Title: Organic materials: all-in-one systems for Mott physics - Quantum criticality, preformed pairs and spin liquids

Date: May 12, 2016 01:30 PM

URL: http://pirsa.org/16050037

Abstract: A many-body quantum system on the verge of instability between competing ground states exhibits emergent phenomena. Interacting electrons on triangular lattices are likely subjected to multiple instabilities in the charge and spin degrees of freedom, affording diverse phenomena related to the Mott physics. The molecular conductors are superior model systems for studying the Mott physics because of the designability and controllability of material parameters such as lattice geometry and bandwidth by chemical substitution and/or pressure. In this symposium, I first introduce the fundamentals of organic materials and then present various quantum manifestations that interacting electrons in triangular-lattice organics show under variable correlation on the verge of the Mott metal-insulator transition. The topics include i) the quantum criticality of the Mott transition revealed by the resistivity that obeys quantum-critical scaling, ii) the pseudo-gap-like behavior of the metallic state, which is found to originate from preformed Cooper pairs that persist up to twice as high as Tc, and iii) the spin liquid state that emerges in the Mott insulating state, depending on the lattice geometry. I may touch the recent finding on a doped triangular lattice that exhibits a possible BEC-to-BCS crossover in superconductivity.
The work presented here was performed in collaboration with T. Furukawa, H. Oike, J. Ibuka, M. Urai, Y. Suzuki, K. Miyagawa (UTokyo), Y. Shimizu (Nagoya Univ.), M. Ito, H. Taniguchi (Saitama Univ.) and R. Kato (RIKEN)

Organic materials: all-in-one systems for Mott physics

K. Kanoda, *Applied Physics, UTokyo*

Collaborators

UTokyo	T. Furukawa, J. Ibuka, H. Oike, M. Urai, Y. Suzuki, K. Miyagawa,
Saitama Univ.	M. Ito, H. Taniguchi
Tohoku Univ.	T. Sasaki, M. Saito, S. Iguchi
RIKEN	R. Kato

i) Mott transition *Quamtum criticality*

ii) Superconductivity *Preformed Cooper pairs*

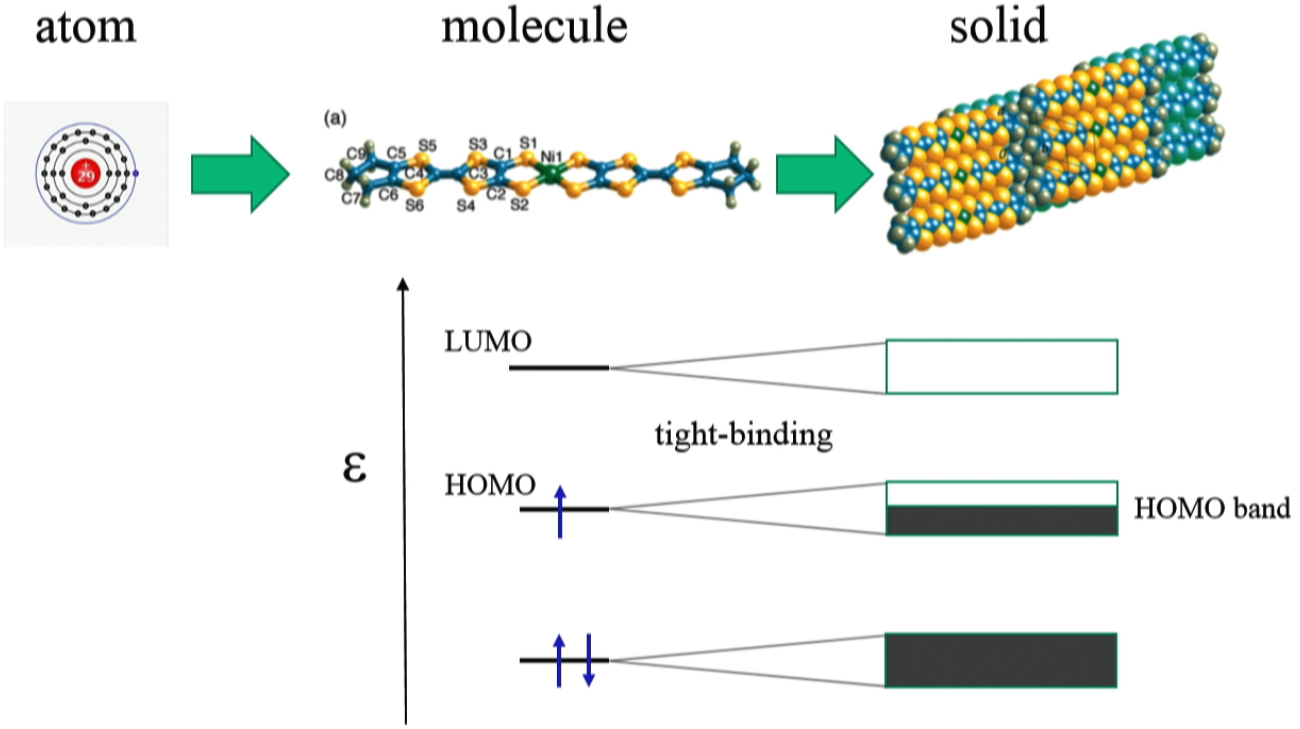
iii) Frustrated magnetism *Spin liquid in △ lattices*

Quantum disorder by quenched disorder

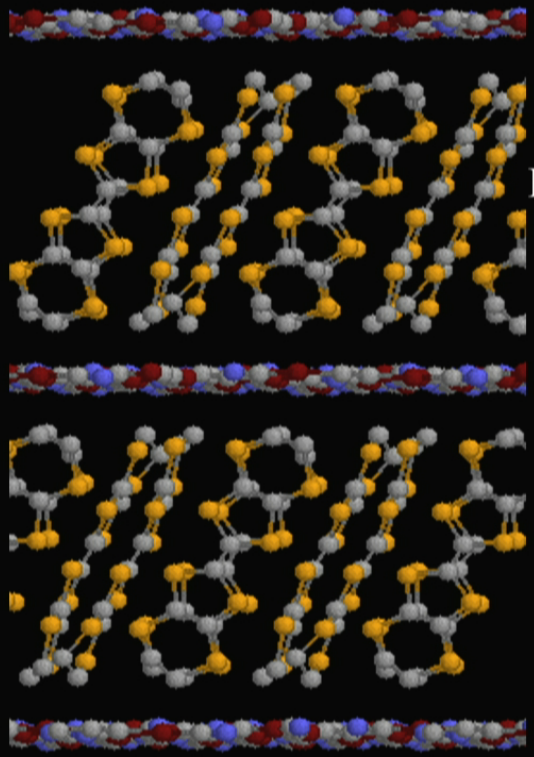
iv) Doping a spin liquid *Anomalous non-Fermi liquid*

Organic conductors

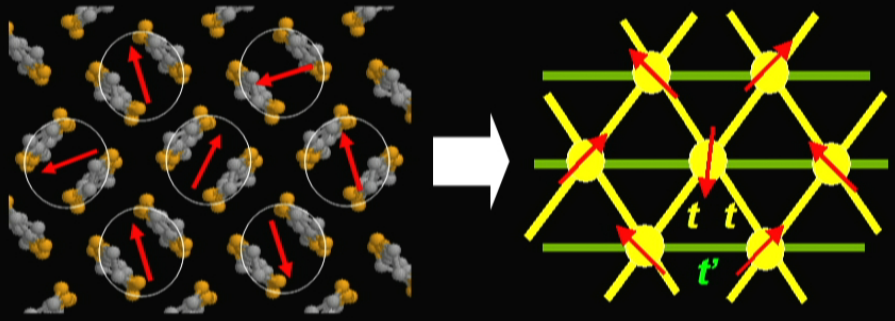
complex in real space, but ***simple band structure***



Organics κ-$(ET)_2X$; designable and cotrollabile



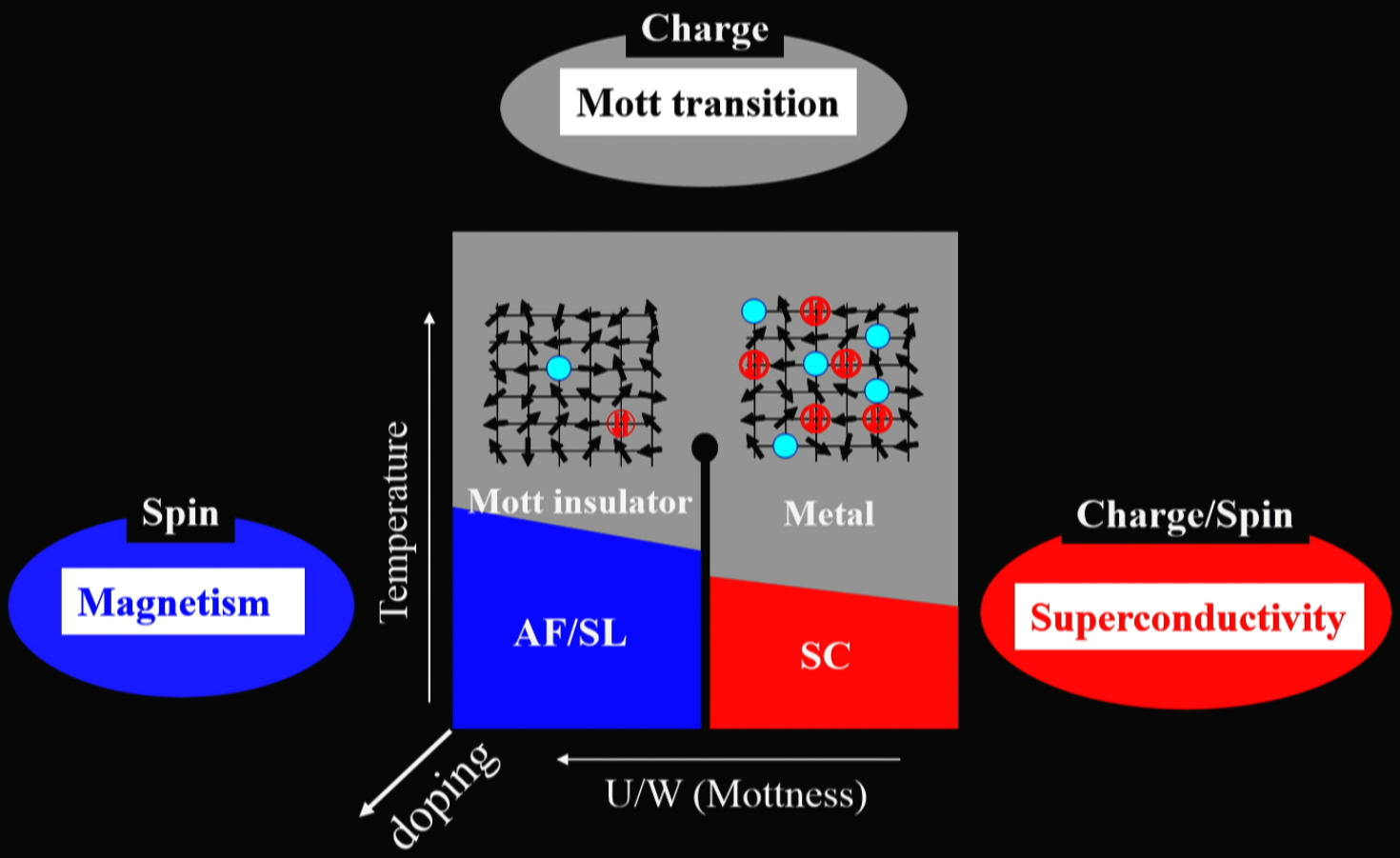
Kino-Fukuyama (1996)



