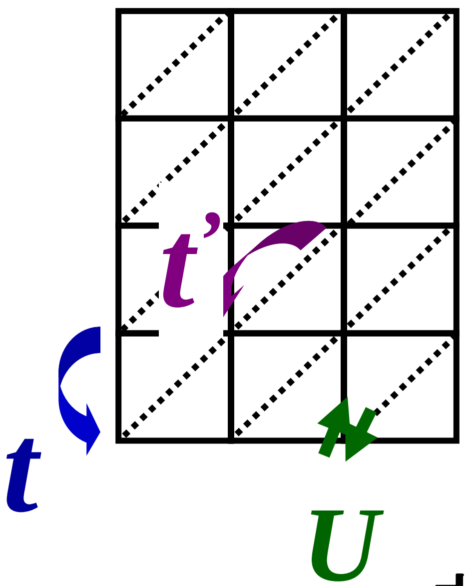
フラストレートした正方格子



Spin melting before charge melting

HF;V

Quantum melting by charge fluctuations

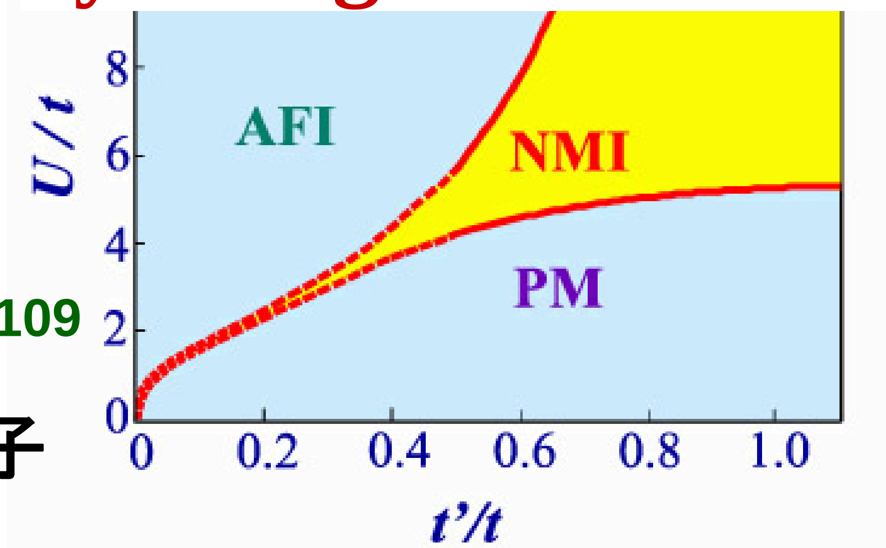


Anisotropic triangular lattice

Morita et al.

