The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
Energy Agency

SMR.1766 - 9

Miniworkshop on
New States of Stable and Unstable Quantum Matter
(14 - 25 August 2006)

Transport and NMR studies on Mott criticality in two dimensions

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ICTP miniworkshop on New States of Stable and Unstable Quantum Matter, Trieste, Aug. 14-25, 2006

Transport and NMR studies on Mott criticality in two dimensions

K. Kanoda (Univ. Tokyo & CREST-JST)

Contents

1. Why organics? What interest?
2. Mott criticality;
   transport and NMR
3. Spin frustration;
   existence of spin liquid
   influence on Mott transition
4. Superconductivity neighboring on spin liquid
   transport and NMR

Collaborators

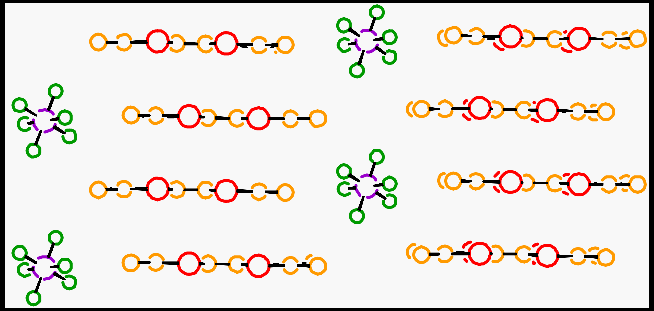
Y. Shimizu	**(now RIKEN)**
F. Kagawa	**(Univ. Tokyo)**
Y. Kurosaki	**(Univ. Tokyo)**
H. Kasahara	**(Univ. Tokyo)**
T. Kobashi	**(Univ. Tokyo)**
K. Miyagawa	**(Univ. Tokyo)**
M. Maesato	**(Kyoto Univ.)**
G. Saito	**(Kyoto Univ.)**

Review; K. K., J. Phys. Soc. Jpn. 75 (2006) 051007

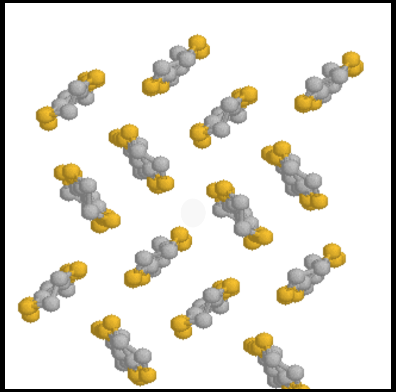
Organics; rich variation in lattice geometry with fixed carrier density

The diversity understandable in a unified manner

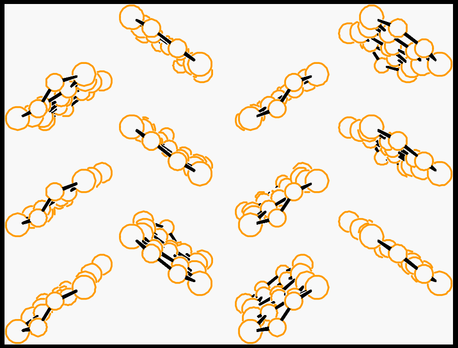
Kino, Seo, Hotta, Fukuyama



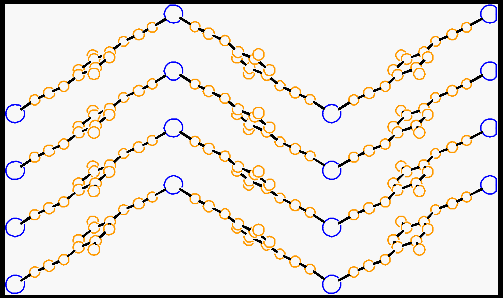
Overhauser SDW
Spin-Peierls transition
Wigner crystallization
Tomonaga-Luttinger liquid
Fermi liquid
(Triplet SC)
Kanamori Ferro. fluctuations



Mott transition
AF/ Spin liquid
d-wave SC
Exotic spin pairing

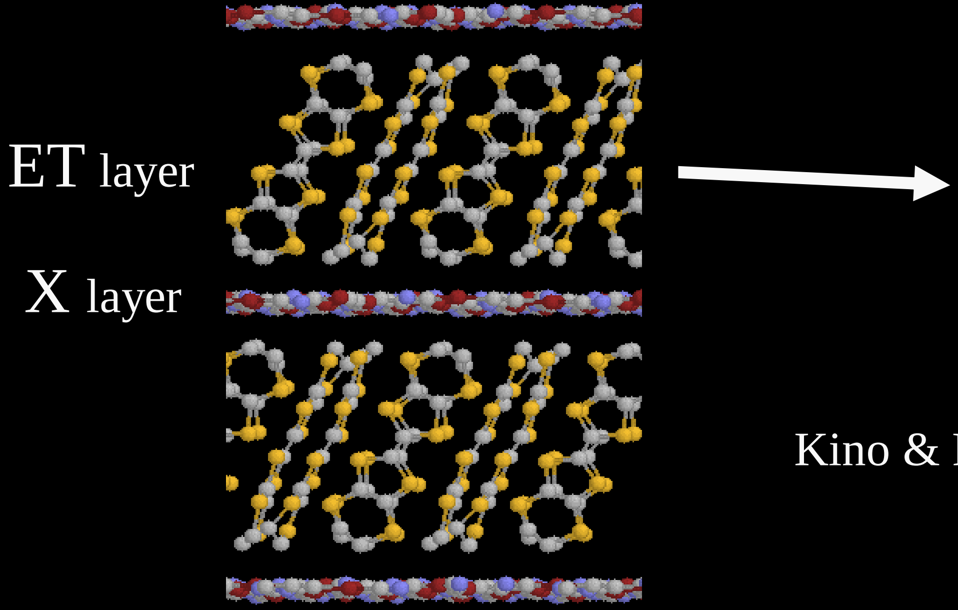


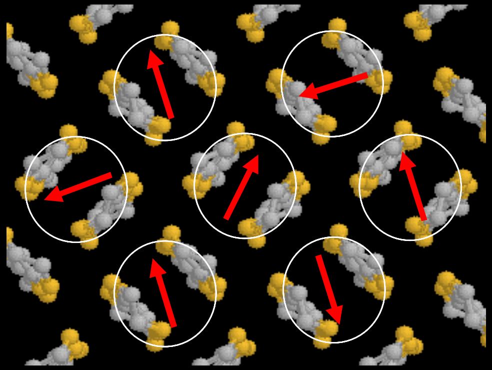
Wigner crystal/glass/liquid
Valence bond solid/glass
Massless Dirac Fermion



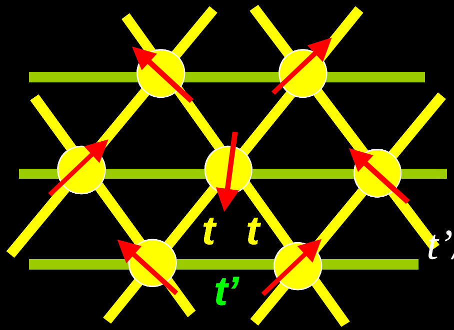
Special Issue “Organic conductors”
J. Phys. Soc. Jpn. No.5, 75 (2006)

Q2D organics κ-$(ET)_2X$; spin-1/2 on triangular lattice





Kino & Fukuyama dimer model



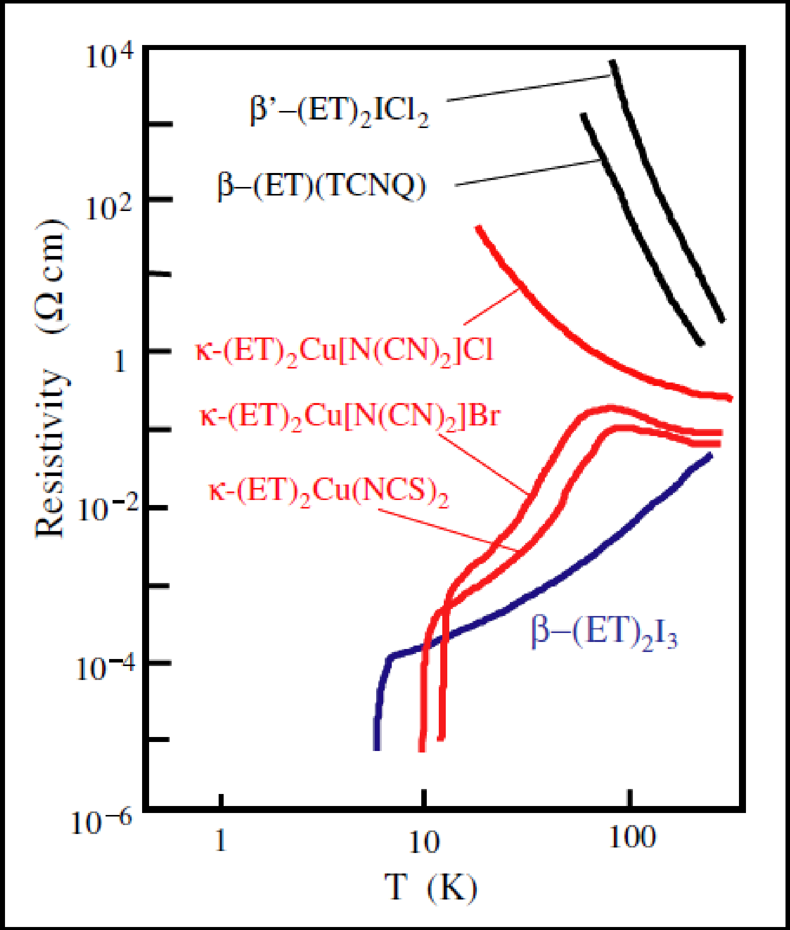
$t'/t = 0.5 \sim 1.1$

Triangular lattice
Half-filled band

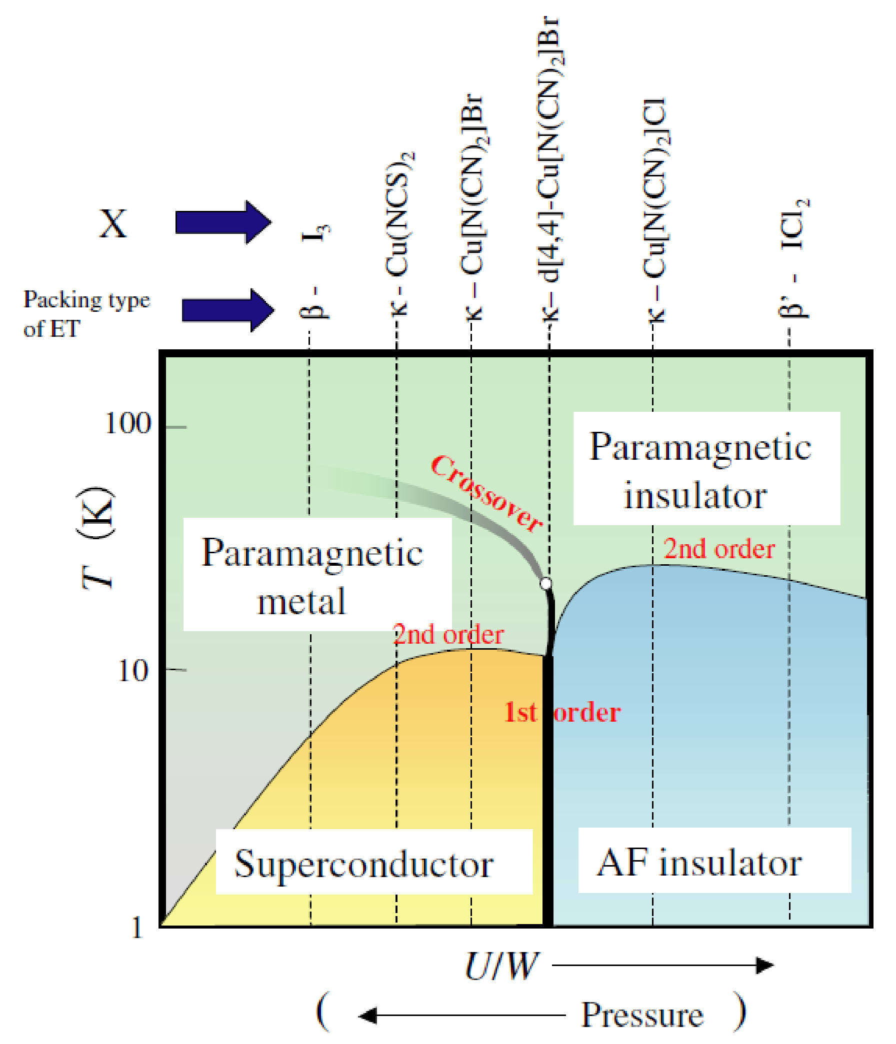
X^-	Ground State	t'/t
$Cu_2(CN)_3$	Mott insulator	1.06
$Cu[N(CN)_2]Cl$	Mott insulator	0.75
$Cu[N(CN)_2]Br$	SC	0.68
$Cu(NCS)_2$	SC	0.84