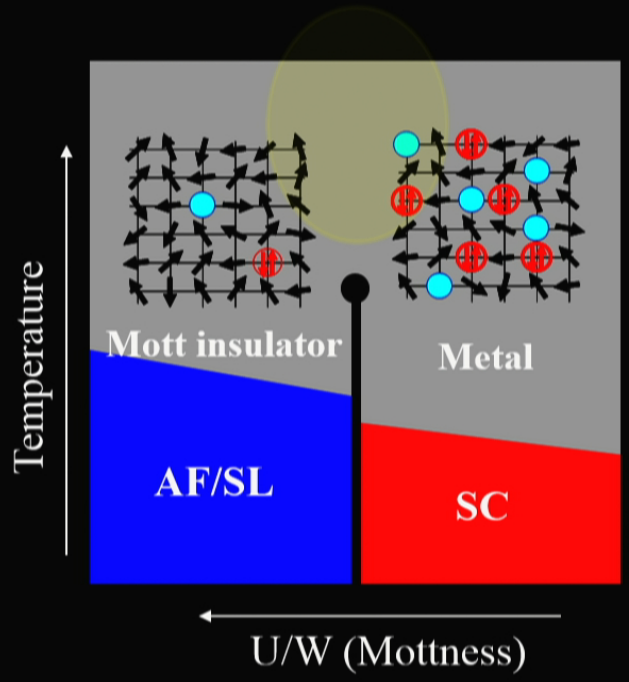
X-	Ground state at ambient pressure	U/t	t'/t	
$Cu_2(CN)_3$	Mott ins.	8.2	1.06	0.80
$Cu[N(CN)_2]Cl$	Mott ins.	7.5	0.75	0.44
$Cu[N(CN)_2]Br$	Metal (SC)	7.2	0.68	
$Cu(NCS)_2$	Metal (SC)	6.8	0.84	
$Cu(CN)[N(CN)_2]$	Metal (SC)	6.8	0.68	
$Ag(CN)_2 H_2O$	Metal (SC)	6.6	0.60	
I_3	Metal (SC)	6.5	0.58	

Ab initio
Kandpal *et al.*(2009)
Nakamura *et al.*(2009)