JPSJ 71(2002) 2109

非等方三角格子



Nonmagnetic Mott insulator phase

Spin-gapless phase

ギャップレス相

gapless spin excitations

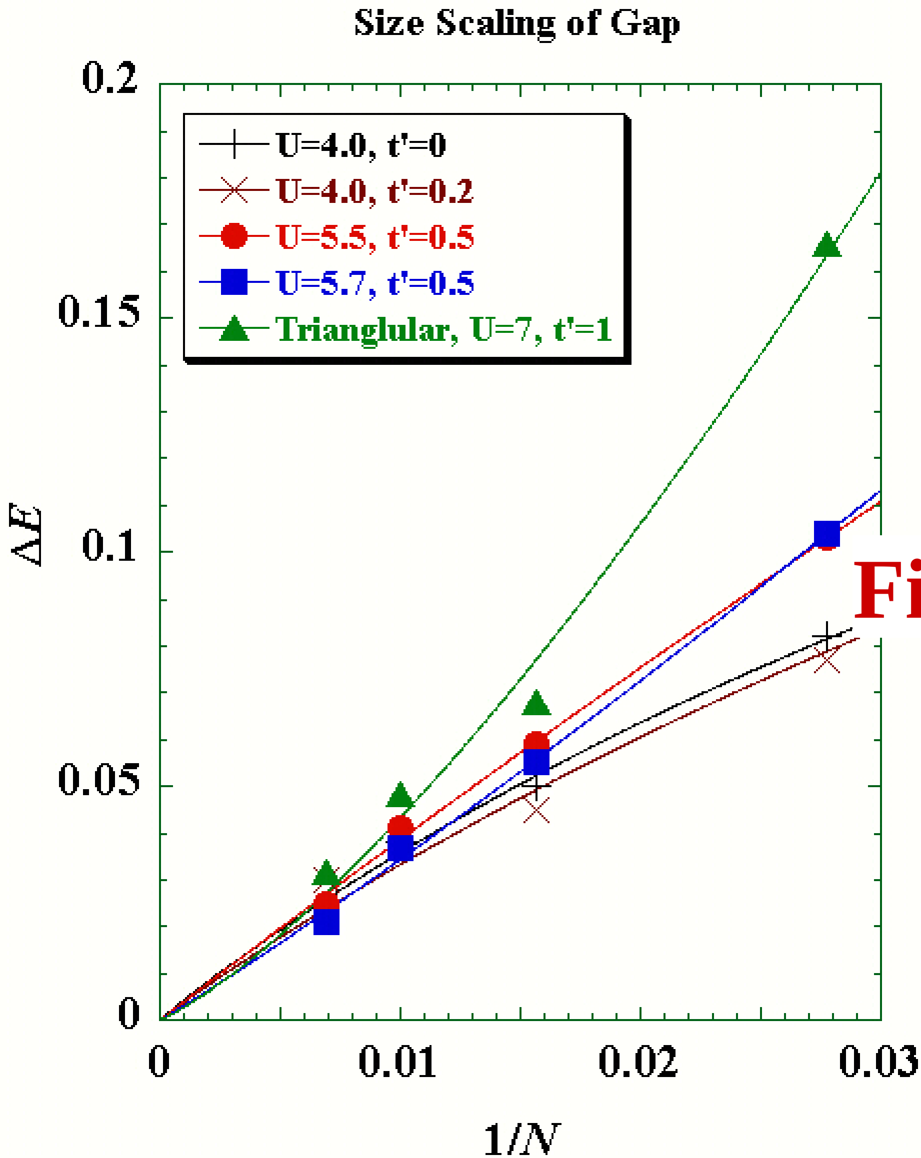
$\Delta E \sim 1/N$

Triplet excitation gap collapses with increasing system size

Long-ranged singlet bonds

Finite uniform susceptibility

有限な一様帯磁率



AIP Conf. Proc. 690 (2003) 207

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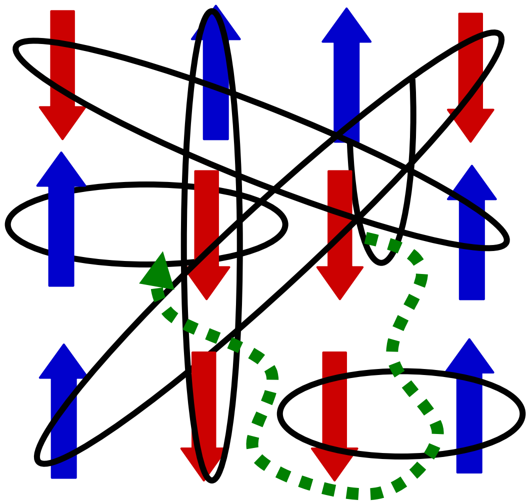
A possible interpretation of spin liquid



Long-ranged singlet bonds RVB

Gapless spin excitation
Finite, nonzero susceptibility

Unbound spinon scattered
by sea of dynamical RVB singlets

Incoherent (localized) spinons?
No spinon Fermi surface?
No fractionalization?

triangular lattice +tiny randomness ⇒ spin glass
order by disorder
MI(1986)
coupling to lattice

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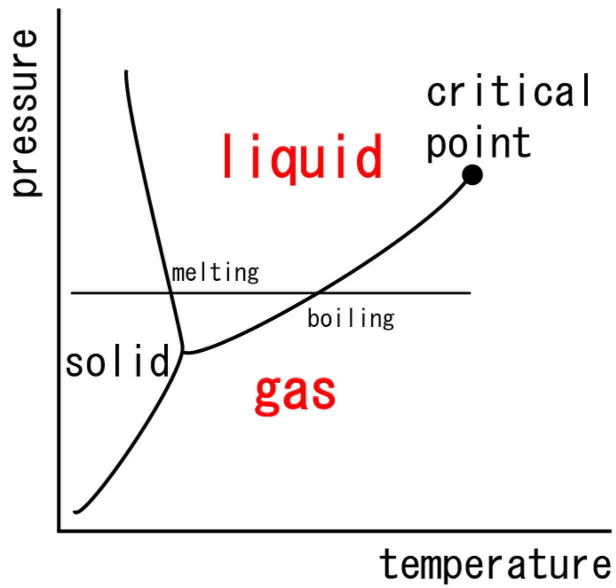
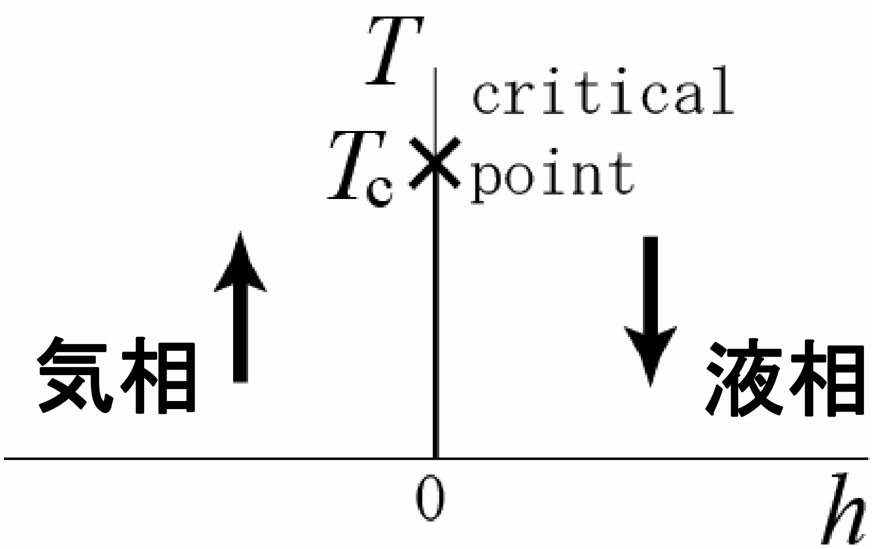
Novel Quantum Criticality