Interacting electrons in κ-(ET)$_2X$ are near Mott transition

resistivity



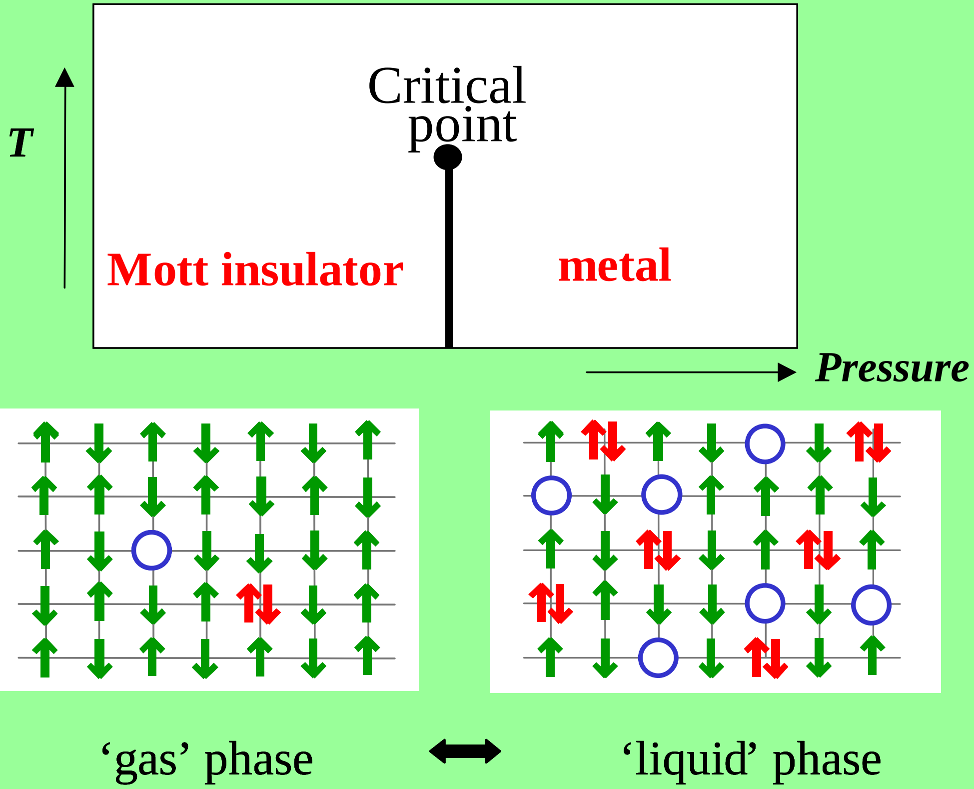
Conceptual phase diagram



K. K., J. Phys. Soc. Jpn. 75 (2006) 051007

Mott transition

Competition between Coulomb energy and kinetic energy

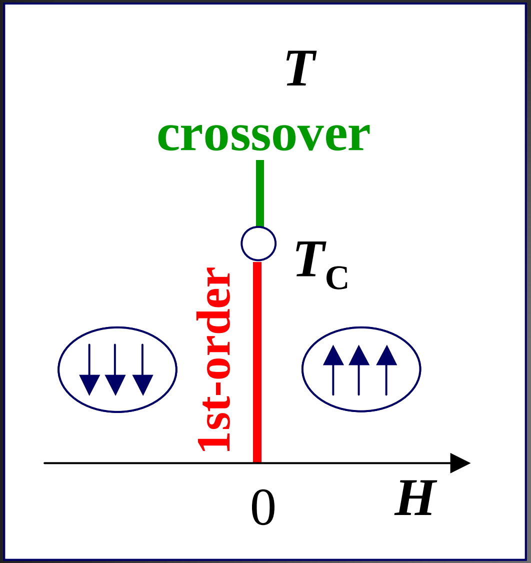


Fluid of **doubly-occupied sites** or **holes**

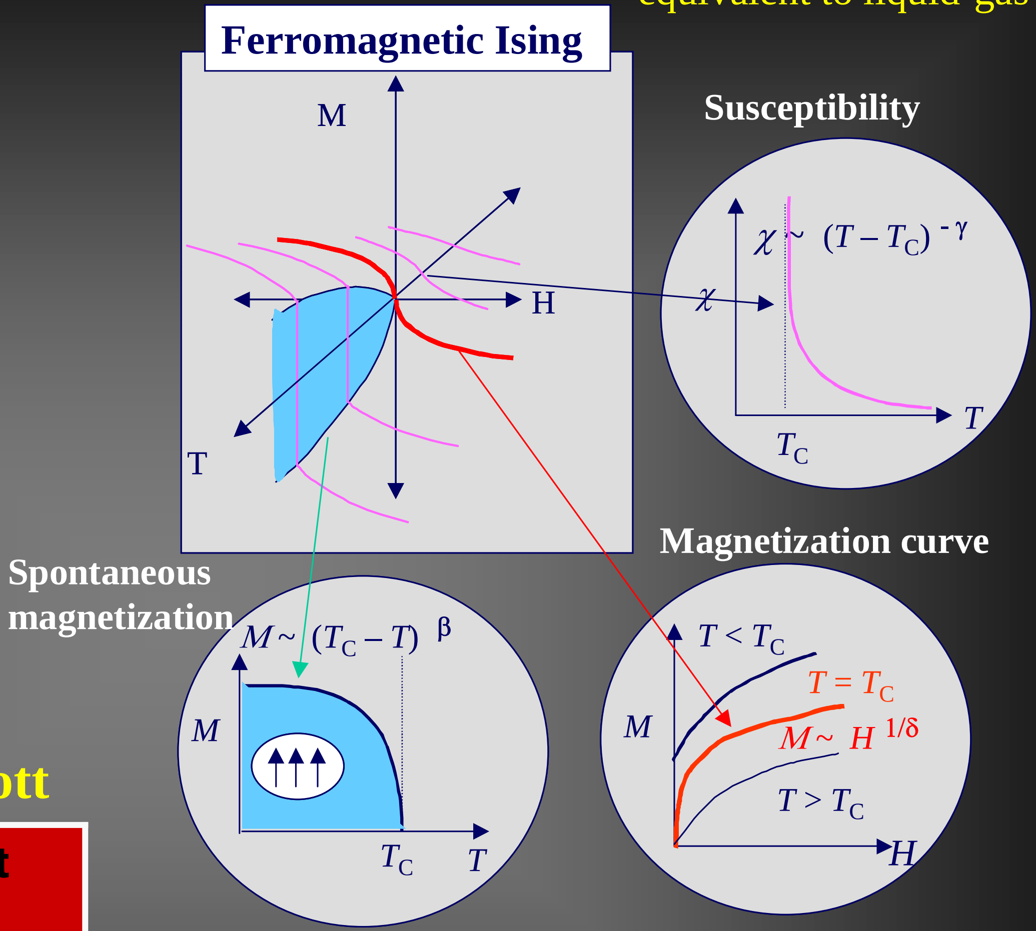
Castellani (1979)

⇨ Mott criticality is identical with classical liquid-gas criticality?

Criticality



equivalent to liquid-gas



(Order) parameter of magnet, gas-liquid and Mott

	spin	Gas-liquid	Mott
Temperature	$T-T_C$	$T-T_C$	$T-T_C$
External parameter	H	$P-P_C$	$P-P_C$
(Order) parameter	M	V_G-V_L	?

Quasi-particle spectral weight
Holon/doublon density

We assume

$\propto \sigma - \sigma_0$

near a fixed point

Experimental

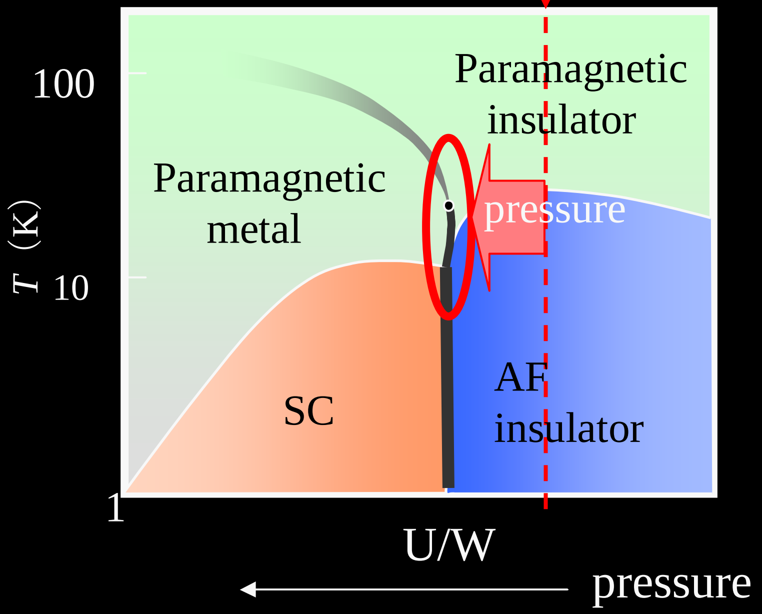
Conductivity measurements under pressure sweep at low T.

Ultrasonic
Fournier *et al.*

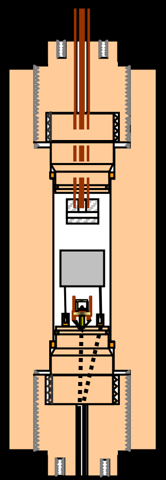
NMR, ac-χ
Lefebvre *et al.*

Resistivity
Ito *et al.*
Limelette *et al.*

κ-$(ET)_2Cu[N(CN)_2]Cl$



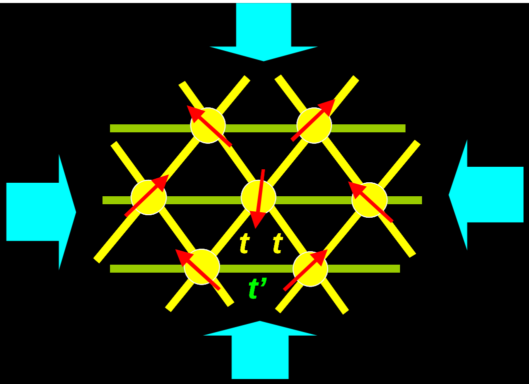
He gas pressure



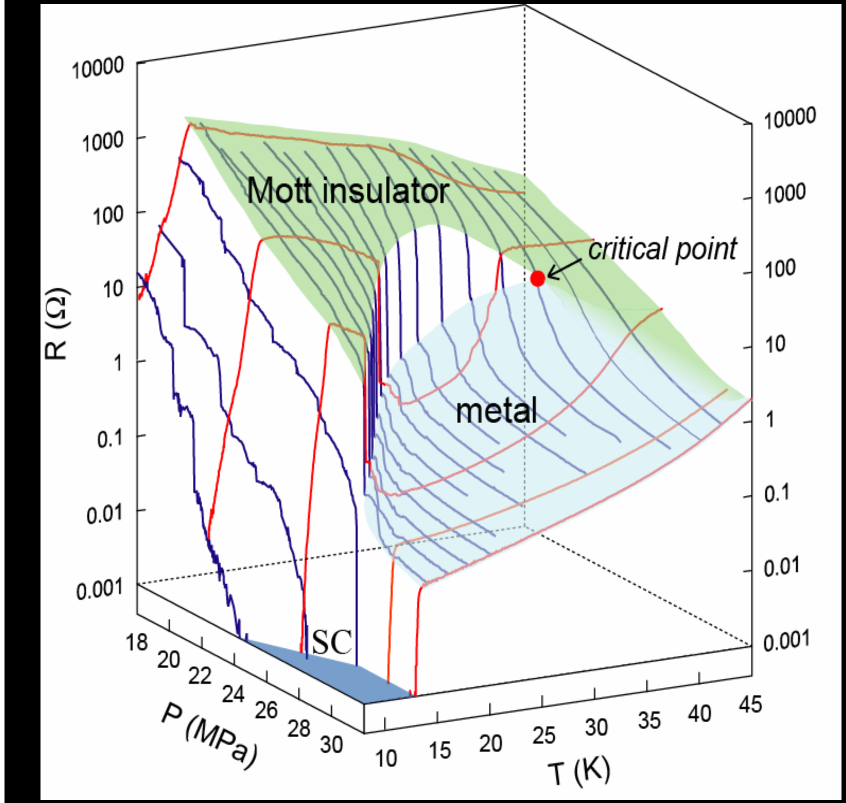
Mott transition in by pressure

κ-(ET)$_2$Cu[N(CN)$_2$]Cl

(t'/t =0.75)