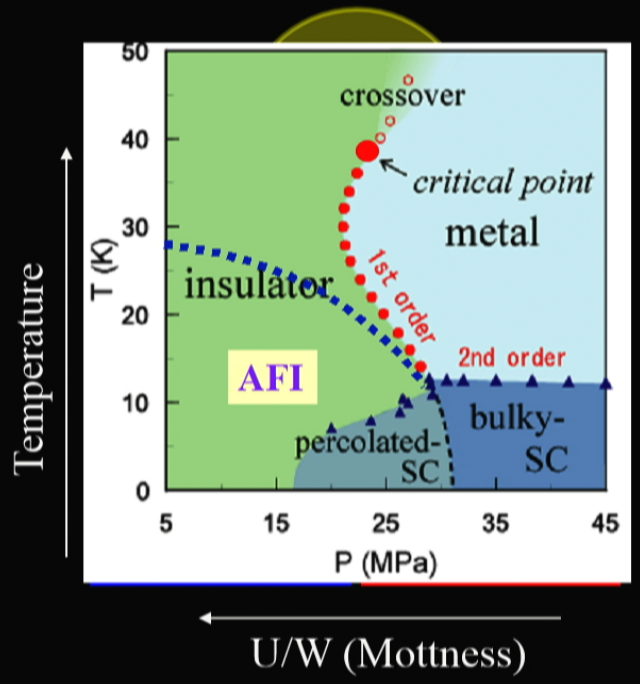
Mott physics in 2D organics



High-energy Mott physics

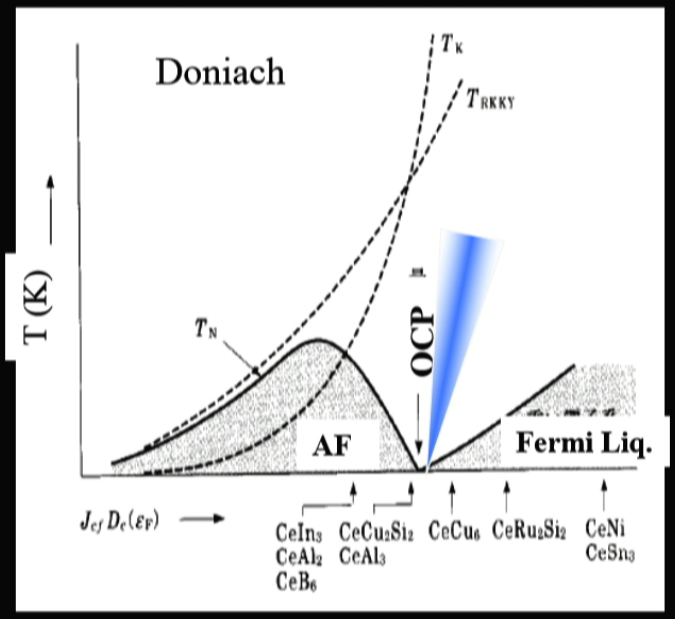


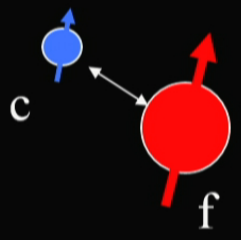
High-energy Mott physics



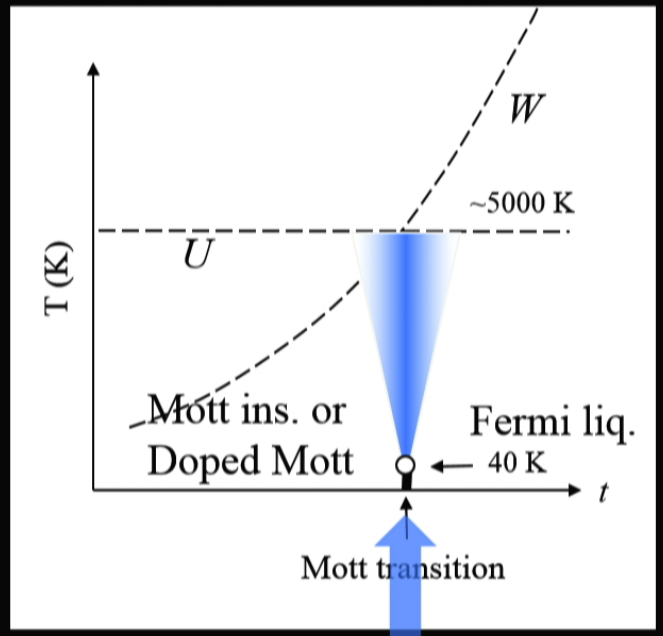
Kondo and Mott

RKKY vs Kondo



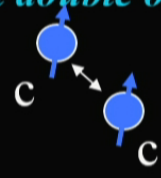


Kinetic energ vs Coulomb



Marginal double occupancy

Magnetic or extended singlet

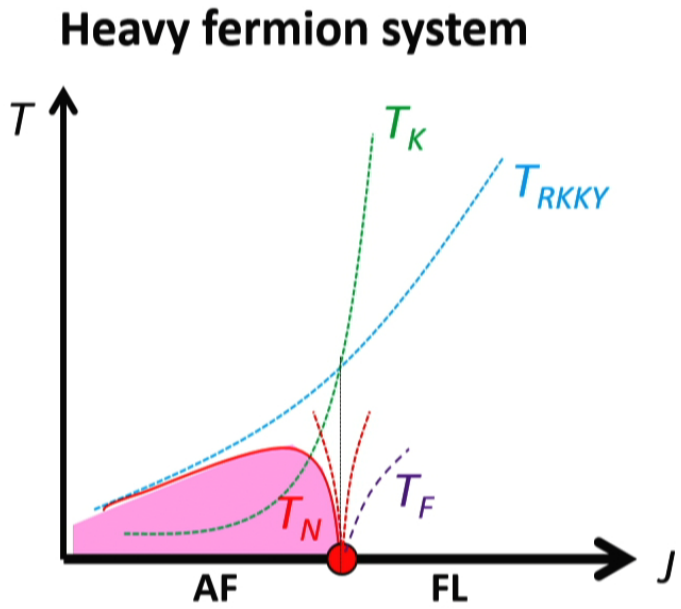


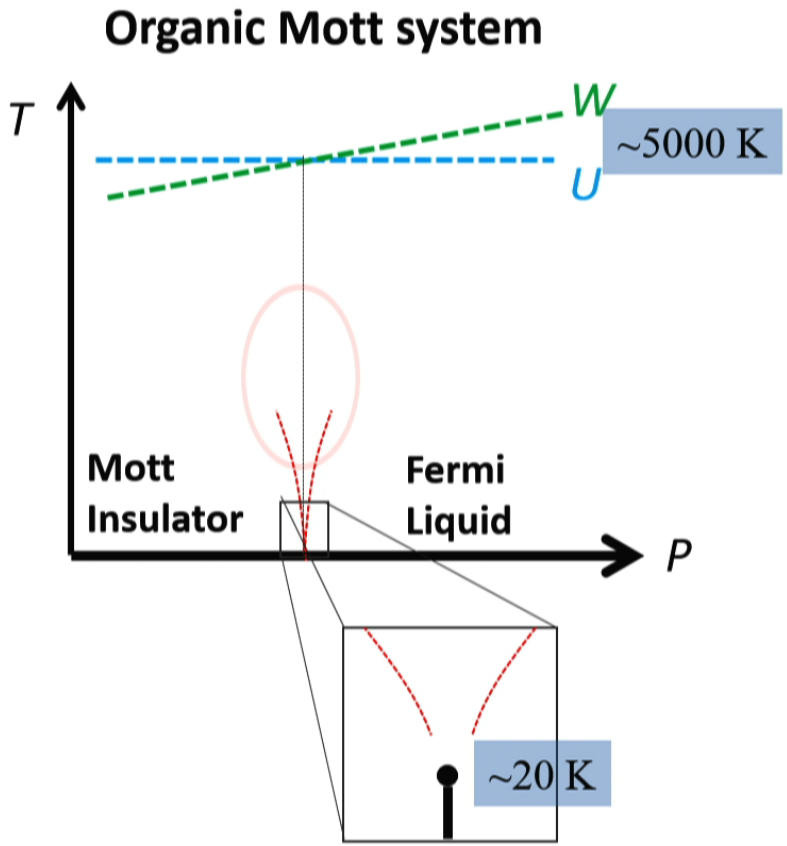
local singlet

Half-filled → Insulator-metal transition

Doped → quantum phase transition

Possible quantum critical behavior in an intermediate energy range

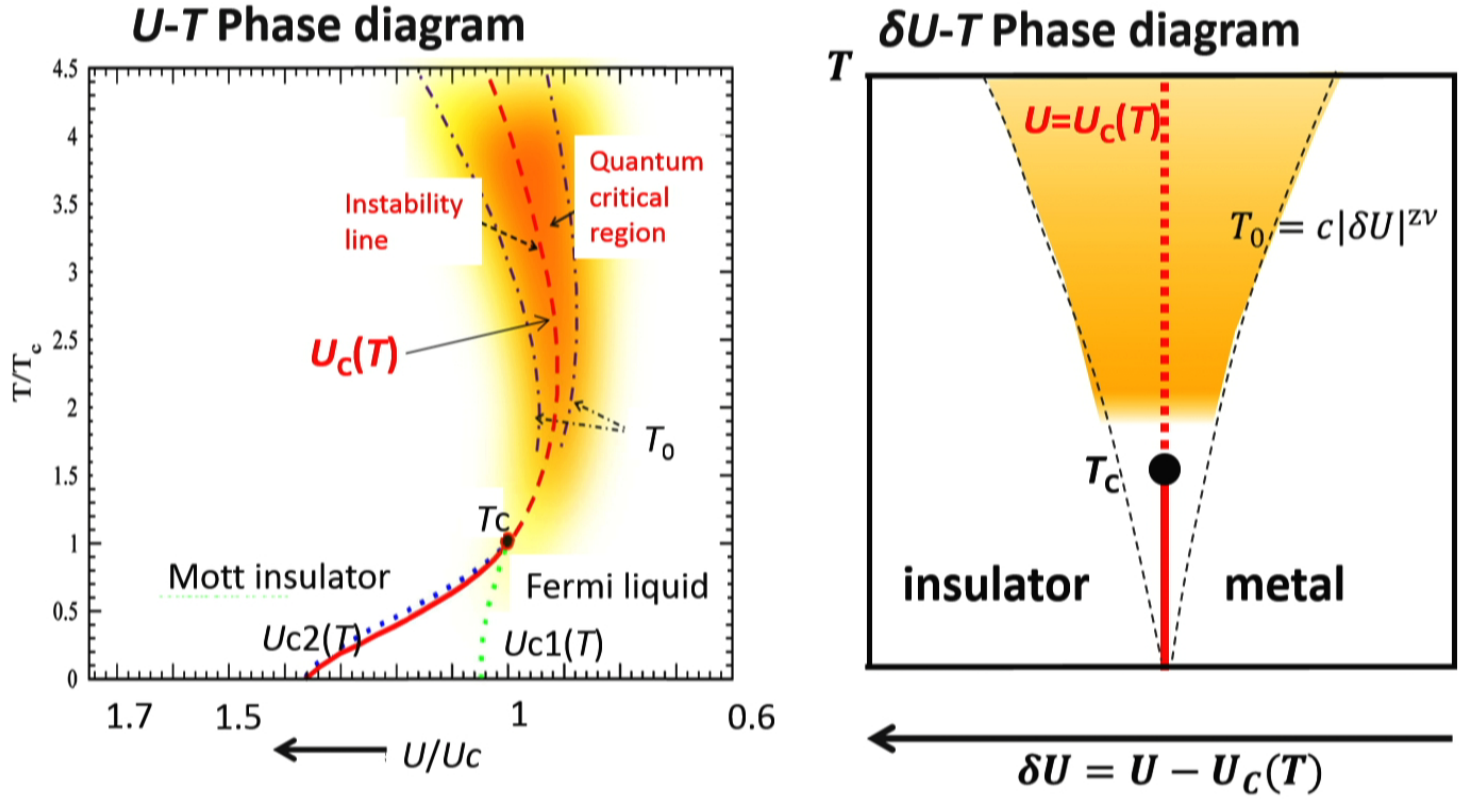




Quantum criticality ($T_c < T << t,U$)

Single-site DMFT of Hubbard model

H.Terletska , V.Dobrosavljevic *et al.,Phys. Rev. Lett* **107**, 026401(2011)



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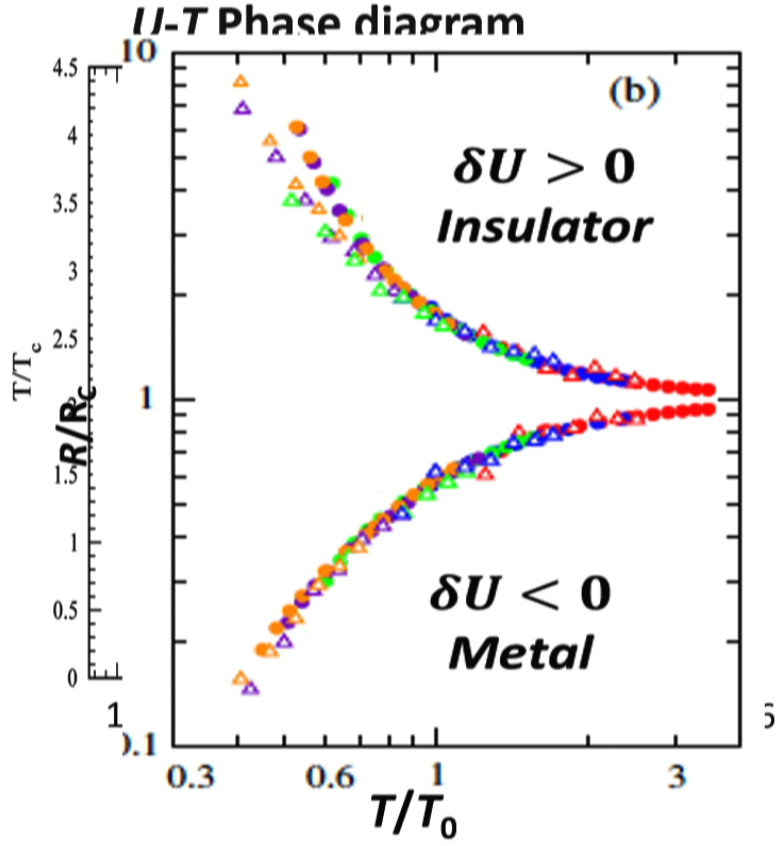
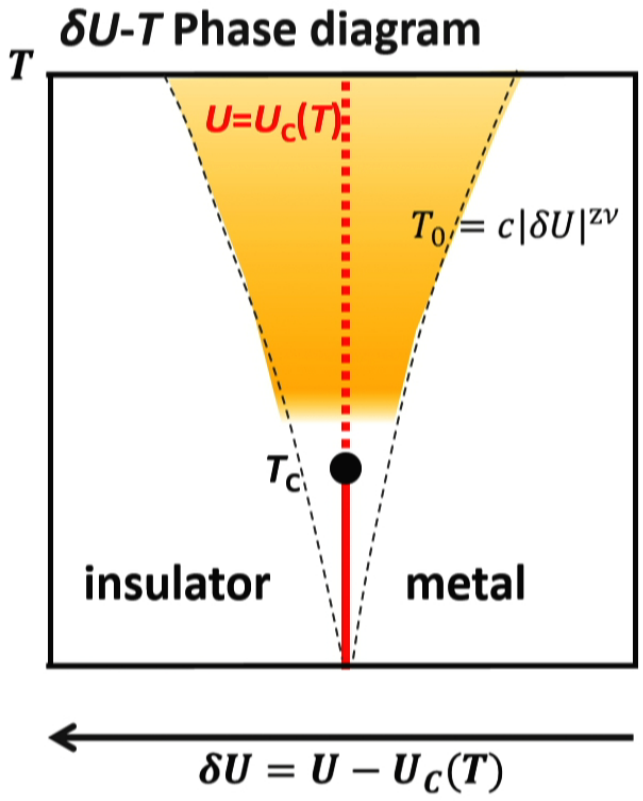
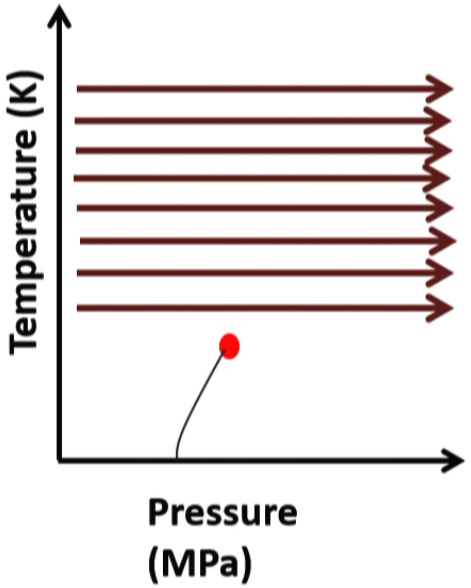