密度ゆらぎの発散を伴う量子臨界



χ =dn/dμ : **compressibility** の臨界点での発散

気相液相転移の臨界温度が量子縮退温度以下になるとき？



★Ising 型相転移として表わされなくなる場合 non-GLW型

★密度ゆらぎ発散と量子縮退（フェルミ面効果）の相乗

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Valence Criticality

Valence instabilities of Ce systems

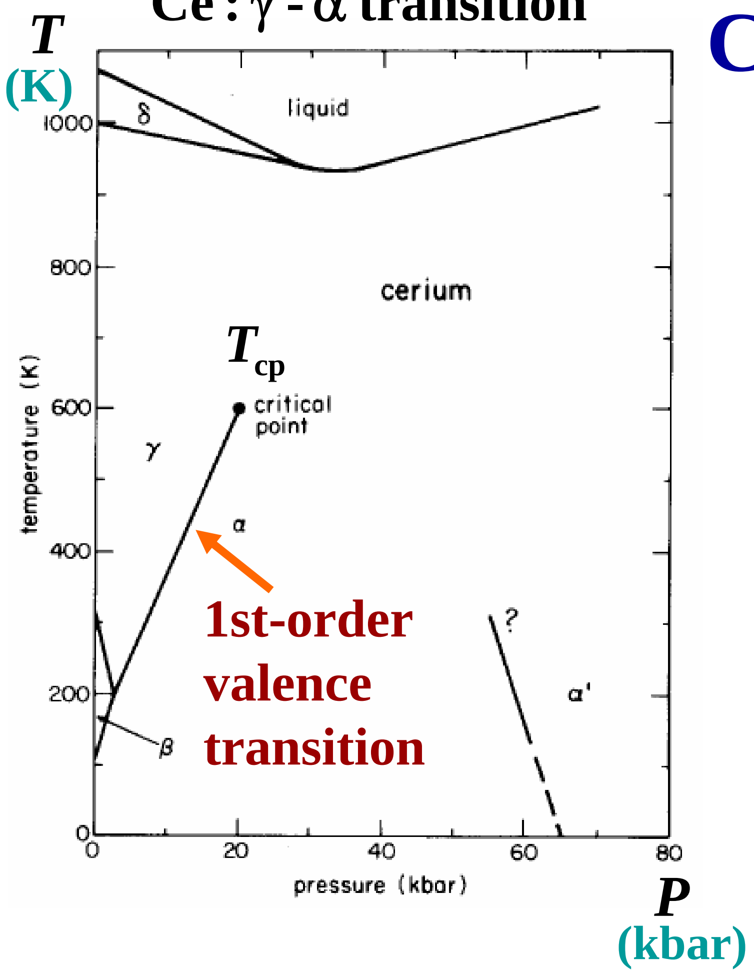
Watanabe Poster07

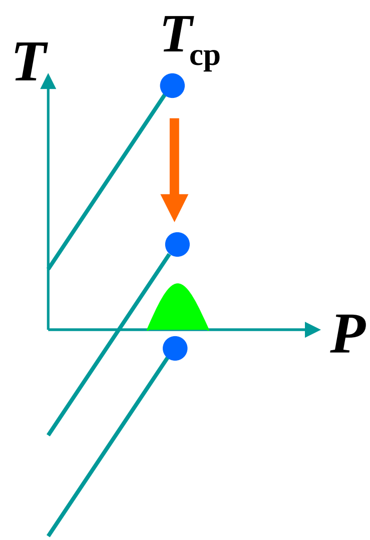
Ce compounds:

T_{cp} is suppressed ($\ll E_F$)

Superconductivity

Ce : γ - α transition





$CeCu_2Ge_2$
$CeCu_2Si_2$
$CeCu_2(Si_{1-x}Ge_x)_2$
$CeCoIn_5$
$CeIrIn_5$

Diverging valence fluctuation +Fermi degeneracy

"Handbook on the Physics and Chemistry of Rare Earths", North-Holland (1978) p340