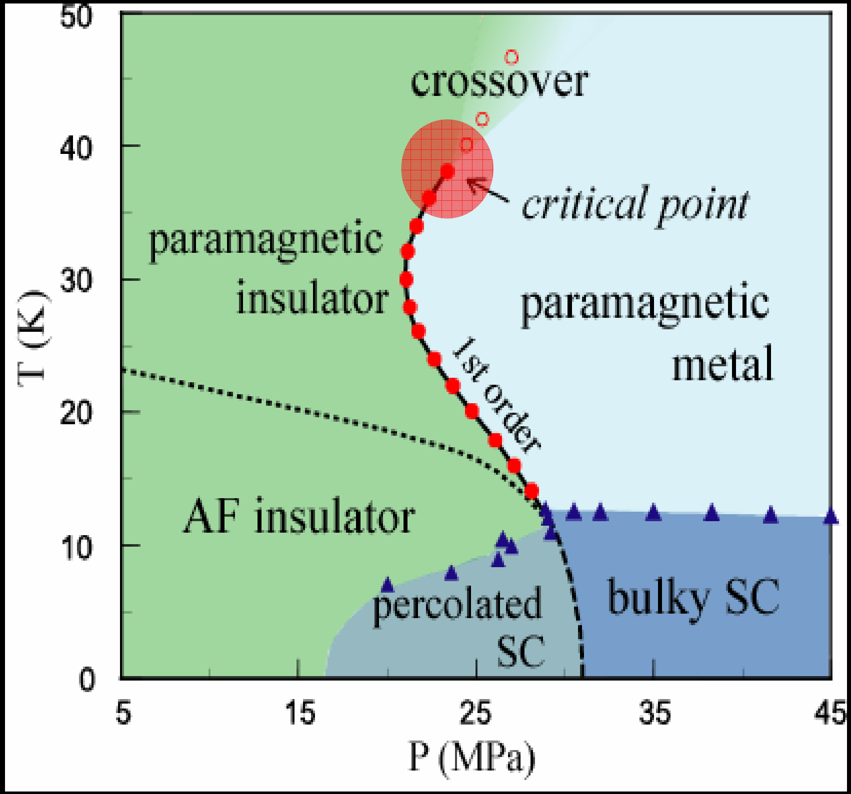


Resistance



Kagawa *et al.*, PRB 69 (2004) 064511

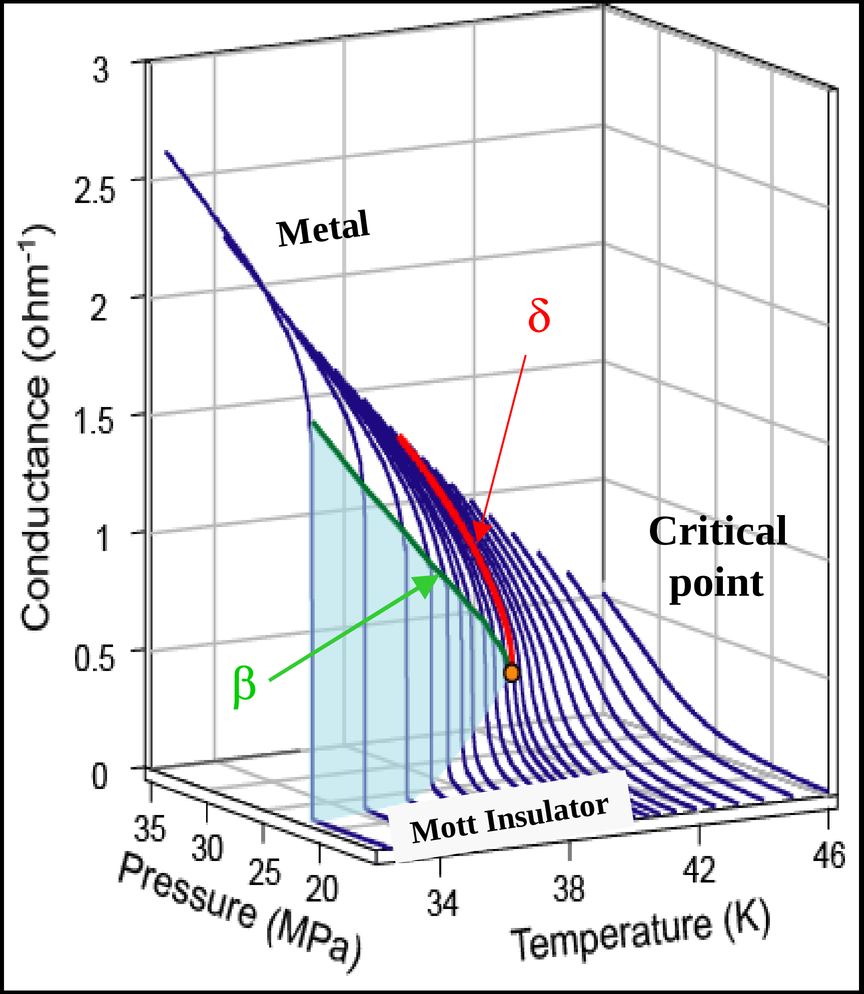
Mott phase diagram



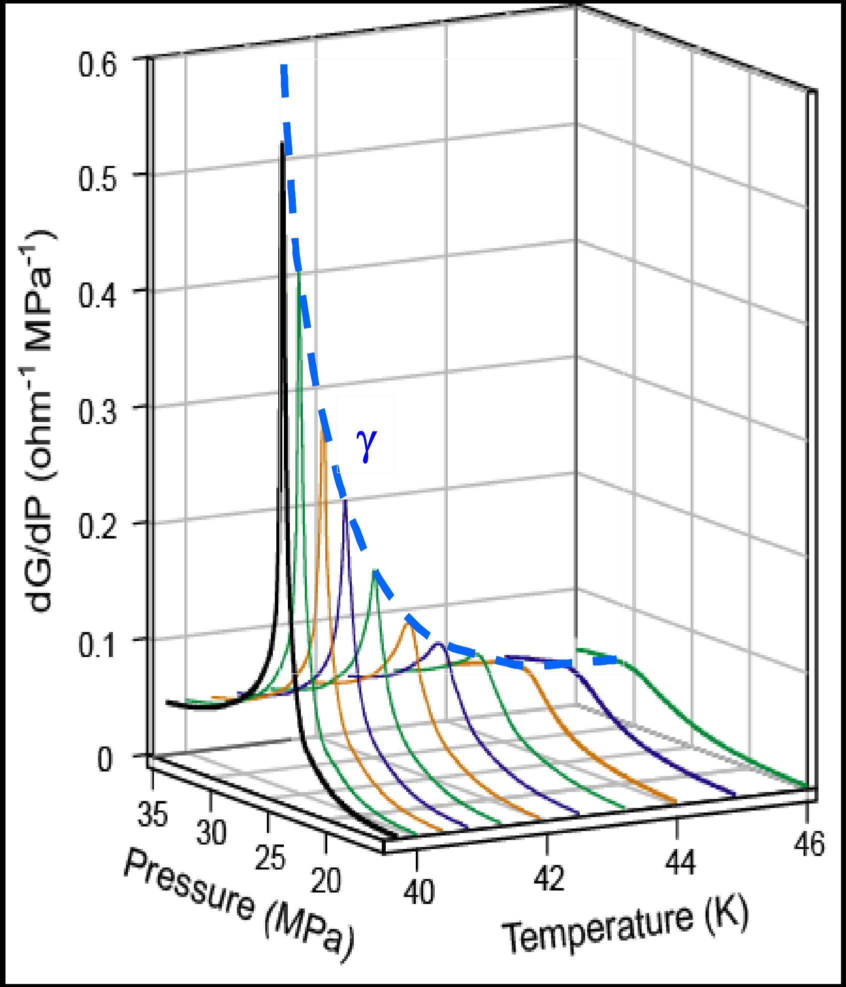
Kagawa *et al.*, PRL 93 (2004) 127001

Mott Criticality and Mott scaling

Conductance, *G*



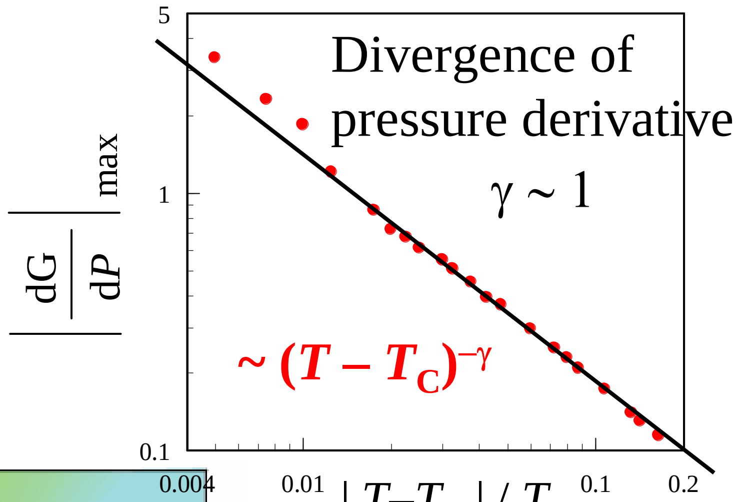
Pressure derivative of Conductance, *dG*/*dP*

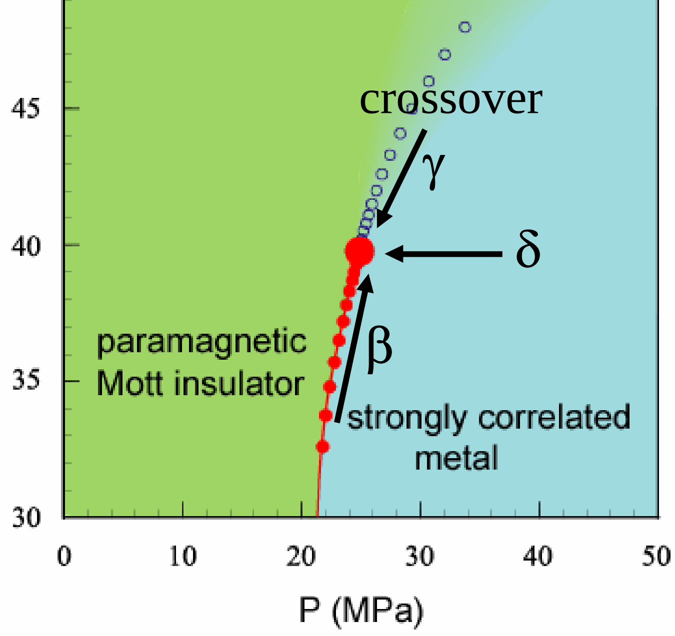


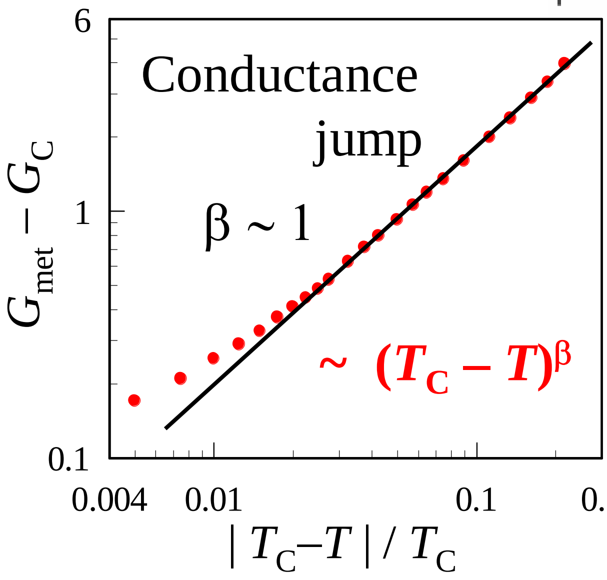
Kagawa *et al.*, Nature 436 (2005) 534

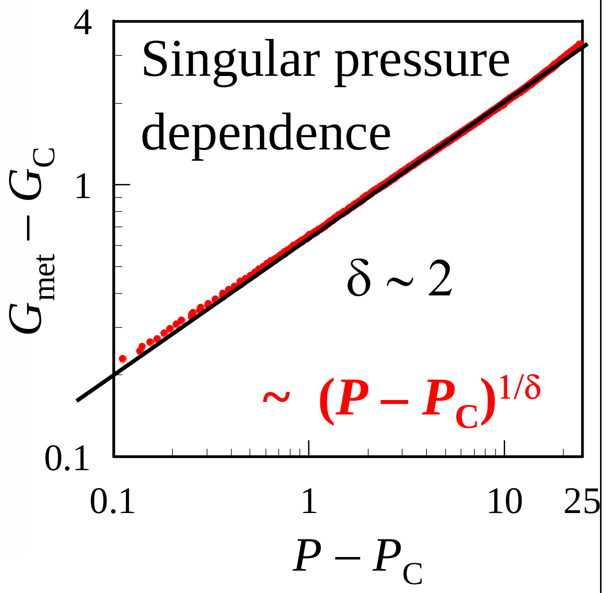
Unconventional critical exponents

$(\delta, \beta, \gamma) \sim (2, 1, 1)$



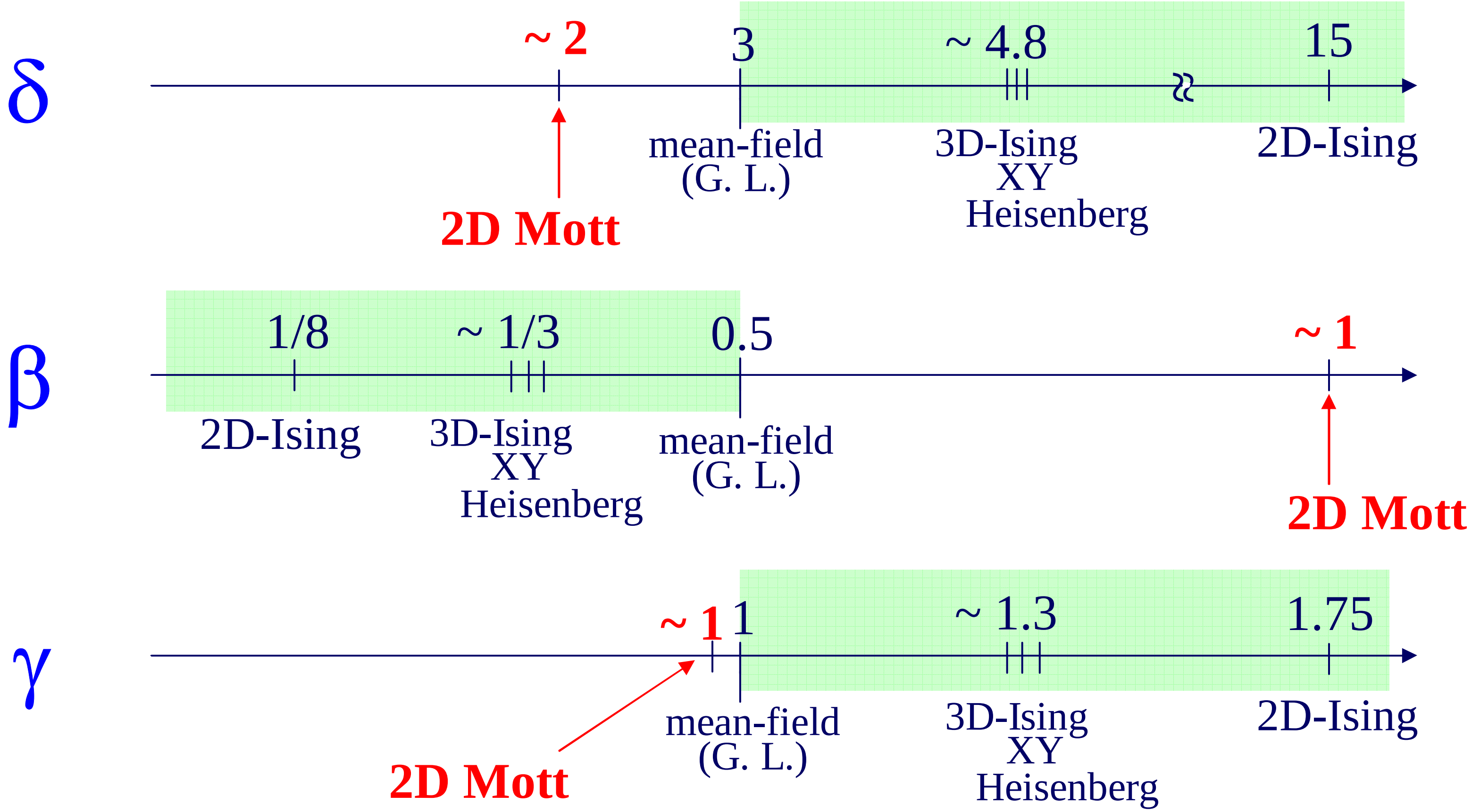






Comparison of critical exponents

Anomalous exponents (δ, β, γ) ~ (2, 1, 1)



δ

~ 2 3 ~ 4.8 15

mean-field
(G. L.)