Experimental test of scaling

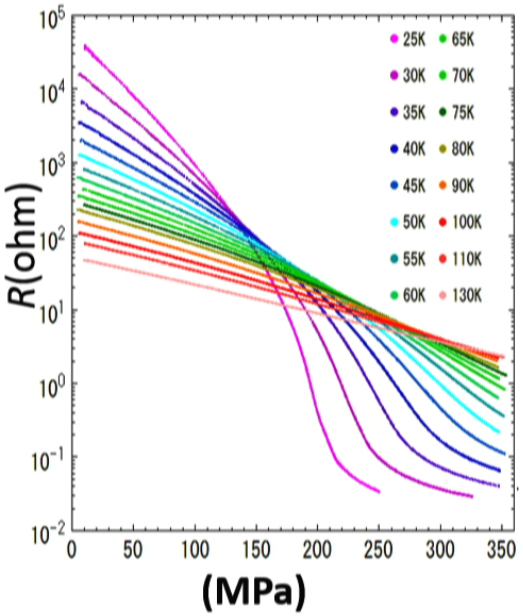
Furukawa et al.,
Nat. Phys 11 (2015) 221



Under He-gas pressure

Experimental test of scaling

Furukawa et al.,
Nat. Phys 11 (2015) 221



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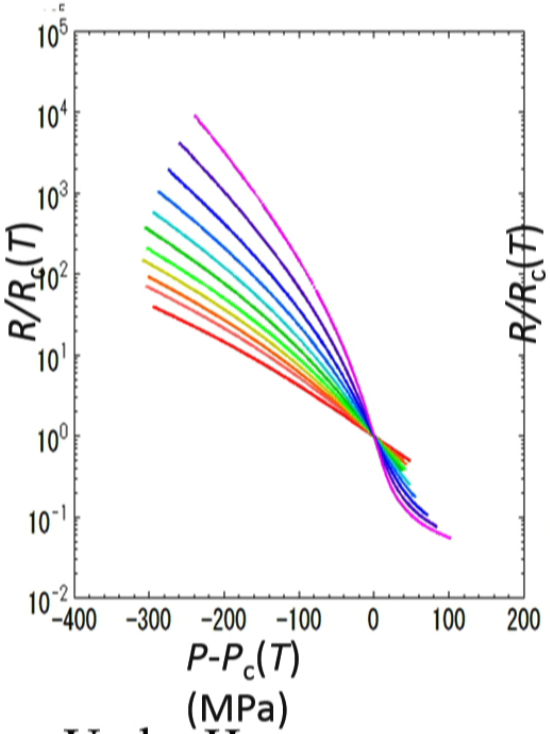
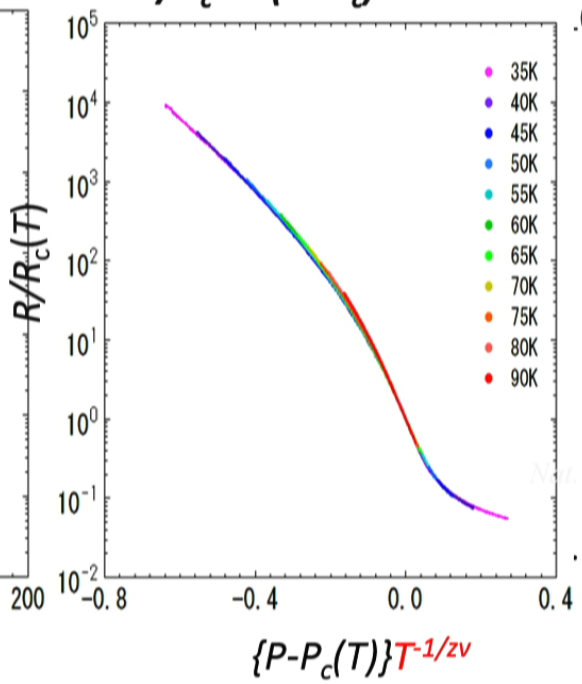


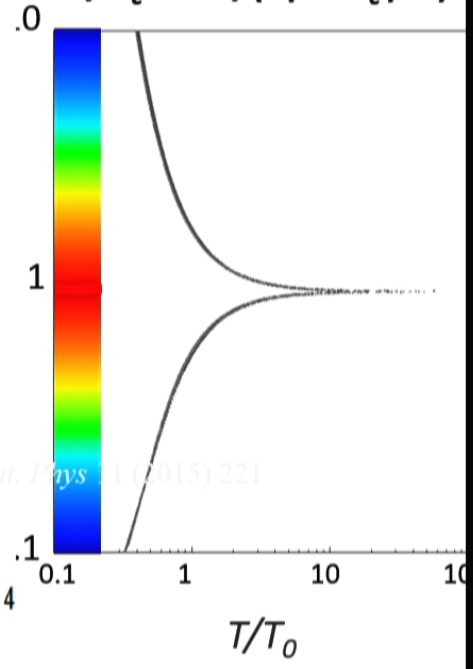
Under He-gas pressure

R/R_c vs $(P\text{-}P_c)*T^{-1/zv}$



$zv=0.6$

R/R_c vs $T/(c|P\text{-}P_c|^{0.6})$



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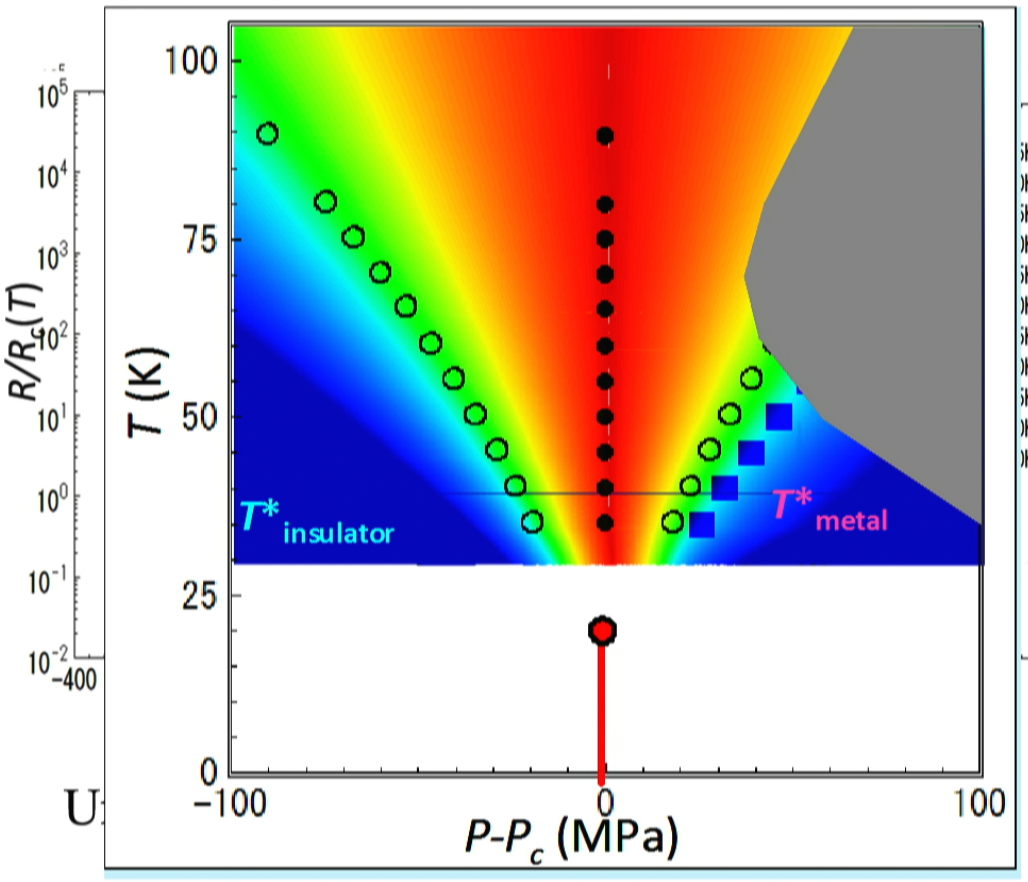
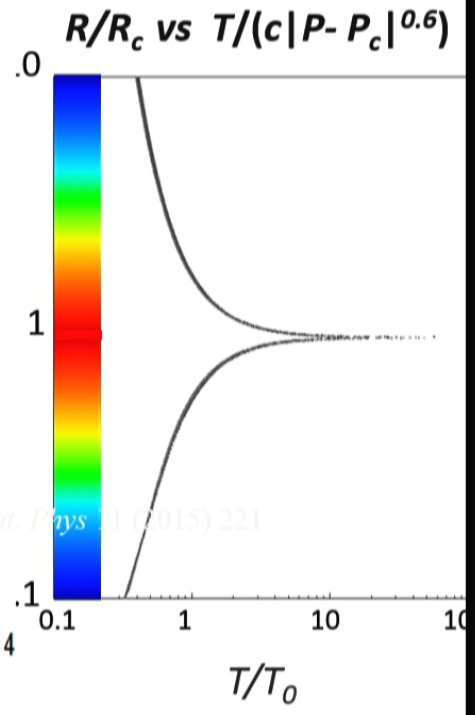
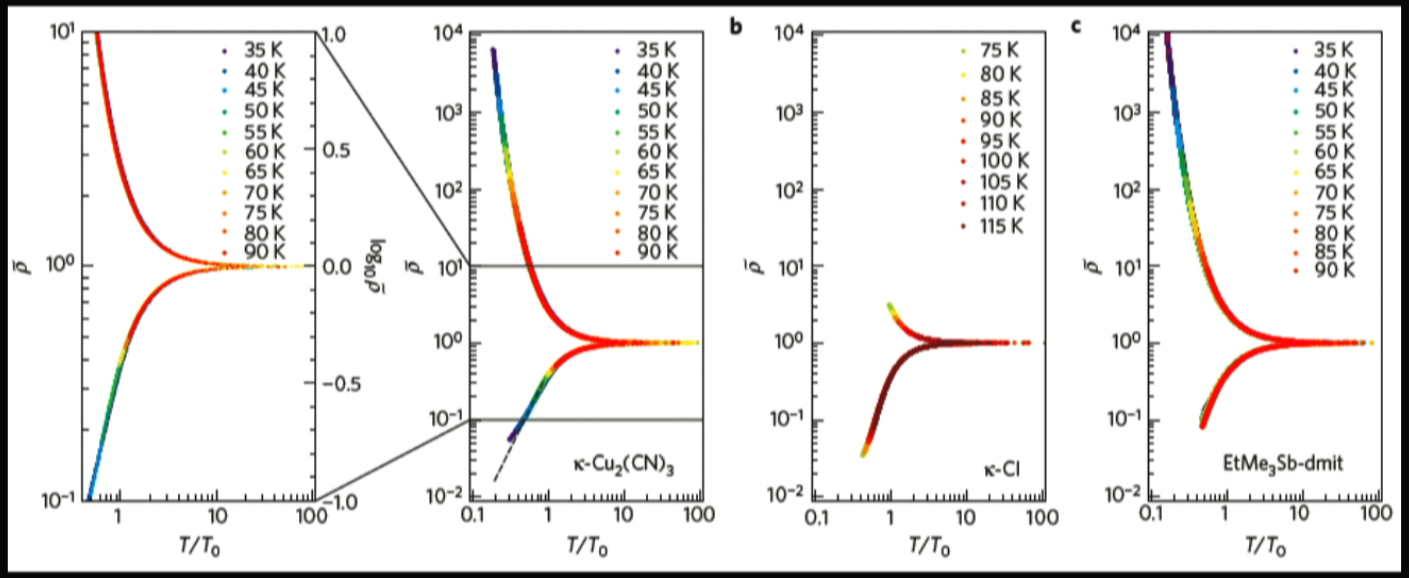