K. Miyake, et al: PhysicaB 259-261 (1999)676

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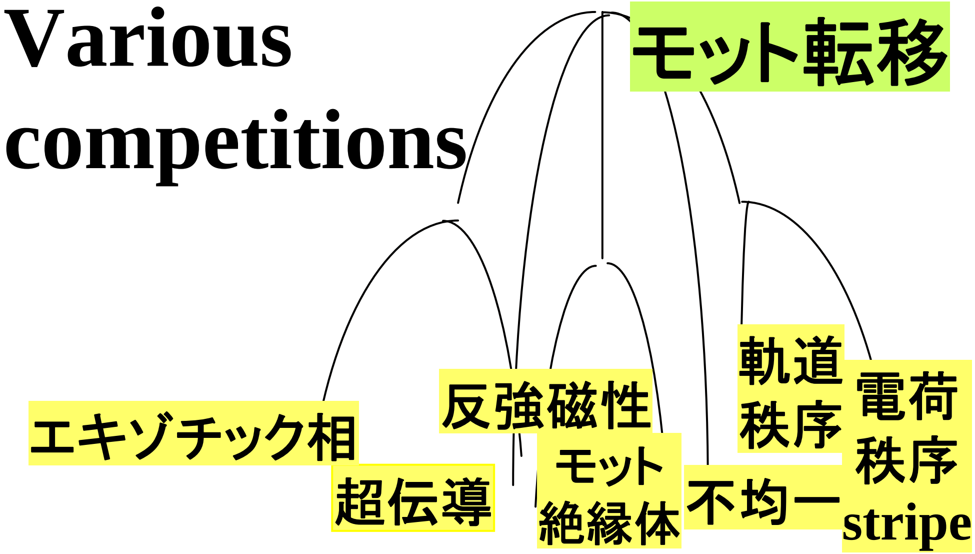
Quantum Mott Criticality

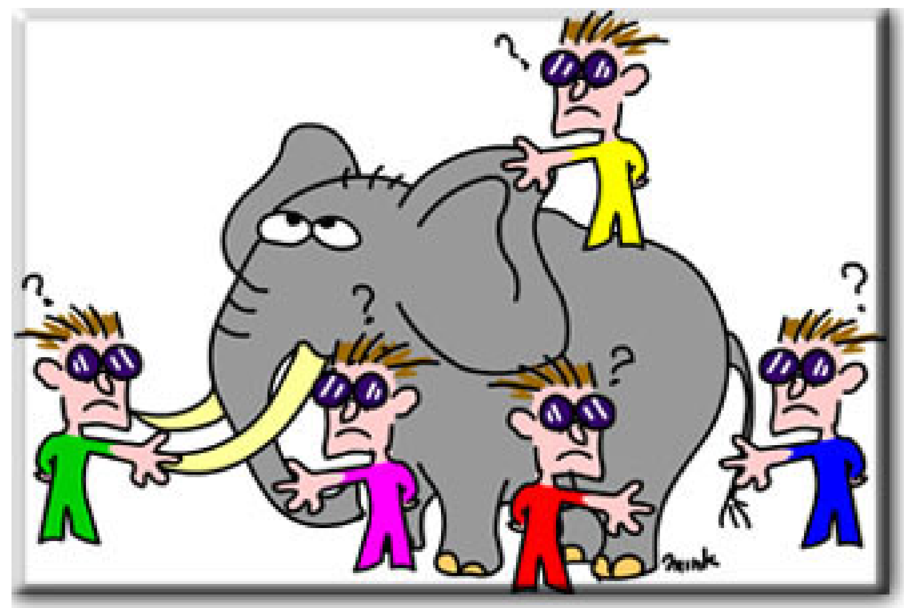
密度ゆらぎの増大＋フェルミ面効果
――→ Competing Orders

Breakdown of simple quantum criticality

Various competitions



モット臨界性；
新たな階層構造の原因
母転移→multi-furcation



では大域構造を決める
母転移(モット転移)の
正体は何なのか？

Filling Control Transition 1990’s

phase separation

Emery-Kivelson

Physica C 209 (1993) 597

critical divergence of compressibility

Furukawa and MI

JPSJ 61 (1992) 3331

^{3}He monolayer

Saunders et al., Fukuyama

Cuprates

stripe, charge order

Tranquada et al.

Nature 375 (1995) 561

patch structure in STM

Davis et al. (2000)

Phase separation の瀬戸際

モット転移は電子の

電荷(密度)自由度の転移

orbital fluctuations

divergence of

single length scale ξ;