3D-Ising
XY
Heisenberg

2D-Ising

2D Mott

β

1/8 ~ 1/3 0.5 **~ 1**

2D-Ising

3D-Ising
XY
Heisenberg

mean-field
(G. L.)

2D Mott

γ

~ 1 1 ~ 1.3 1.75

mean-field
(G. L.)

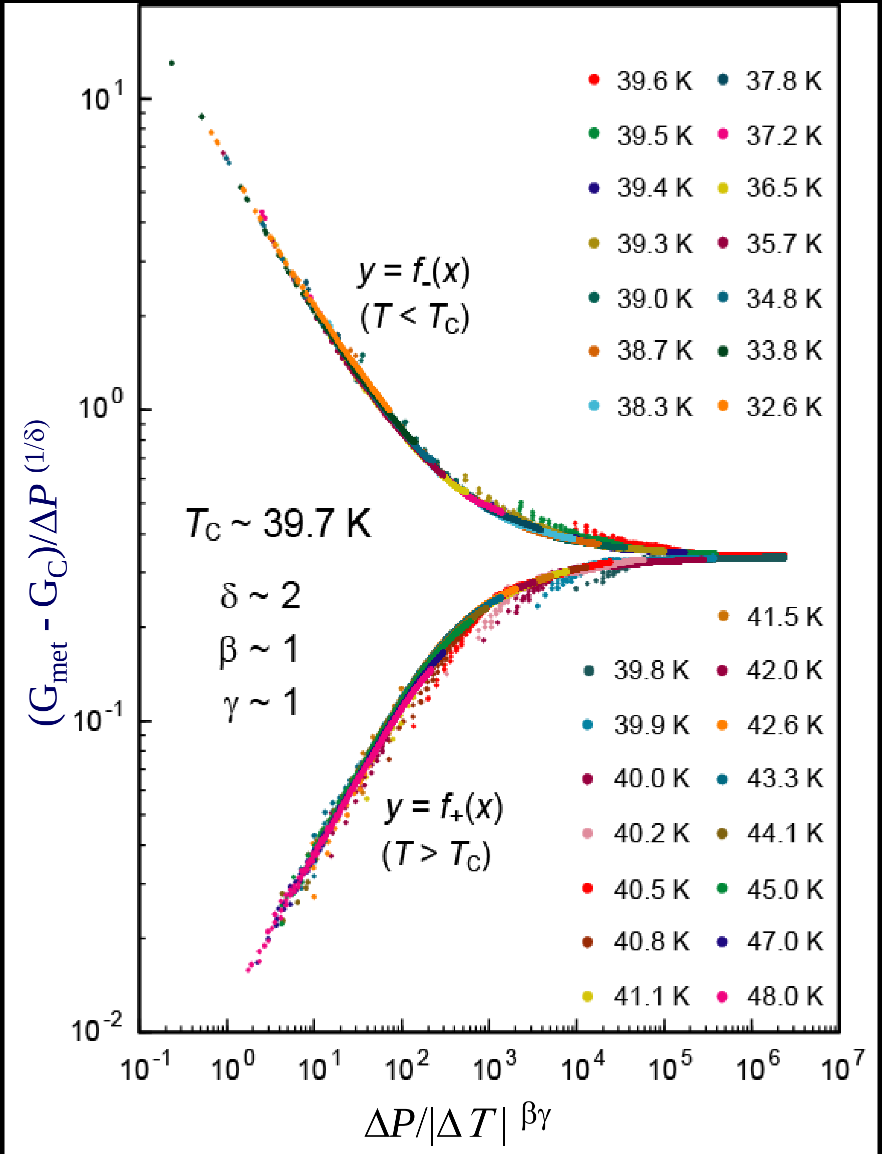
3D-Ising
XY
Heisenberg

2D-Ising

2D Mott

Quantum critical nature; Imada, Misawa

Mott scaling



The critical exponents (δ, β, γ) ~ (2, 1, 1)

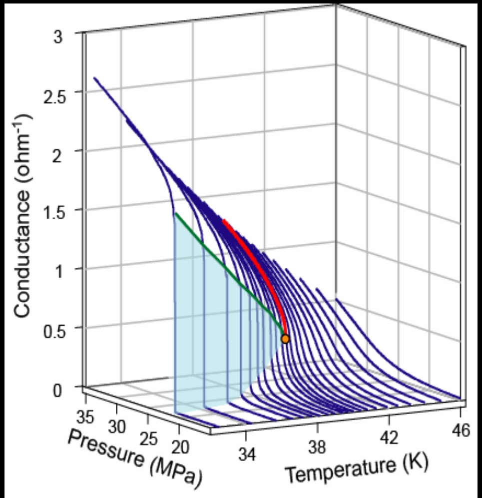
Scaling relation is fulfilled

$$\delta = 1 + (\gamma / \beta)$$

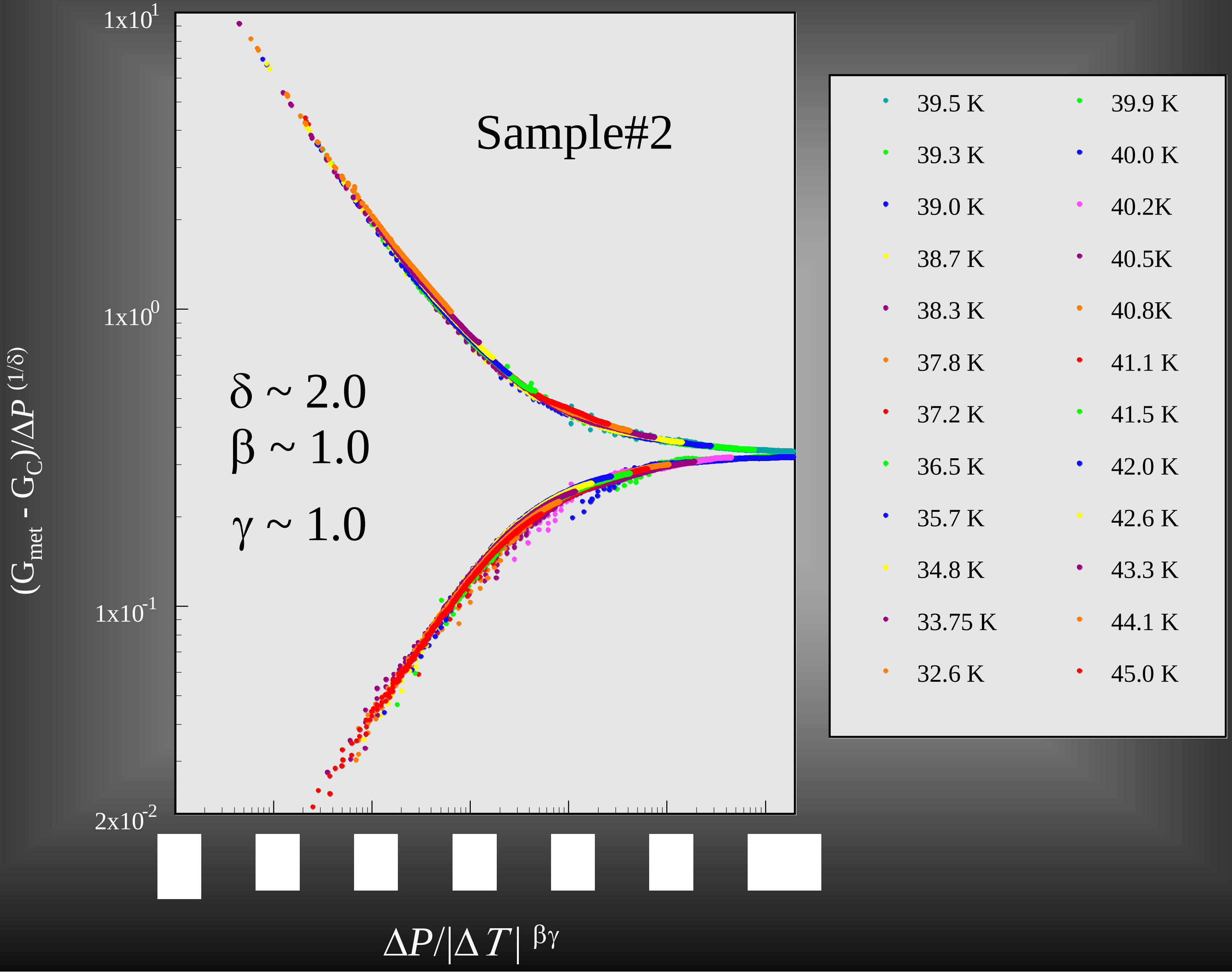
Successful scaling of conductance

Scaling function

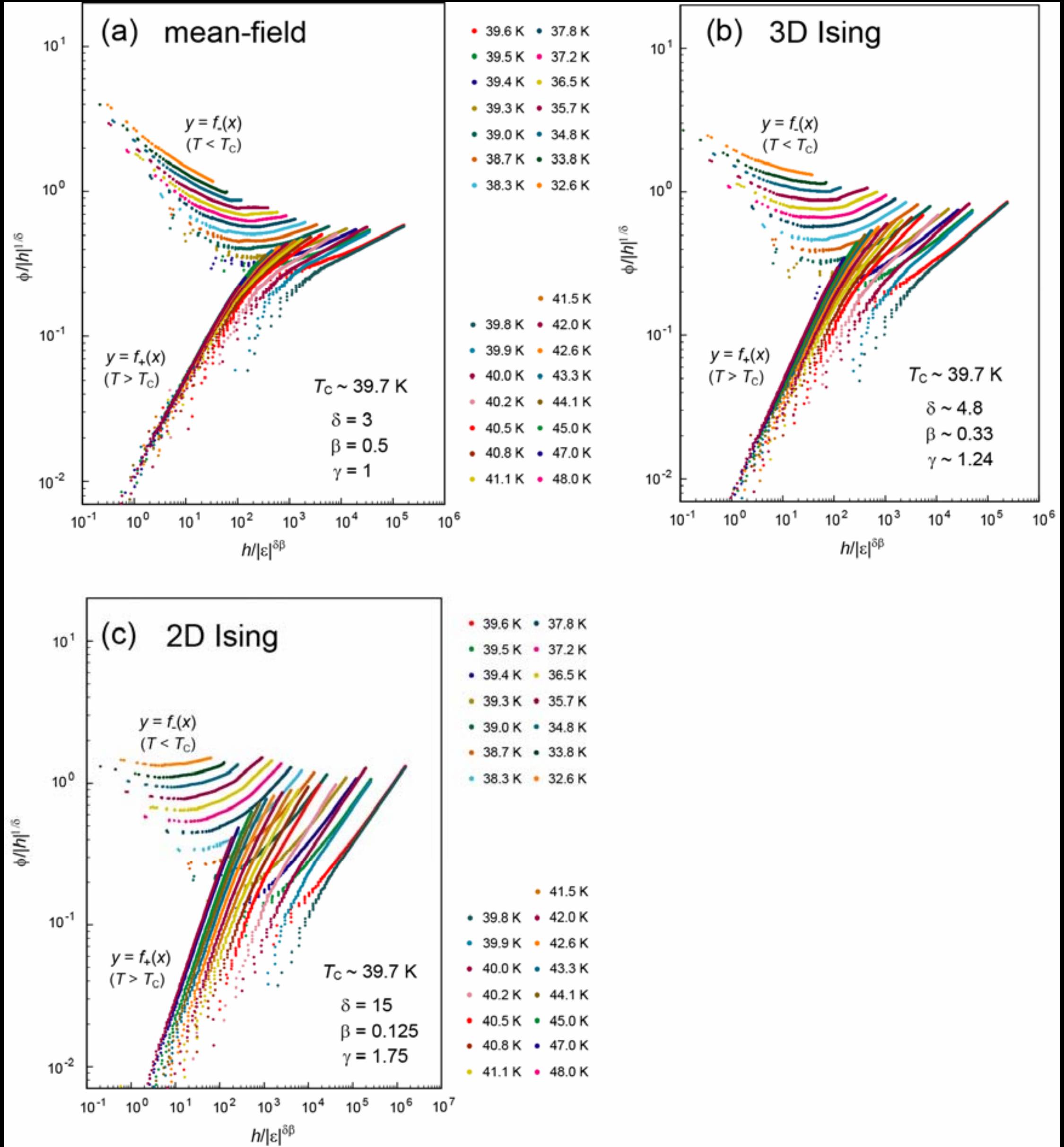
$$G_{met}(P, T) - G_C = (\Delta P)^{1/\delta} f_{\pm}\left(\frac{\Delta P}{|\Delta T|^{\beta\gamma}}\right)$$