Perfect scaling
for $T > 1.5T_c$

QC scaling --- nearly material -independent

Furukawa et al., Nat. Phys 11 (2015) 221



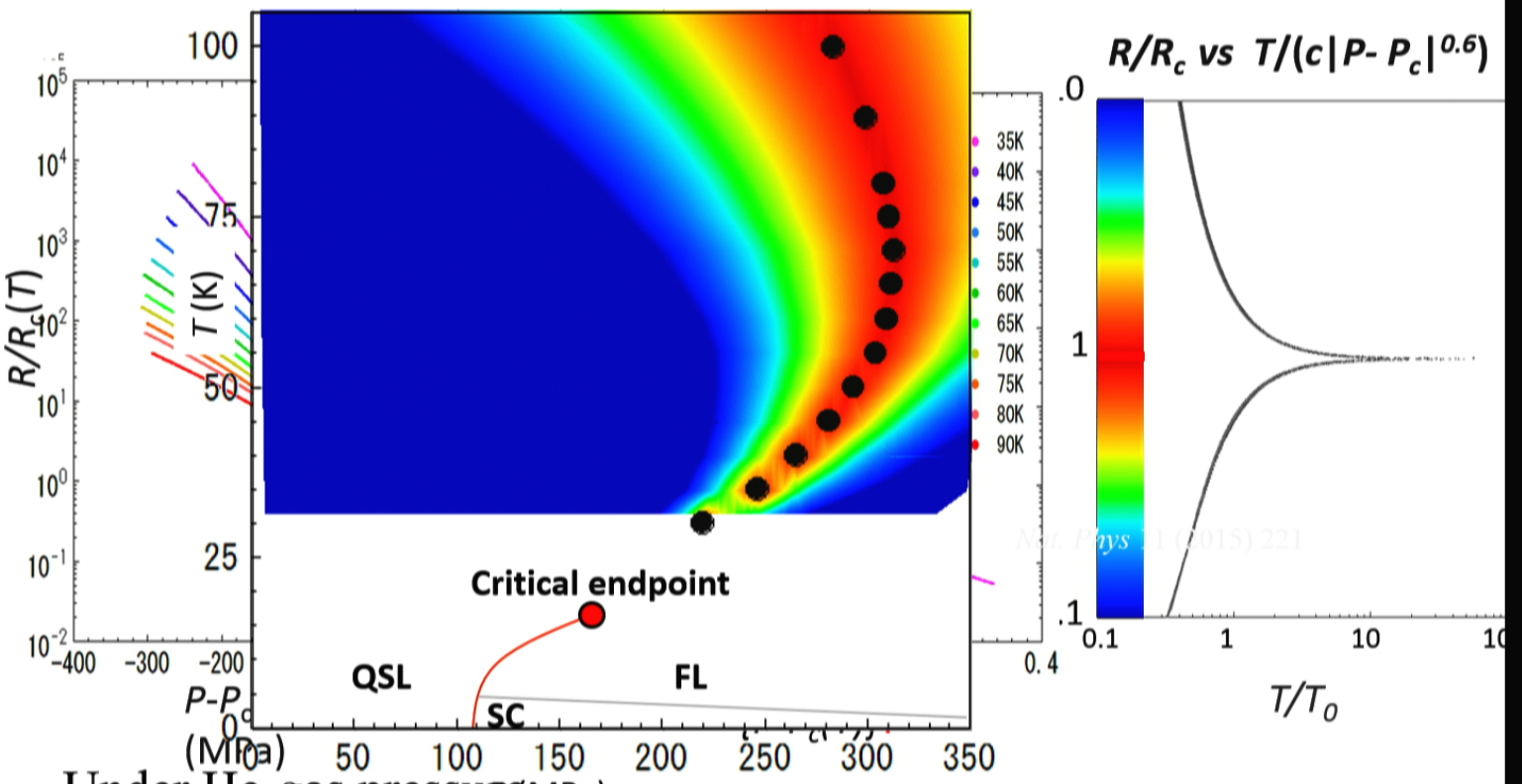
κ-$(ET)_2Cu_2(CN)_3$ | κ-$(ET)_2Cu[N(CN)_2]Cl$ | $EtMe_3Sb[Pd(dmit)_2]_2$

SL/SC | AFI/SC | SL/Metal

$z\nu=0.62\pm0.02$ | $z\nu=0.49\pm0.01$ | $z\nu=0.68\pm0.04$

Experimental test of scaling

Furukawa et al.,
Nat. Phys 11 (2015) 221



Under He-gas pressure

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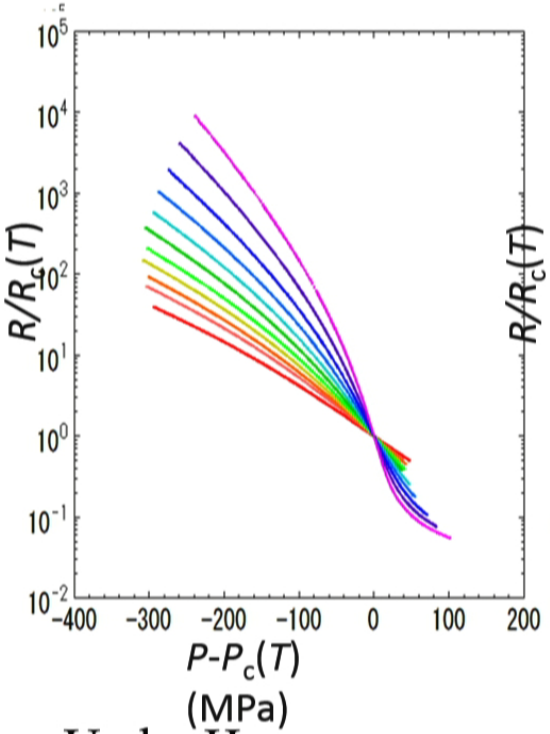
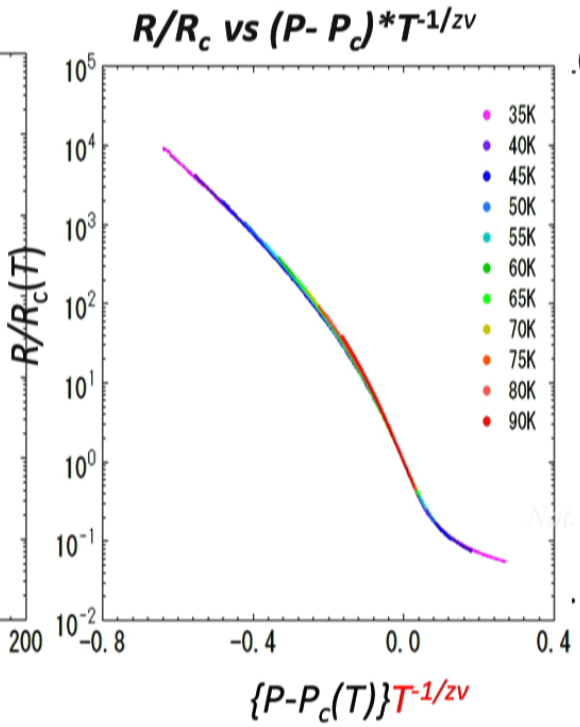
Experimental test of scaling

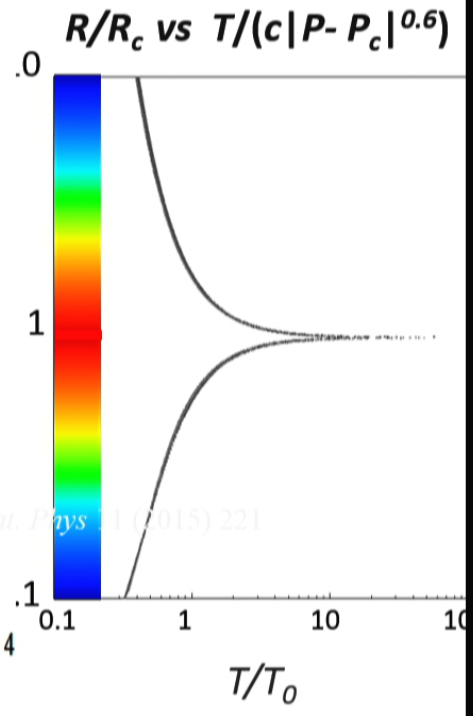
Furukawa et al.,
Nat. Phys 11 (2015) 221