mean distance of carriers

scaling theory &hyperscaling

$$F(\mu) = \xi^{-d-z} f(\xi^{y_\mu}\mu)$$

$$y_\mu = 4, \quad z = 4$$

MI, JPSJ 64 (1995) 2954

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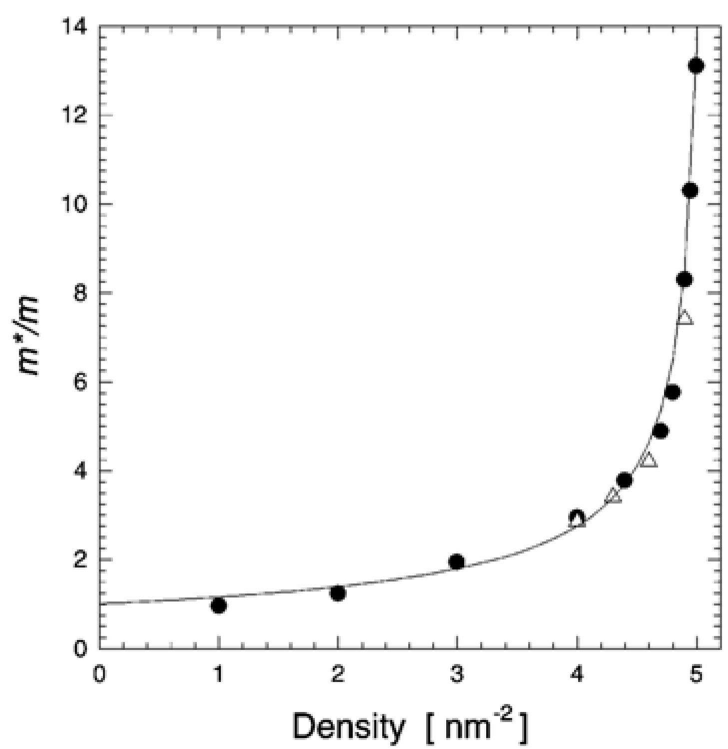
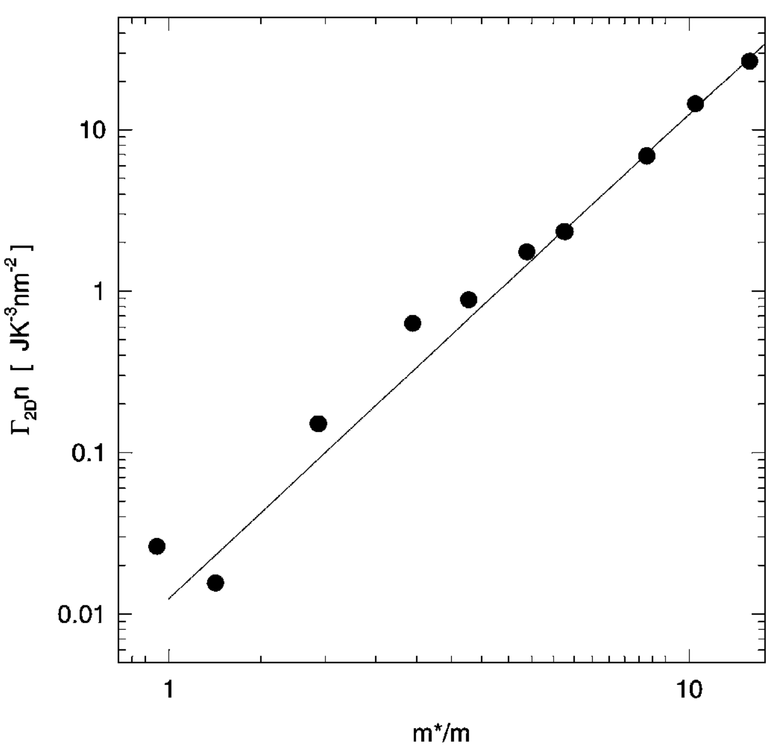
^{3}He; unusual degeneracy temperature