Scaling is reproducible for a different crystal



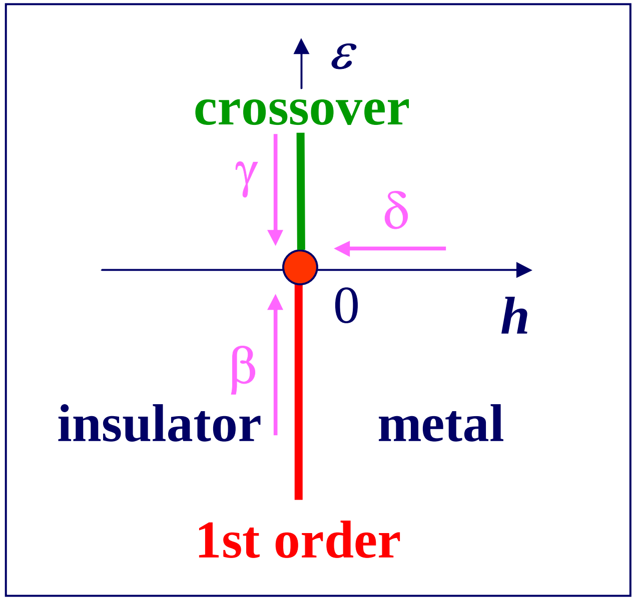
Unsuccessful Scaling fails with Ising or mean-field exponents



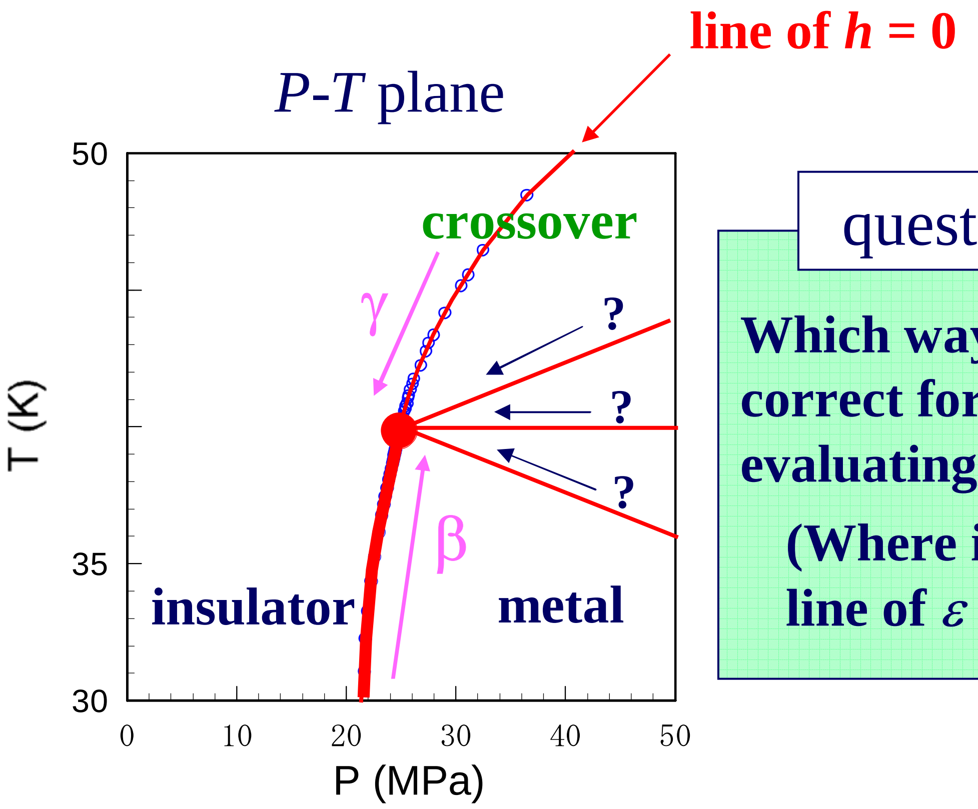
mixing problem

（scaling variables； *h*, ε ）

h-ε plane



P-*T* plane



question

Which way is correct for evaluating δ?

(Where is the line of $\varepsilon = 0$?)

in the *P*-*T* plane, phase boundary and crossover line are inclined

➡ **($h \Leftrightarrow \Delta P$), ($\varepsilon \Leftrightarrow \Delta T$) are inaccurate**

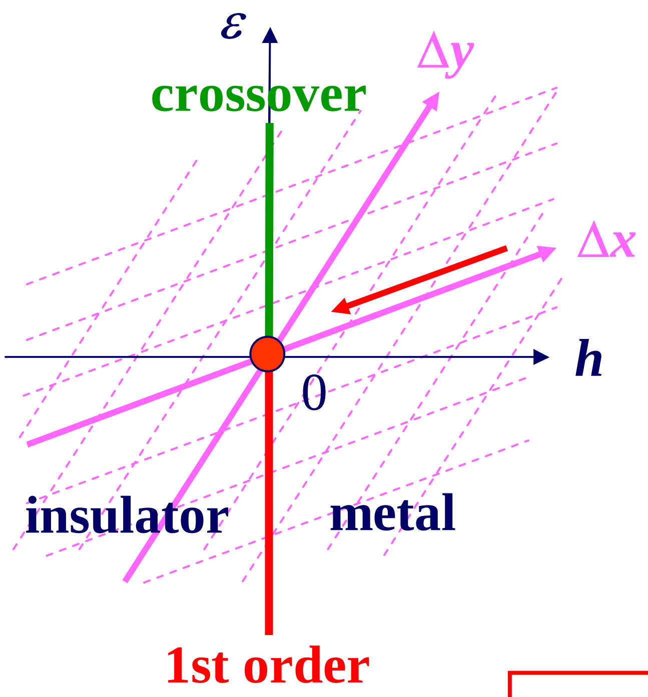
h and ε depend on both Δ*P* and Δ*T*

（mixing problem）

$$\begin{cases} h = h(\Delta P, \Delta T) \\ \varepsilon = \varepsilon(\Delta P, \Delta T) \end{cases}$$

discussion (1)

Assume that one analyzes along incorreect scaling axes Δx & Δy



assumption $\begin{cases} \varepsilon \sim a \cdot \Delta x + b \cdot \Delta y \\ h \sim c \cdot \Delta x + d \cdot \Delta y \end{cases}$

$$\phi = \phi_{\mathrm{scale}}(h, \varepsilon) \qquad (h\text{-}\varepsilon \text{ plane})$$

$$= \phi_{\mathrm{exp}}(\Delta x, \Delta y) \qquad (\Delta x\text{-}\Delta y \text{ plane})$$

question

Along Δx-axis (axis of $\Delta y = 0$),

one can obtain the correct δ ?

$$\phi_{\mathrm{exp}}(\Delta x, \Delta y=0) \propto (\Delta x)^{1/\delta} \quad ??$$

discussion (2)

universal form of equation of state : $\phi_{\mathrm{scale}}(h, \varepsilon) = h^{1/\delta} f_{\pm}\left(\frac{h}{|\varepsilon|^{\beta\delta}}\right)$

Go on to h-ε coordinate system

$$\phi_{\mathrm{exp}}(\Delta x, \Delta y) = \phi_{\mathrm{scale}}(h, \varepsilon)$$
$$= \phi_{\mathrm{scale}}(c \cdot \Delta x + d \cdot \Delta y,\ a \cdot \Delta x + b \cdot \Delta y)$$

---

along Δx-axis($\Delta y = 0$), let me analyze $\phi_{\mathrm{exp}}(\Delta x, \Delta y = 0)$ as a function of Δx

$$\phi_{\mathrm{exp}}(\Delta x, \Delta y) = \phi_{\mathrm{scale}}(c \cdot \Delta x,\ a \cdot \Delta x)$$
$$\propto \Delta x^{1/\delta}\ \underbrace{f_{\pm}\left(\frac{c}{|a|^{\beta\delta}\,|\Delta x|^{\beta\delta-1}}\right)}_{\text{if } \beta\delta - 1 > 0,\ \text{const.}\ (\Delta x \to 0)}$$

∵ $f_{\pm}(\infty) = \mathrm{const.}$

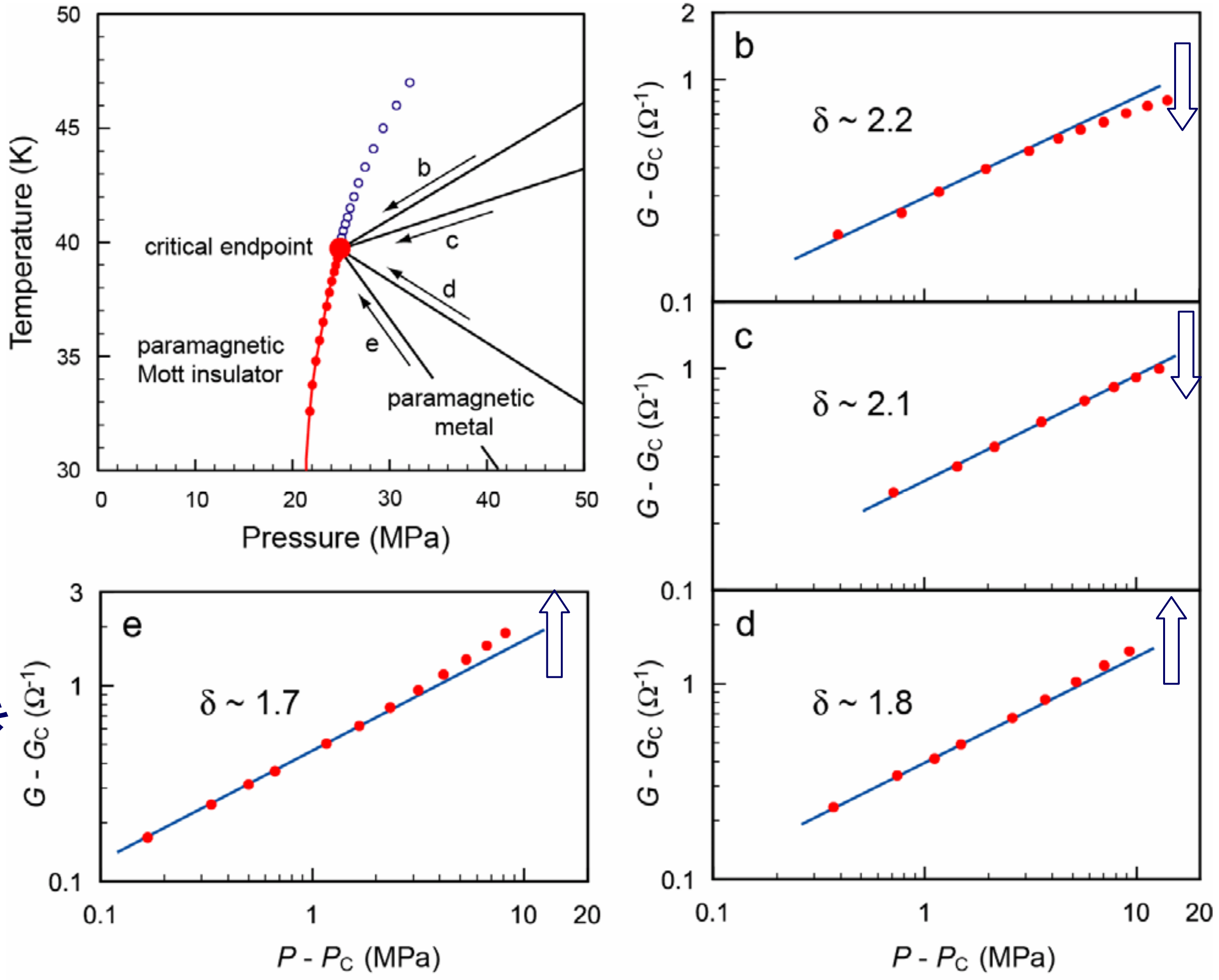
Near $\Delta x = 0$, one can obtain the correct δ along any axis.