Under He-gas pressure

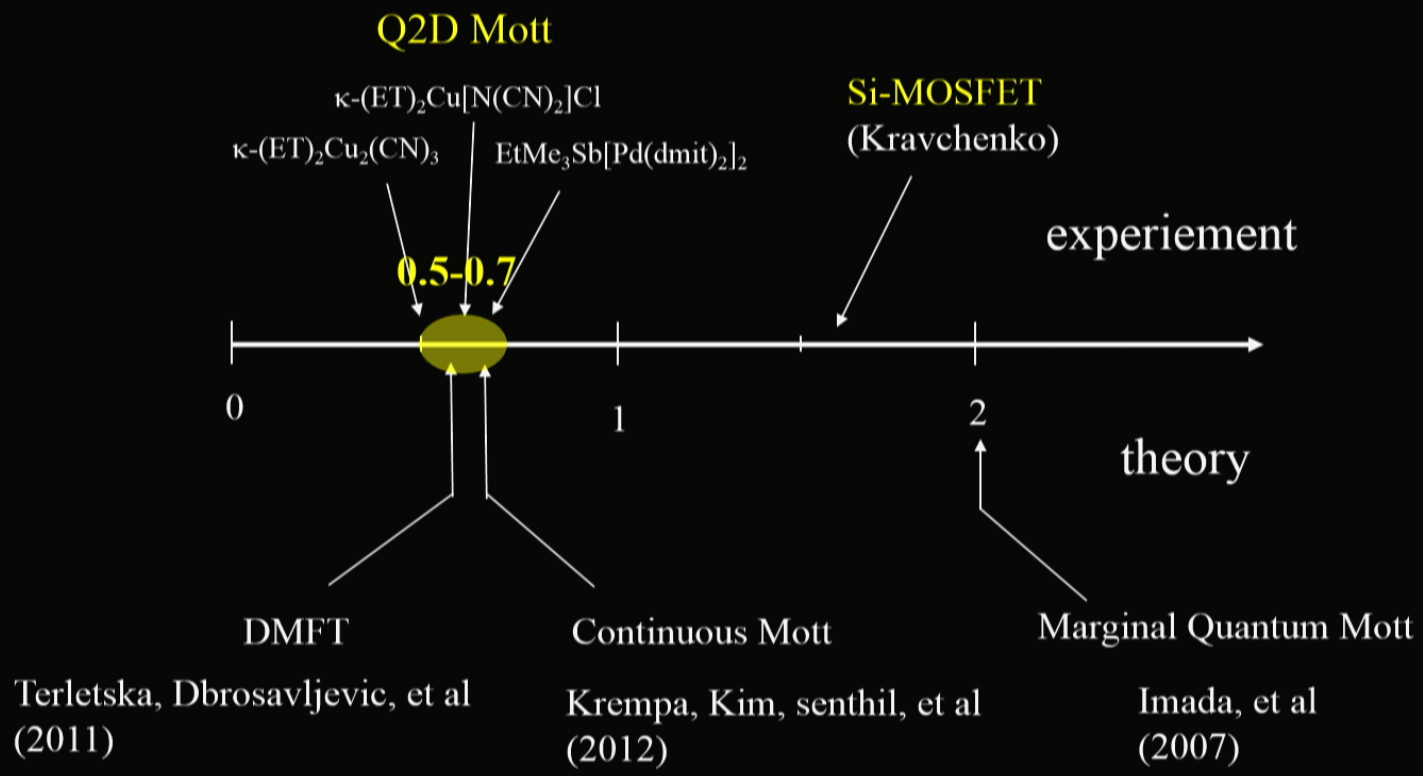


zv=0.6



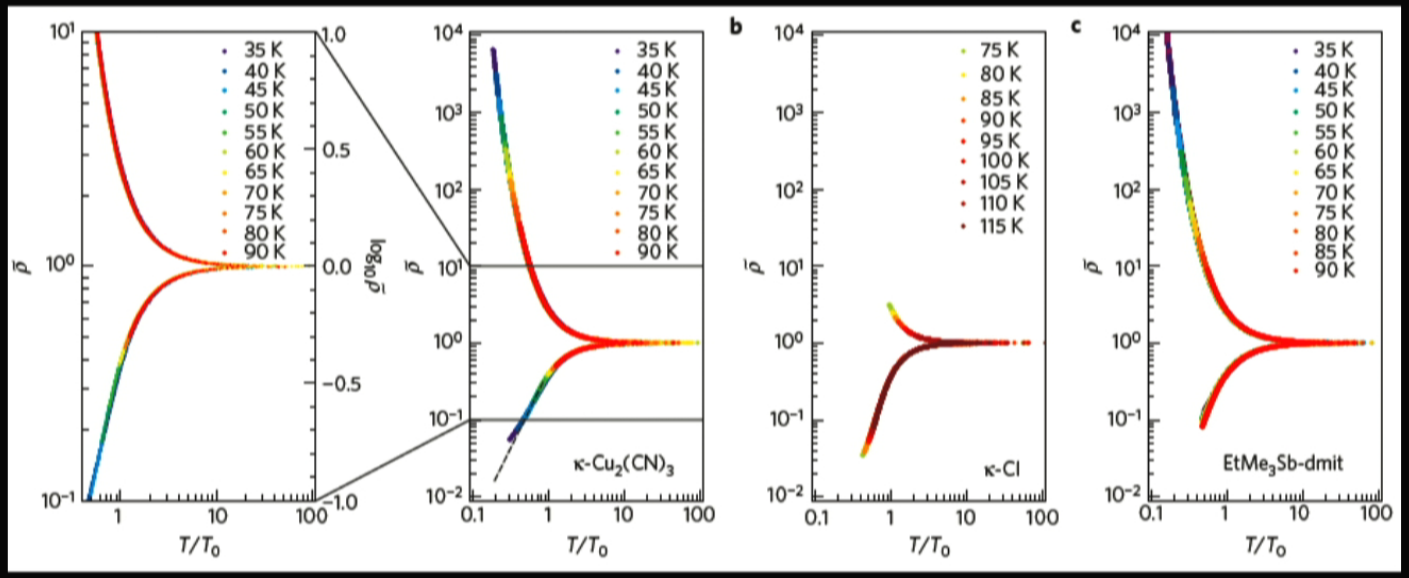
Perfect scaling
for $T > 1.5T_c$

Critical exponents, z ν, in metal-insulator transitions



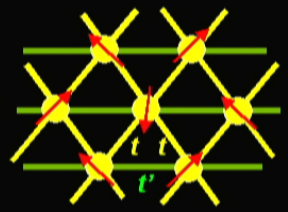
QC scaling --- nearly material -independent

Furukawa et al., Nat. Phys 11 (2015) 221



κ-$(ET)_2Cu_2(CN)_3$	κ-$(ET)_2Cu[N(CN)_2]Cl$	$EtMe_3Sb[Pd(dmit)_2]_2$
SL/SC	AFI/SC	SL/Metal
$z\nu=0.62\pm0.02$	$z\nu=0.49\pm0.01$	$z\nu=0.68\pm0.04$