$$C = \gamma T + \Gamma_{2D} T^2$$





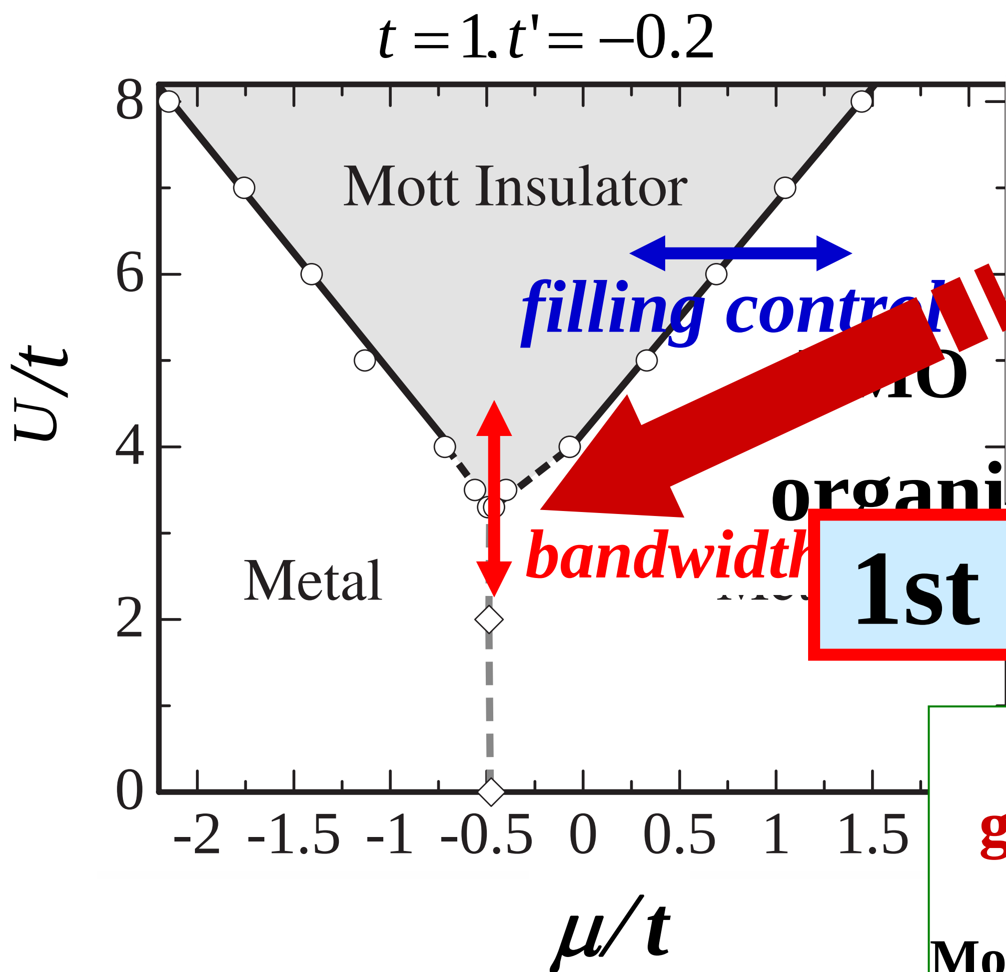
$$m^*/m \propto 1/\delta n$$

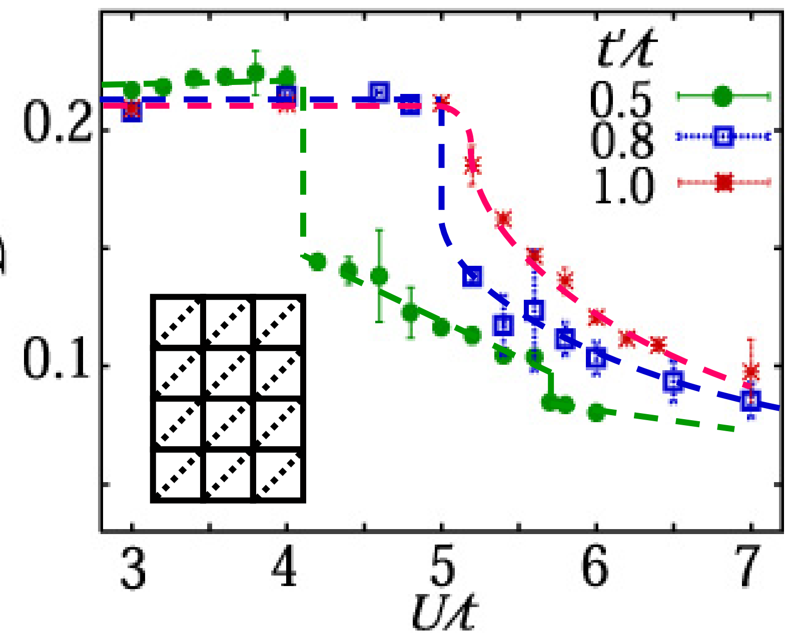
$$T_F \propto \delta n^2$$

Casey et al. PRL 90 (2003) 115301

Phase Diagram of Mott Transition in the 2D Hubbard model

経路積分繰り込み群法
PIRG numerical results





1st order transition

V shape boundary

Lower T_c at larger t'

gapless quantum spin liquid

Kashima, Imada, JPSJ(2001)

Morita, Watanabe, Imada, JPSJ(2002)

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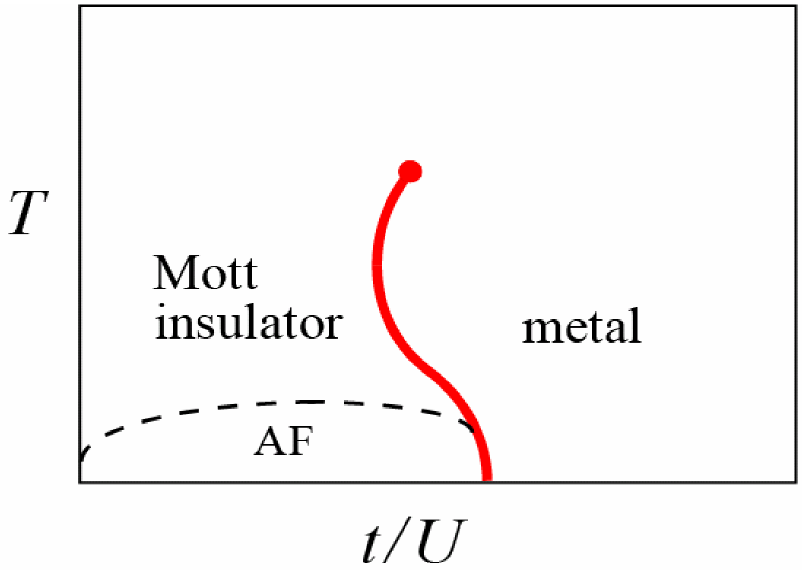
Advantage of Bandwidth Control MIT



★Small energy scale;
suppress Multi-furcation

★Absence of other orders; AF...