(mixing effect is negligible near $\Delta x = 0$)

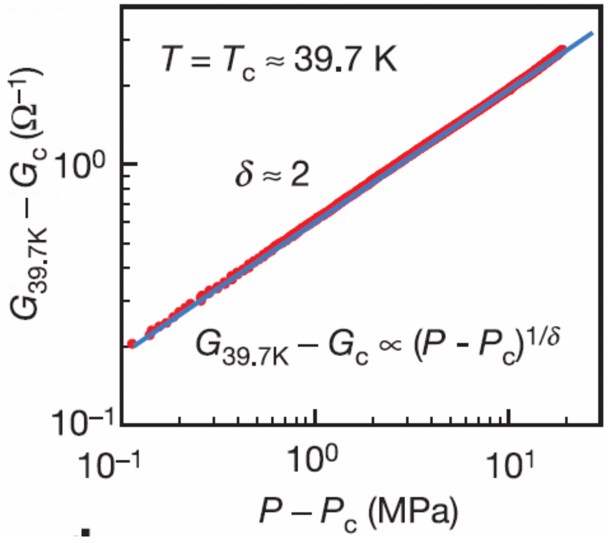
臨界指数δの検討

全ての軸において、
$\Delta x = 0$ の近傍で $\delta \sim 2$

c軸、d軸は比較的よく
フィットできている



cf. 圧力軸で解析したとき



- 真のh軸は、c軸とd軸の間にありそう
（かなり圧力軸に近い）
- power lawからのずれ方はスケーリング関数のx 依存性とconsistent

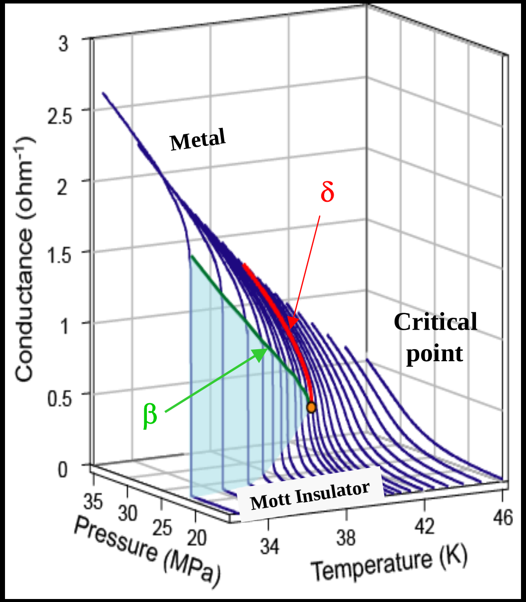
Critical exponents of Mott transition

In two dimensions

κ-$(ET)_2Cu[N(CN)_2]Cl$

Present results

δ	2.0 ±0.15
β	1.0 ±0.1
γ	1.0 ±0.1



In three dimensions

just near (P_c, T_c)

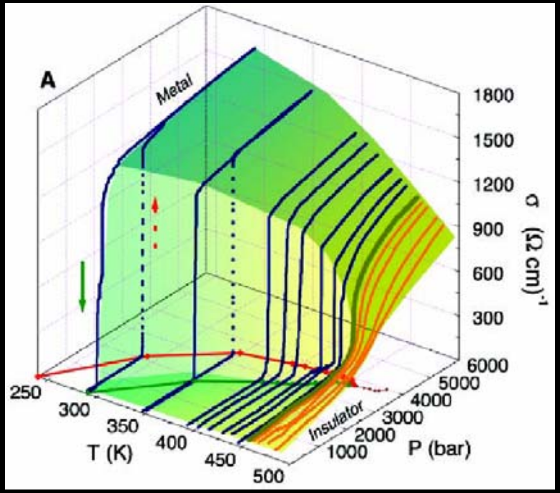
V_2O_3

P. Limelette *et al.*
Science **302**, 89 (2003)

δ	~3	~5
β	~0.5	~0.34
γ	~1	

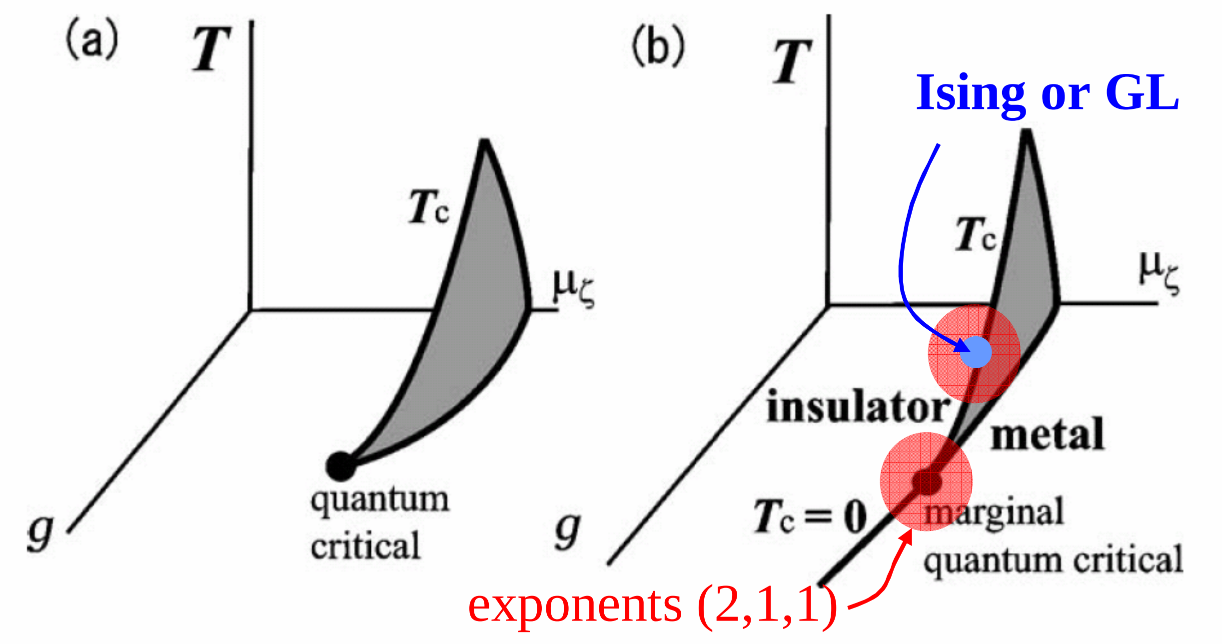
mean-field values

3D Ising values
(liquid-gas)



Universality class of quantum Mott transition; (δ, β, γ)=(2,1,1)

BC Mott; Imada, Misawa, Yamaji (2005,2006)

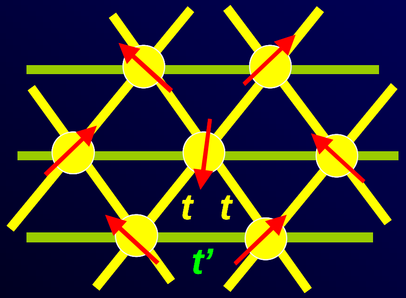


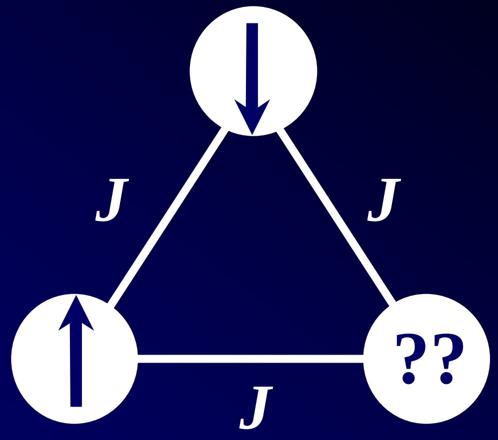
A possible involvement of quantum fluctuations
at low but finite temperatures

Interacting electrons in κ-(ET)$_2X$ are

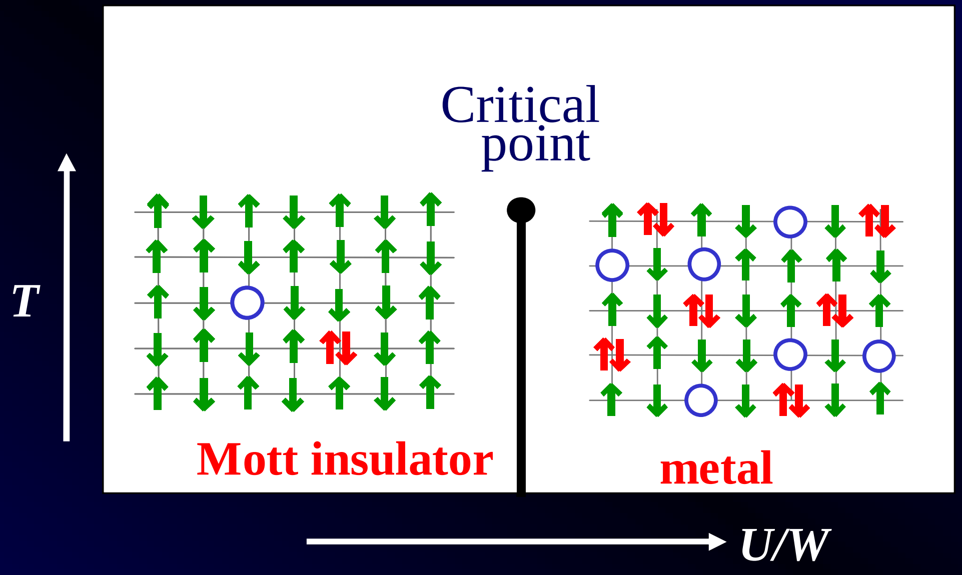
near Mott transition and **on triangular lattice**

X^-	Ground State	t'/t
$\mathrm{Cu_2(CN)_3}$	Mott insulator	1.06
$\mathrm{Cu[N(CN)_2]Cl}$	Mott insulator	0.75
$\mathrm{Cu[N(CN)_2]Br}$	SC	0.68
$\mathrm{Cu(NCS)_2}$	SC	0.84



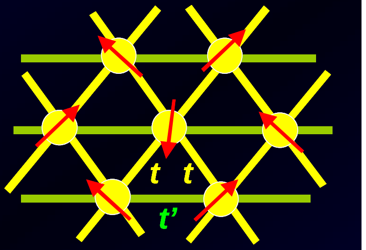


Frustration
in spin degrees of freedom

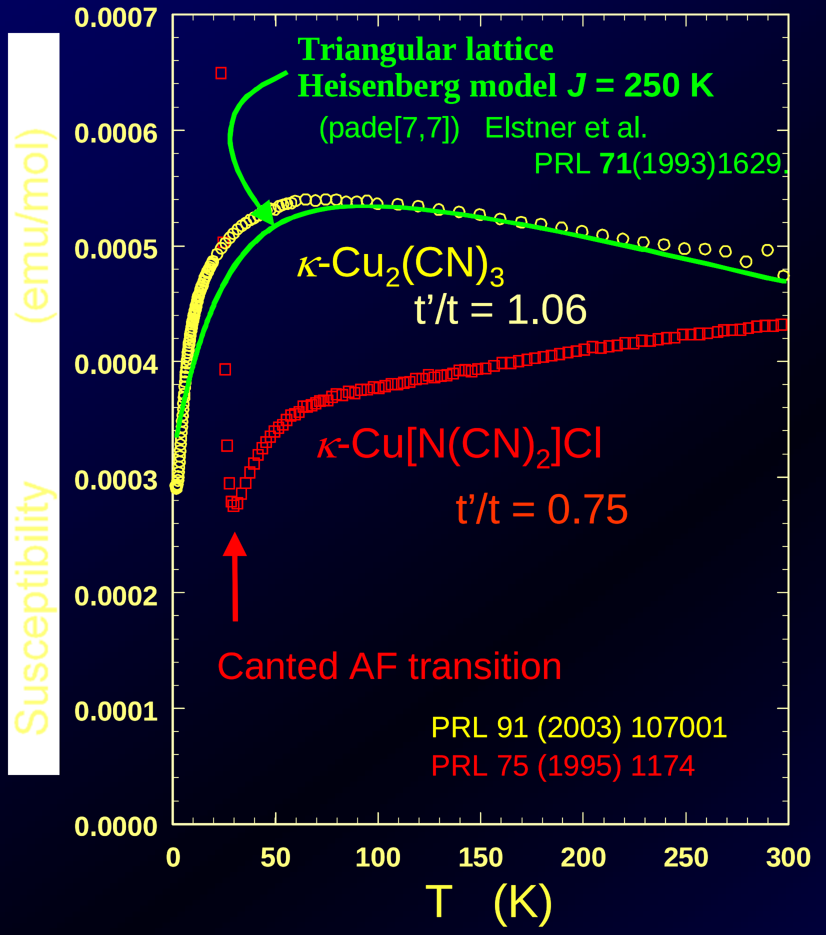


Particle nature/ wave nature competition
in charge degrees of freedom

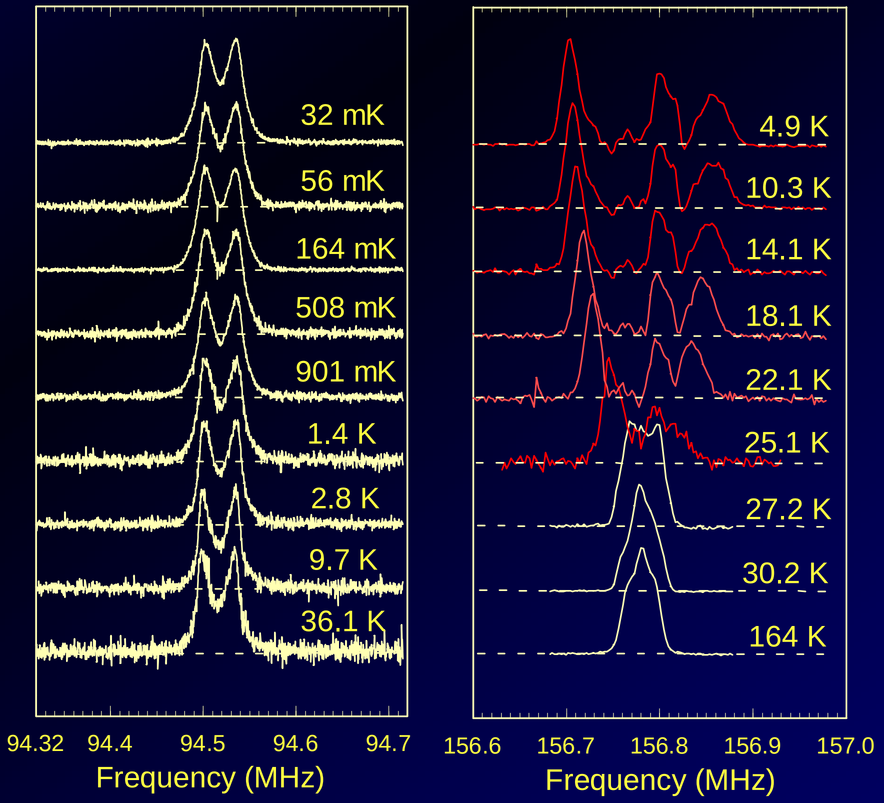
Ordering (for t'/t=0.75)
versus
quantum liquid (for t'/t=1.06)



Magnetic susceptibility



^{1}*H NMR spectrum*



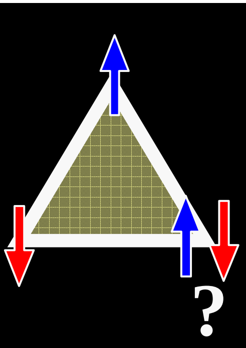
κ-$(ET)_2Cu_2(CN)_3$ κ-$(ET)_2Cu[N(CN)_2]Cl$

t'/*t* =1.06 *t'*/*t* =0.75

Spin liquid ⟺ AF ordered (0.45μ_B)

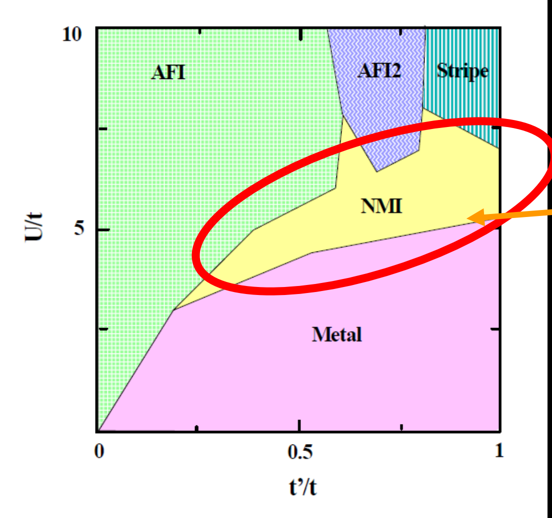
Shimizu et al., PRL 91 (2003) 107001

Why spin liquid instead of the 120° order ?