Mott phase diagrams of quasi-triangular lattices



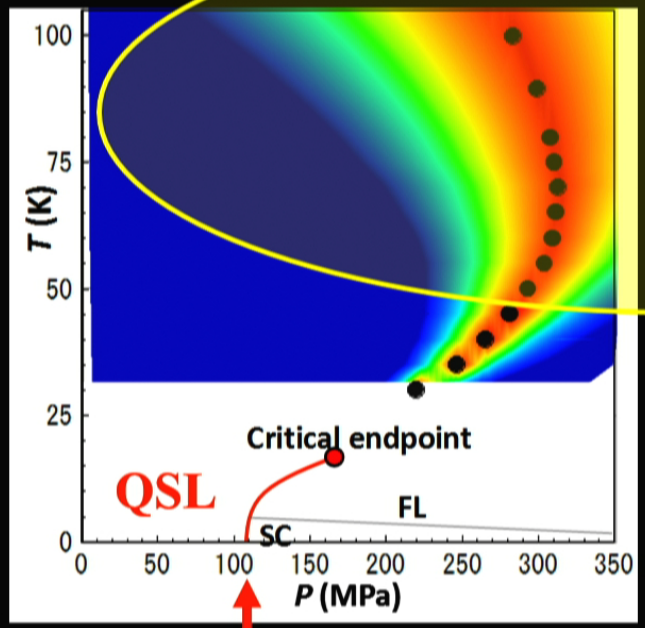
κ-$(ET)_2Cu_2(CN)_3$
t'/t=0.80-1.0

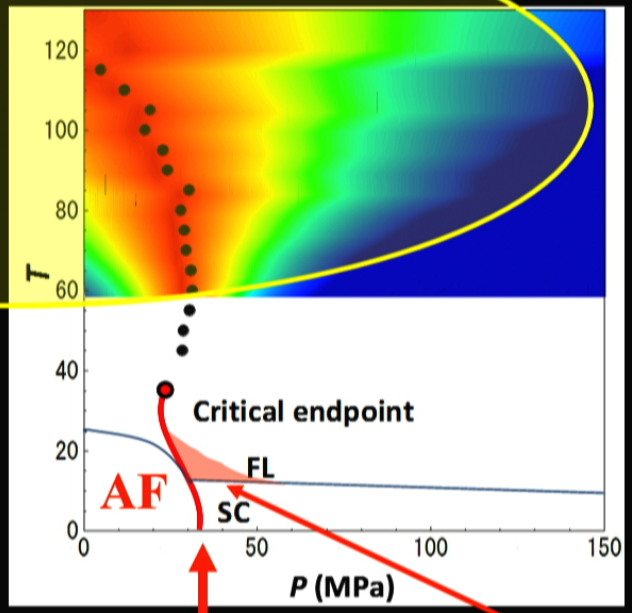
frustrated

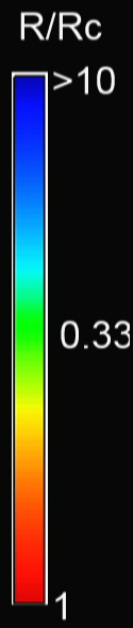
κ-$(ET)_2Cu[N(CN)_2]Cl$
t'/t=0.44-0.75

less frustrated

Similar QC behavior at high T







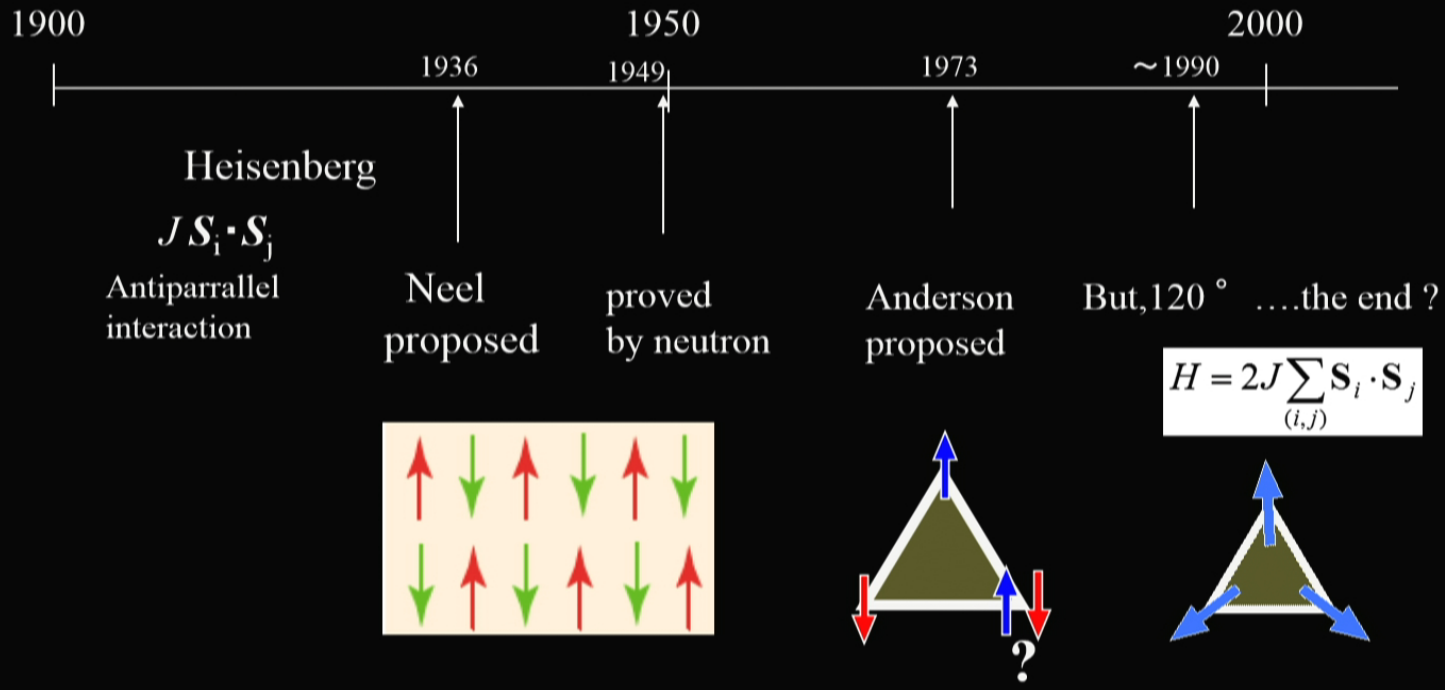
Weak Mott, Low Tc

Strong Mott, High Tc, Pseudo-gap

Remaining degree of freedom in Mott insulator

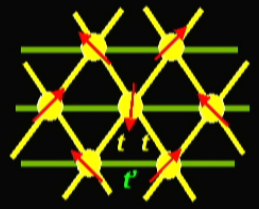
That's spin

Spins orders or not ???

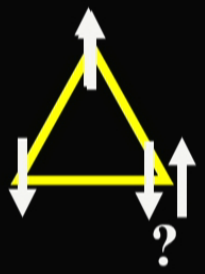


Quantum spin liquid:
the spin version of liquid He

Spins ordered or in a liquid ?



Spin liquid



κ-$(ET)_2Cu_2(CN)_3$

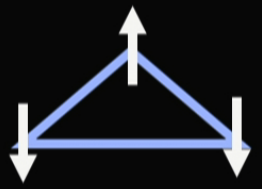
t'/t = 1.06 (0.8)

No ordering

J=250 K

Shimizu et al.,
PRL91 (2003) 107001

Antiferromagnet



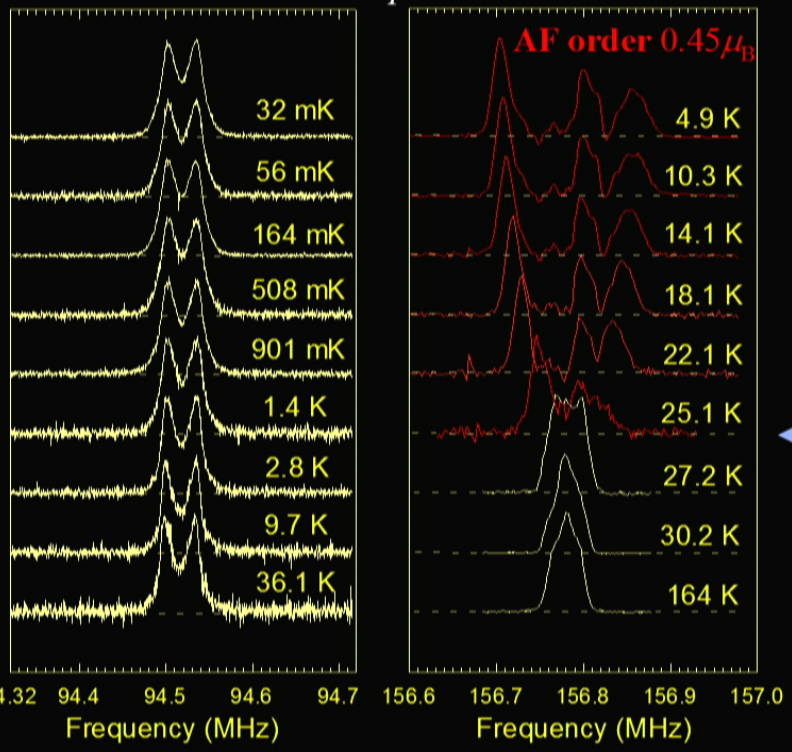
κ-$(ET)_2Cu[N(CN)_2]Cl$

t'/t = 0.75 (0.44)

← AF ordering

Miyagawa et al.,
PRL75 (1995) 1174

^1H NMR spectrum



Low-lying spin excitations in κ-$(ET)_2Cu_2(CN)_3$

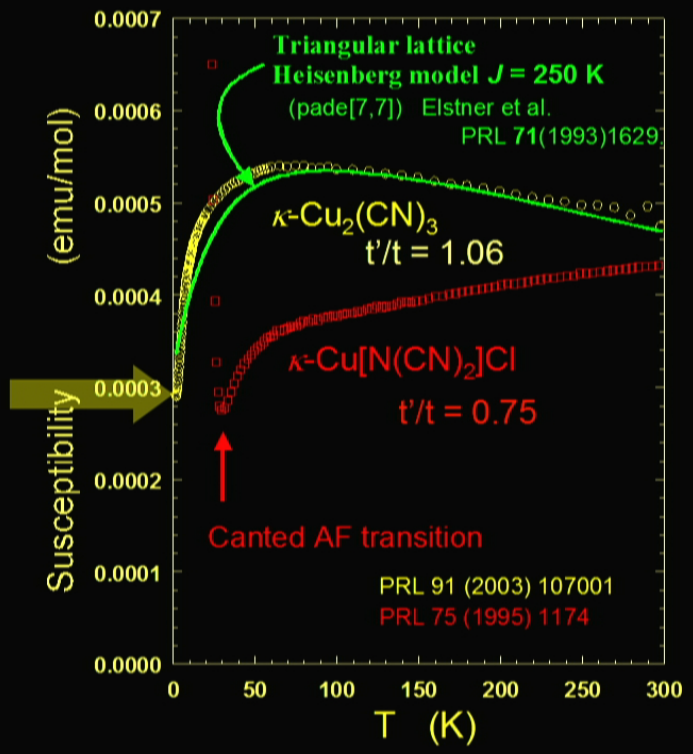
Wilson ratio ~ 1.6 ➡ *Degenerate Fermionic objects without charge*

Spinon Fermi Liq. ?

Motrunich,
P. A. Lee,
…..

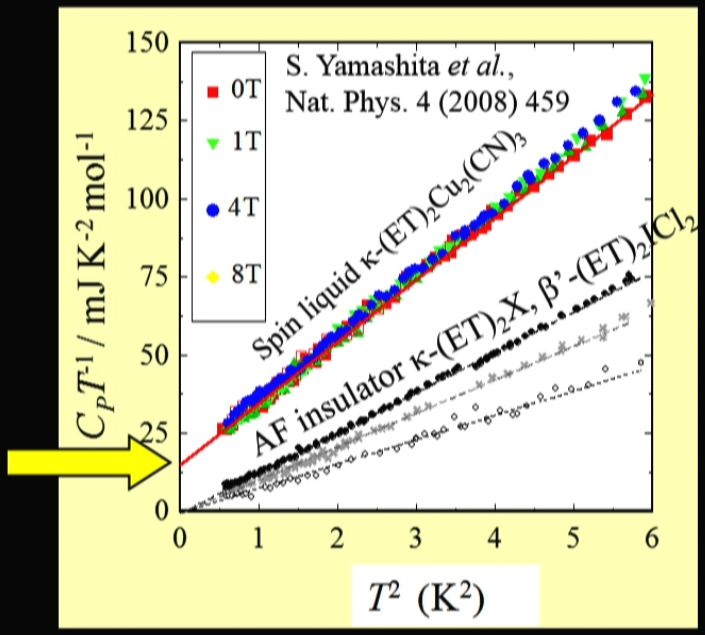
Spin susceptibility

$\chi_{spin} = 3 \times 10^{-4}$ emu/mol



Specific heat

$\gamma = 13$ mJ/K²mol

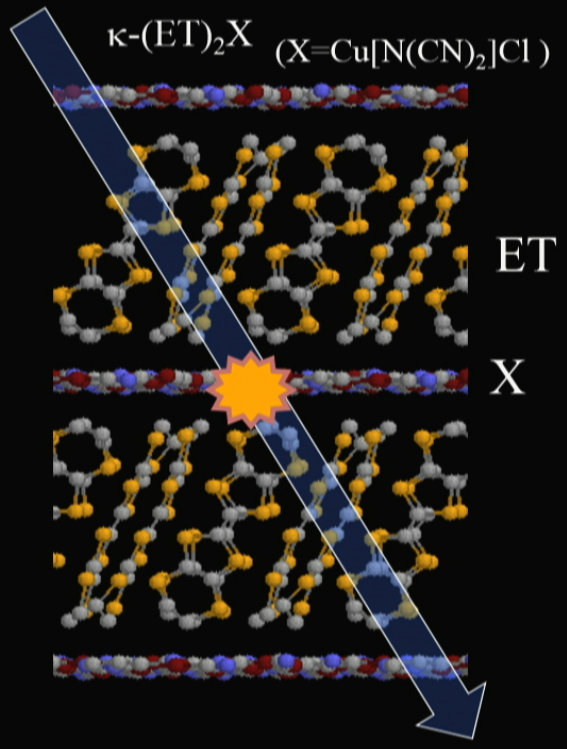


Thermal conductivity → a tiny gap, 0.46 K.