★Absence of long-range
Coulomb effect

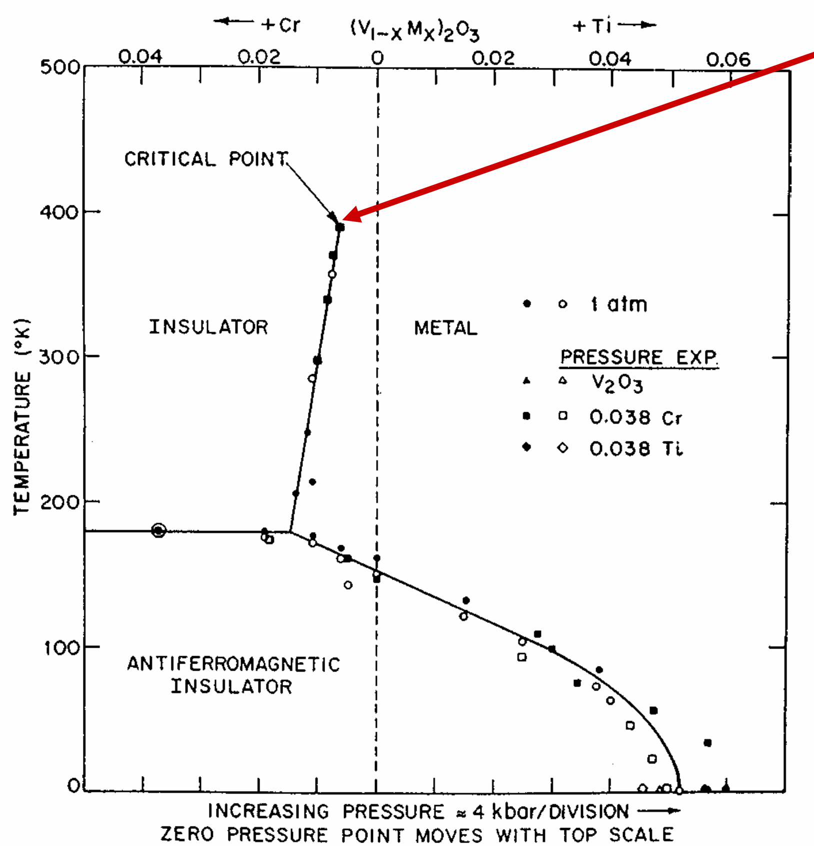
⇔ ^{3}He

"Pure" Mott transition arising from short-ranged repulsion

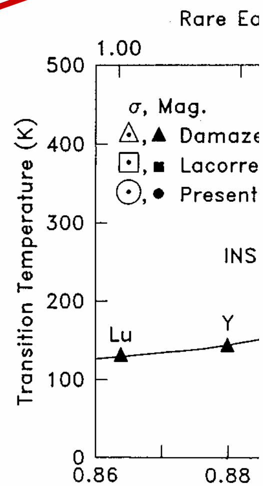
Bandwidth Control MIT

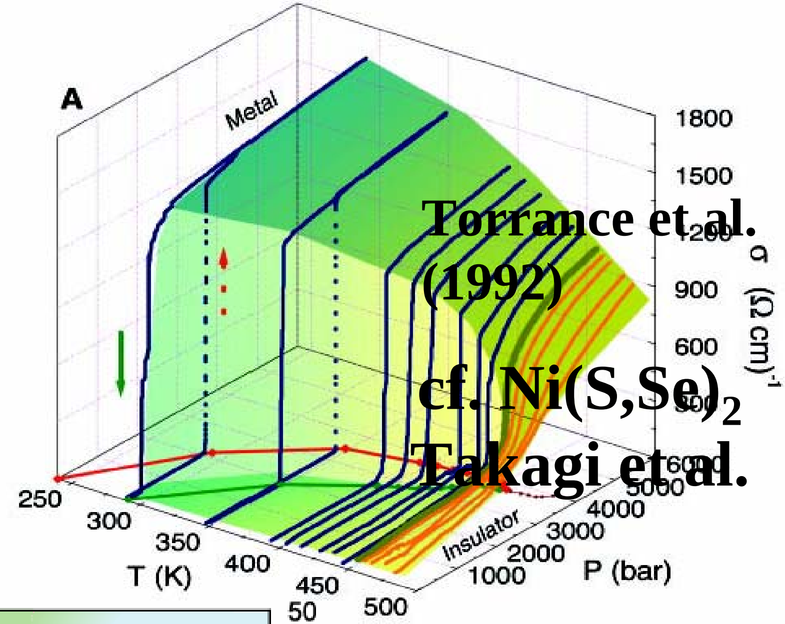
Ising criticality

Limelette et al. (2003)