→ Physics near the Mott transition

Mizusaki & Imada (2006)

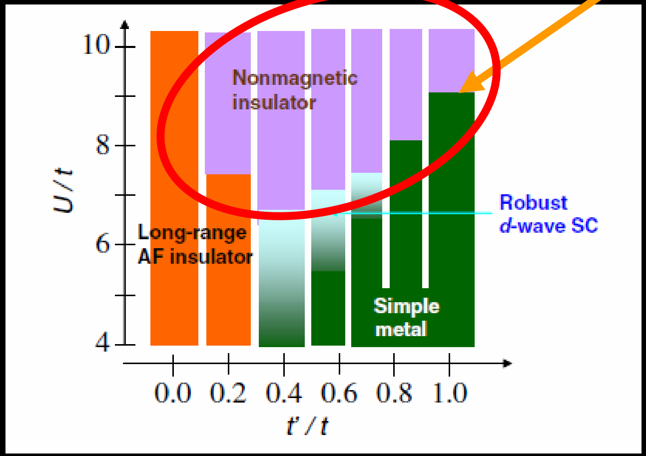


Mott transition

PIRG

Watanabe (2006)

Mott transition

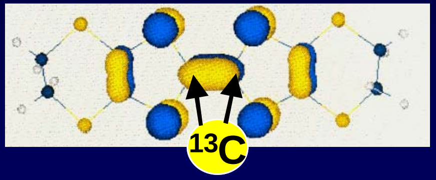


VMC

Nature of spin liquid ? ⇨ Imada & Watanabe, Sorella, P.A. Lee, Senthil, Mismuich et al., Motrunich, M.P.A.Fischer McKenzie, Schmalian, Watanabe………

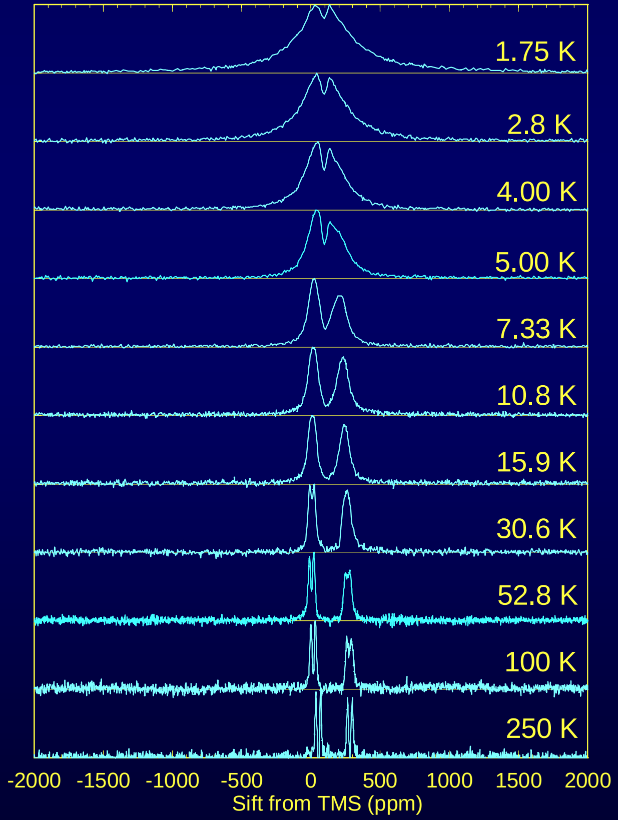
^{13}C NMR of κ-$(ET)_2Cu_2(CN)_3$

Shimizu *et al.*, PRB 70 (2006) 060510

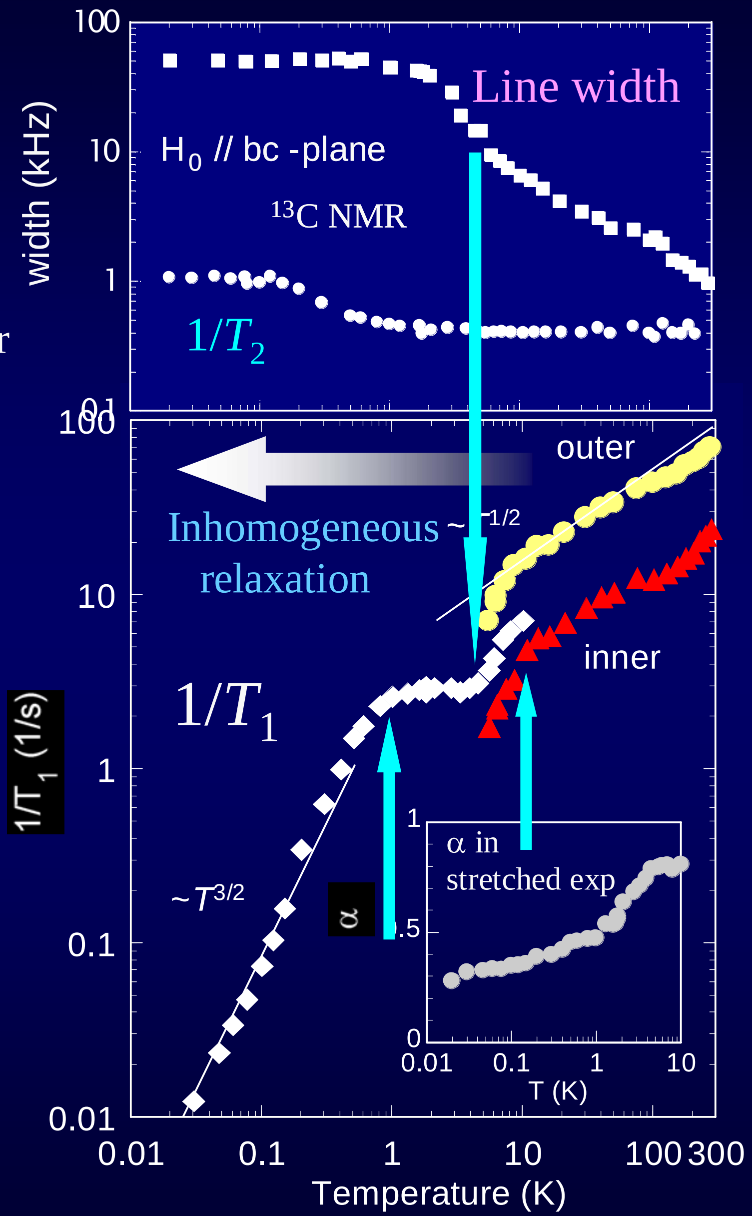


H = 8T ⊥ layer

Spectra

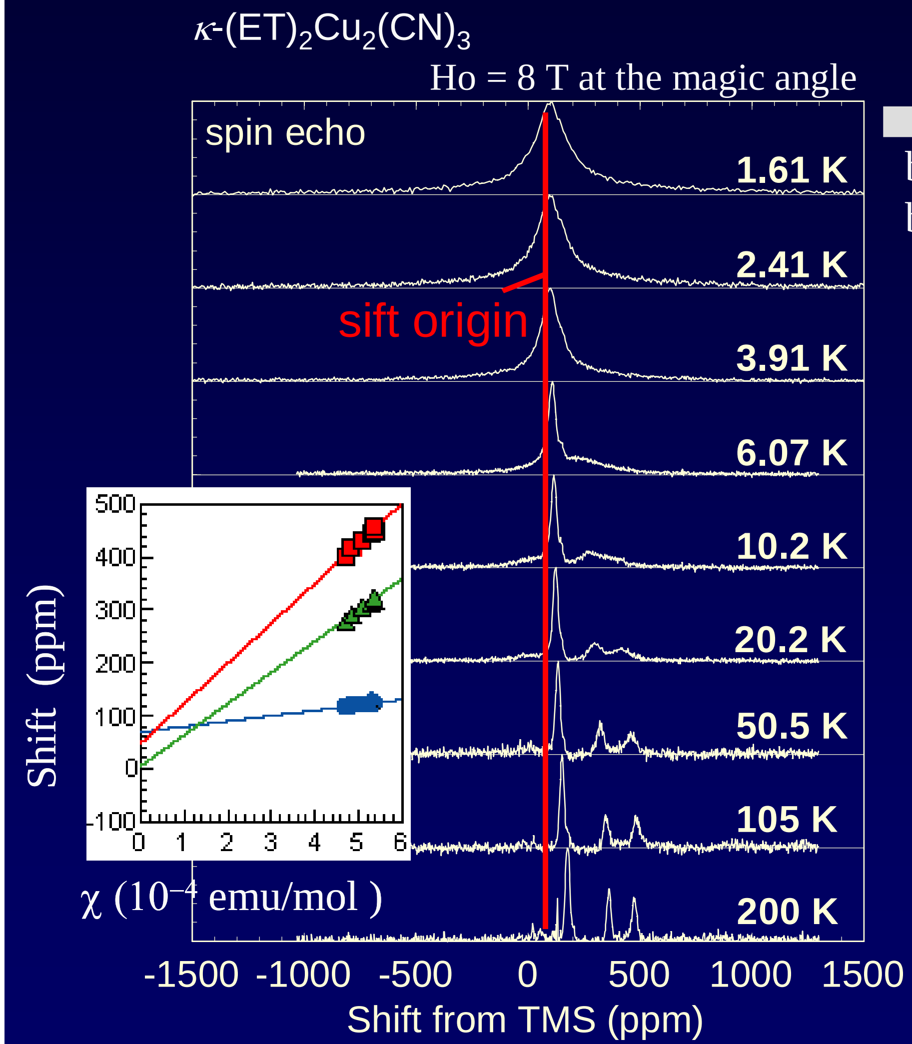


Line broadening



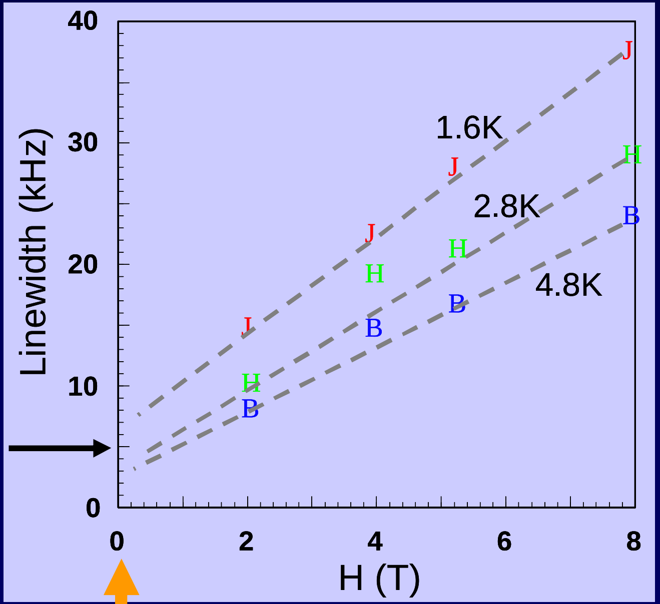
Low-lying spin excitation

Spectral Broadening is due to spatially varying moments induced by magnetic field



bipolar broadening

Spatially varying staggered moments are field-induced.



Nuclear dipolar field

No internal field at H=0 by μSR (Ohira et al)

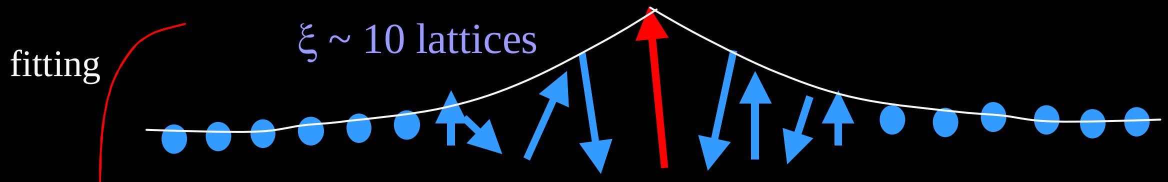
Possible picture of the moment emergence

Local nucleation of staggered or spiral moments

around symmetry-breaking site

(Impurity, defect, grain boundary,…..)