V_2O_3 **McWhan et al. (1972)**

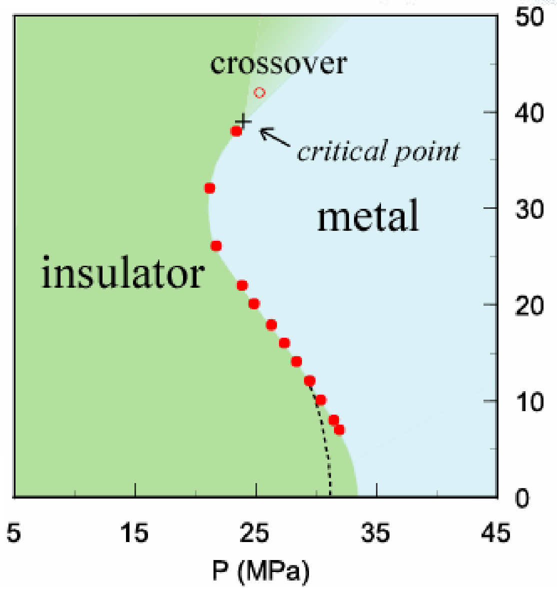


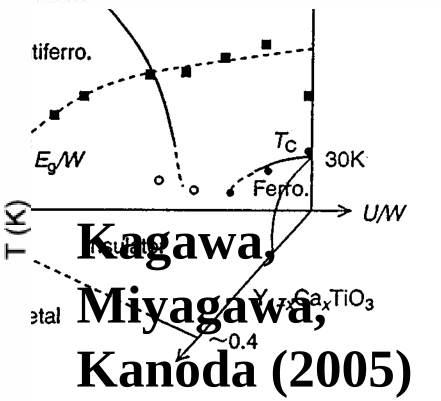


Torrance et al. (1992)

cf. $Ni(S,Se)_2$

Takagi et al.





Kagawa, Miyagawa, Kanoda (2005)

κ-$(ET)_2Cu[N(CN)_2]Cl$

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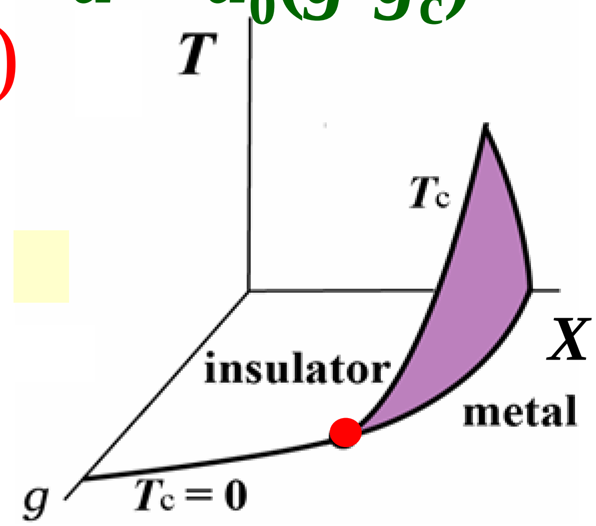
Breakdown of Ginzburg-Landau-Wilson scheme

Ginzburg-Landau-Wilson scheme に従わない相転移

$$F = -\mu X + aX^{(d+2)/d} + bX^{(d+4)/d}$$

$T = 0$

$a = a_0(g-g_c)$



$a > 0$; continuous transition ($T_c = 0$)

quantum region

$\mu > 0$; metal: $\mu < 0$; insulator

$a < 0$; first order

$a \to 0$ **Marginally quantum critical point (MQCP)**

unusual QCP

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Unusual Critical Exponents at MQCP

$$\beta = d/2,\ \gamma = 2 - d/2,\ \delta = 4/d,\ \nu = 1/2,$$
$$z = 4$$

Ginzburg criterion

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

All the dimensions are at the upper critical dimension

"mean field" is basically correct,
while hyperscaling is satisfied

2次元 $\beta = 1,\ \gamma = 1, \delta = 2,\ \nu = 1/2,$

$$z = 4$$

→ **Kagawa, Miyagawa, Kanoda**

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Consequence of Diverging Density Fluctuations

filling control; electron density fluctuation
bandwidth control; excitonic fluctuation

$$\chi = (d^2F/dX^2)^{-1} \sim (aX^{2/d-1} + bX^{4/d-1})^{-1}$$

Marginal quantum critical point; $a \rightarrow 0$

$$\chi \sim X^{1-4/d}$$

秩序化に伴うゆらぎとは別の
波数0近傍の独立なゆらぎ

$$\chi_c(q,\omega) = \frac{\Gamma^{-1}}{-i\omega + D_s(K^2 + (q-Q)^2)}$$

example; 2D

large energy scale; Mott gap

contrast with spin/orbital fluctuations; *J*⇔Mott gap

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Outlook for Super Clean Project

電子やヘリウムの密度自由度が引き起こす
1次転移の消える瀬戸際の物理の確立

Mott
charge order
valence
Lifshitz

1次転移の背景となる
高いエネルギースケール

Summary

Band-width control & filling-control

unified description of quantum Mott criticality

Beyond GLW scheme; unusual universality class

***d* dependent critical exponents**

bandwidth control transitionでの検証

marginal quantum criticality (MQCP)

diverging density (charge) fluctuations

large energy scale ~ Mott gap, small *q*

incoherent response up to high energy

competing orders

(1) electron differentiation ⇒ ARPES structure

(2) tendency for inhomogeneity

(3) density fluctuations drive non-Fermi liquid properties

superconducting mechanism

d-wave, high-T_c

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Outlook

accurate $\varepsilon(k,\omega)$

Mott
charge order
valence
Lifshitz

filling control
bandwidth control