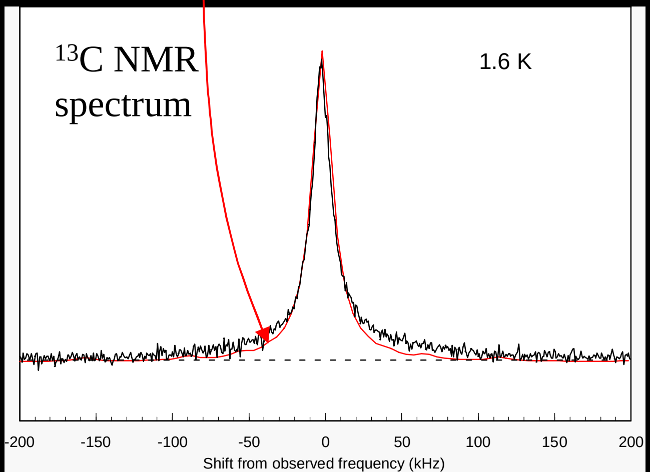
For example, assuming isotropic gap
and 0.01% impurities



m ~ 0.05 μ_B

ξ ~ 10 lattices

fitting



Generic in quantum spin system

Sr_2CuO_3; Takigawa et al. ('97)

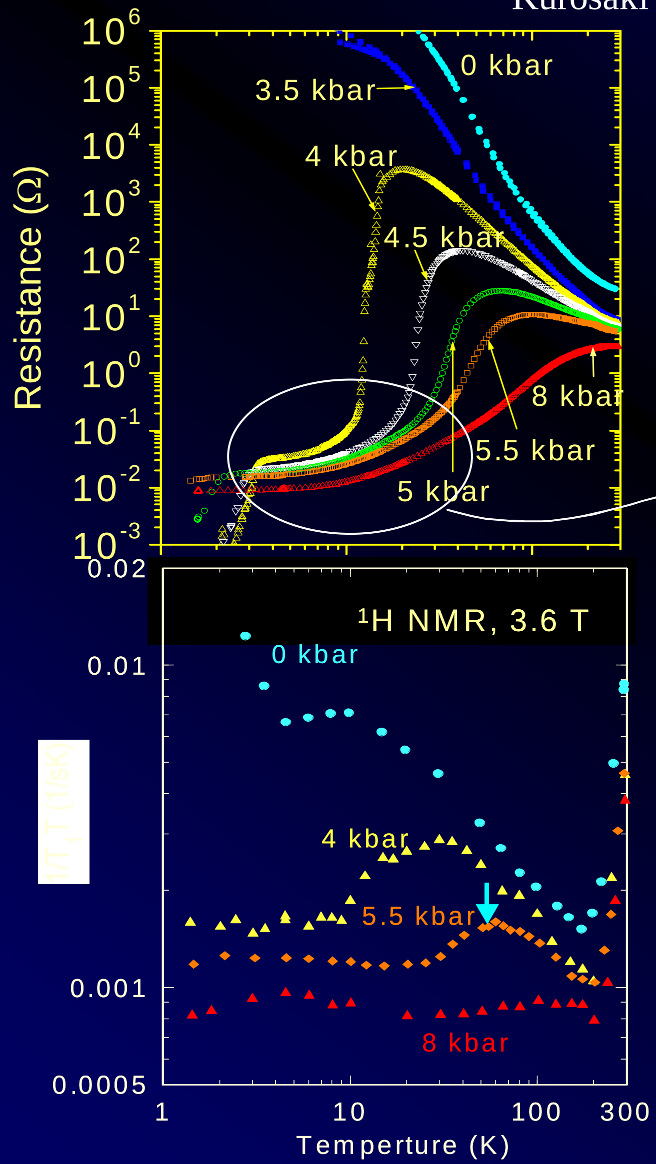
$SrCu_2O_3$; Fujiwara et al. ('98),
Ohsugi et al. ('99)

$CuGeO_3$; Itoh et al. et al ('97)

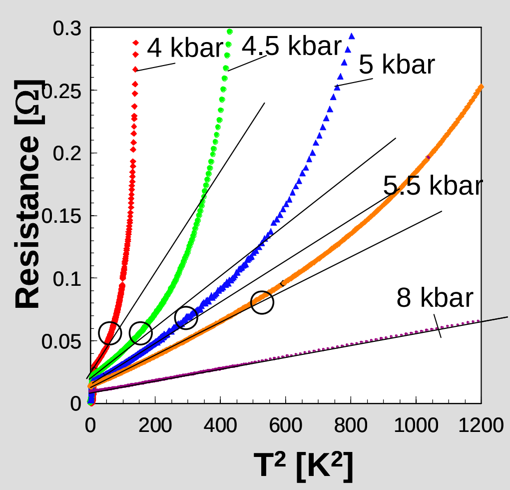
$(TMTTF)_2PF_6$; Brown et al ('98)

Mott transition in κ-$(ET)_2Cu_2(CN)_3$ *under pressure*

Kurosaki et al.; PRL 95 (2005) 177001

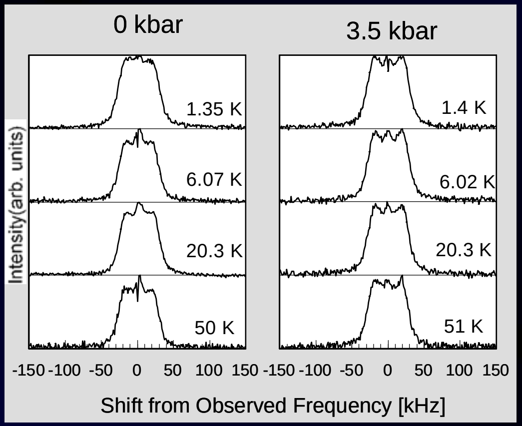


R vs T^2

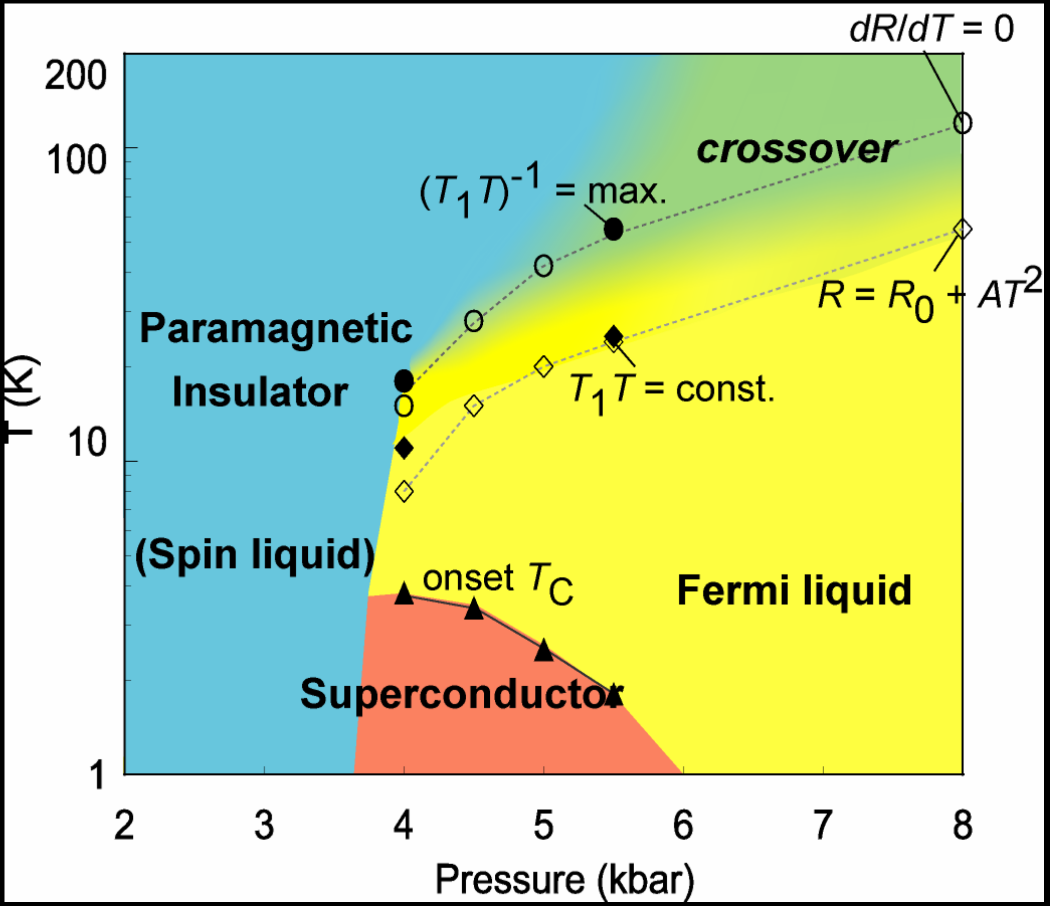


No magnetic ordering under pressures

No change in ¹H NMR spectra



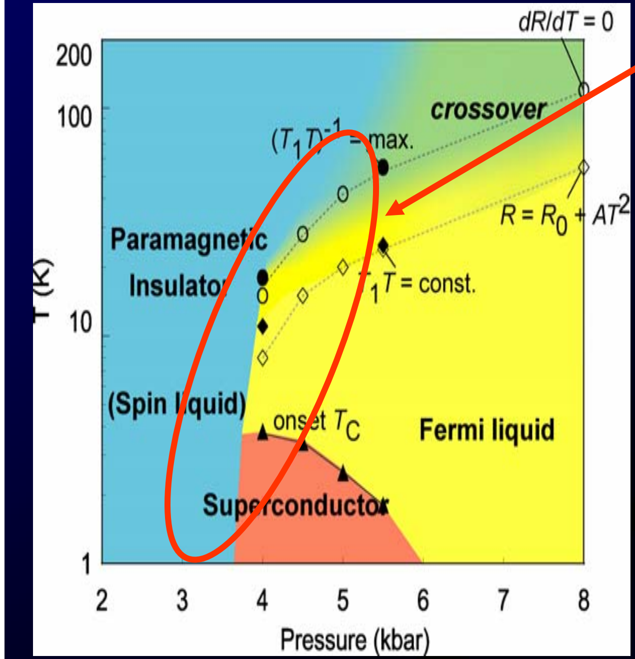
Phase diagram of spin ½ on triangular lattice κ-$(ET)_2Cu_2(CN)_3$



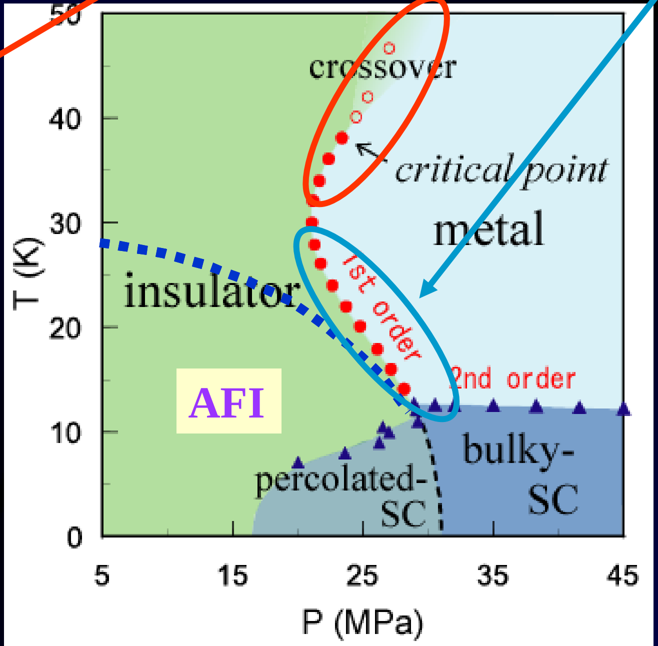
Kurosaki et a., PRL 95 (2005) 177001

Effect of spin frustration to Mott; phase diagram

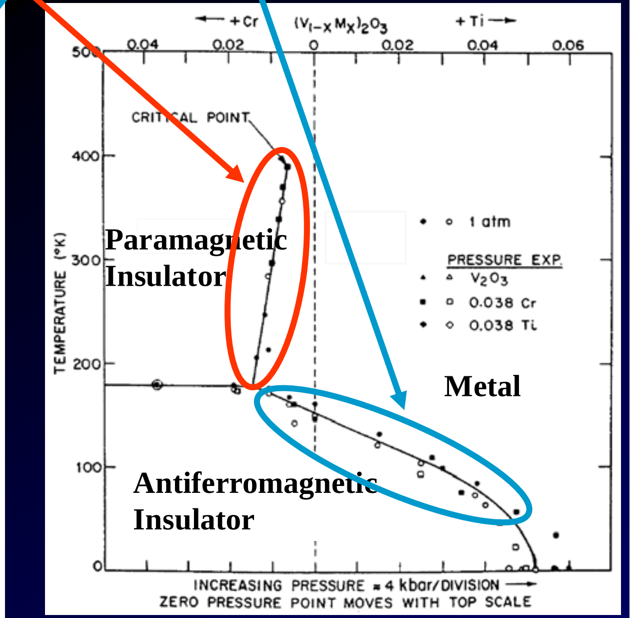
Clausius Clapeyron $dT/dP = \Delta V/\Delta S$ $\boxed{> 0}$ $\boxed{< 0}$



Q2D spin liquid
κ-Cu$_2$(CN)$_3$



Q2D antiferromagnet
κ-Cu[N(CN)$_2$]Cl



3D antiferromagnet
V_2O_3

Entropy of the spin liquid
is larger than that of Fermi liquid down to 1.5 K !

Conclusion

- Mott criticality in κ-ET$_2$X does not belong to the Ising Universality but possibly to Quantum Mott's.
- Spin liquid emergent near Mott transition on triangular lattice
- Spin frustration affects Mott transition
- Superconductivity emerging from spin liquid
    - likely nodal and exotic spin pairing
    - absence of pseudogap