M. Yamashita et a., Nat. Phys. 5 (2009) 44

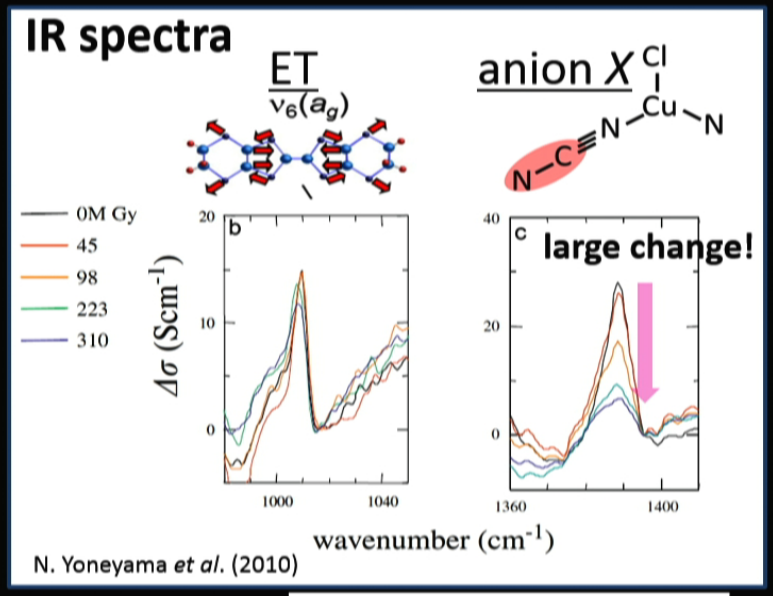
Antiferromagnet disordered by X-ray irradiation

X-ray irradiation to AFM



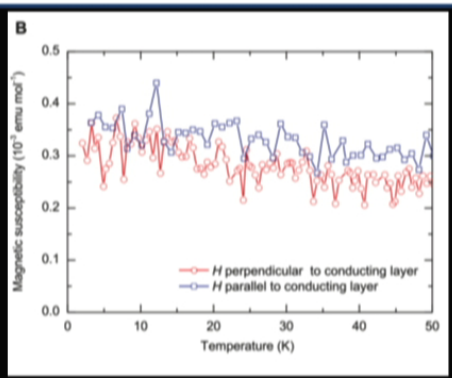
T. Sasaki, *Crystals* **2**, 374 (2012)

Damage in insulating layers



χ_{spin}

No Curie spins !



Antiferromagnet, when disordered, goes to spin liquid

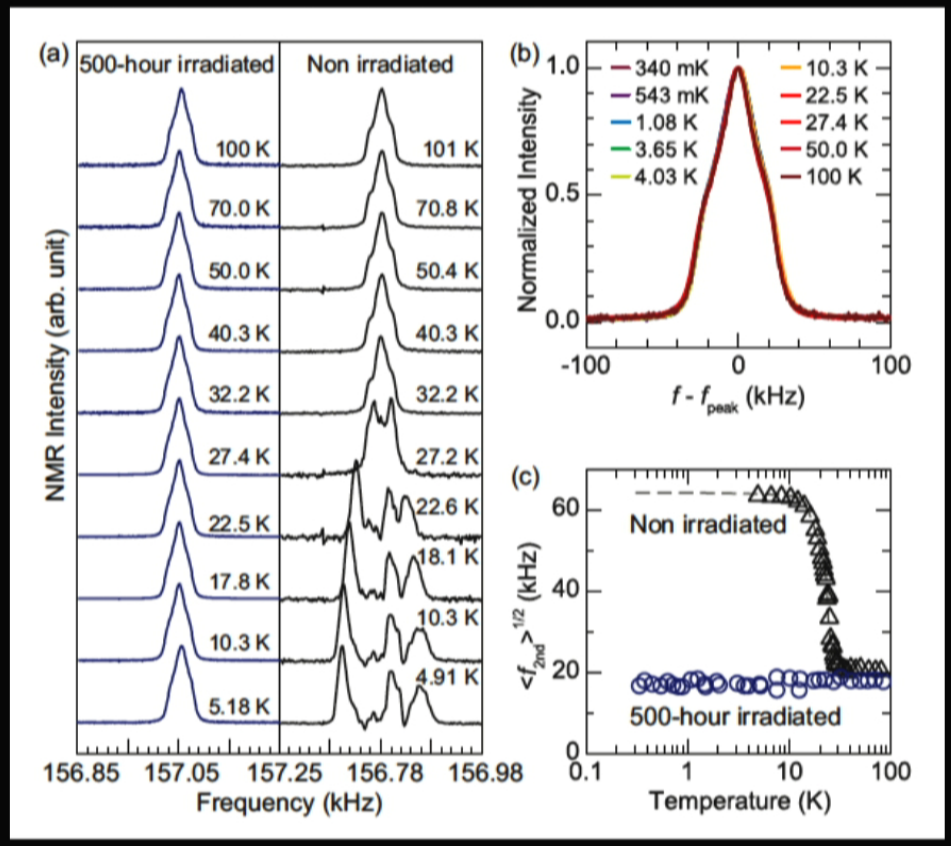
-- quantum disorder by quenched disorder --

AF ordering is gone with X-ray irradiation

κ-$(ET)_2Cu[N(CN)_2]Cl$

^{1}H NMR spectra

Furukawa et al.,
PRL 115 (2015) 077001

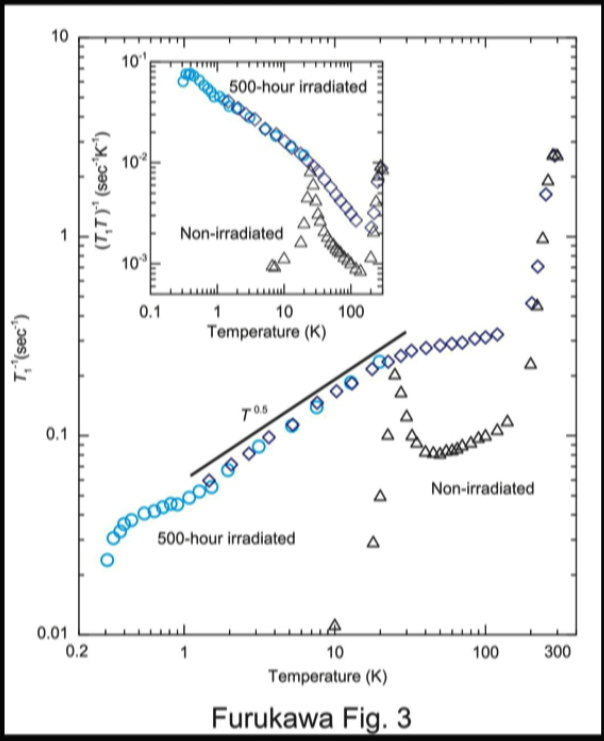


Furukawa et al.,
PRL 115 (2015) 077001

X-ray-irradiated κ-$(ET)_2Cu[N(CN)_2]Cl$

^{1}H NMR relaxation rate $1/T_1$

No critical slowing down

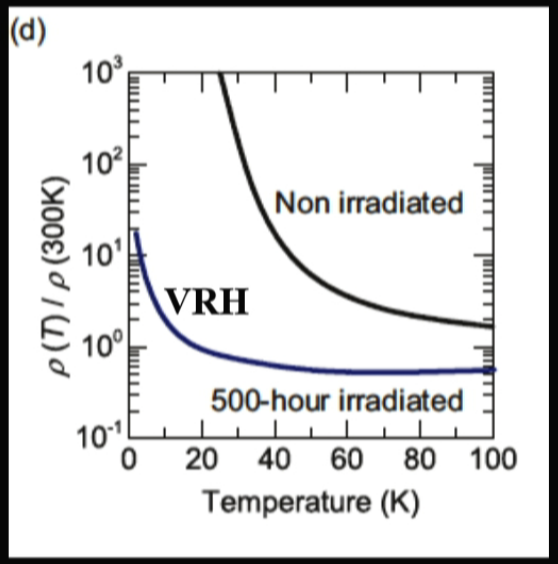


Furukawa Fig. 3

Resistivity

Gapped Mott insulator

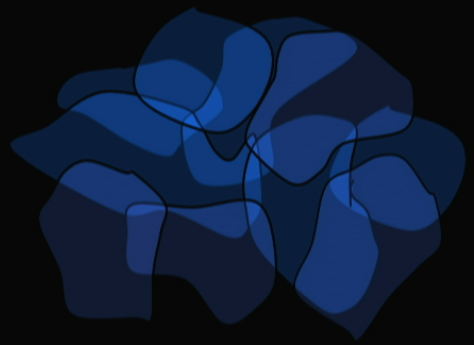
Gapless Mott-Anderson insulator



Two suggestions from experiments

Spin liquid *residing just behind frustrated AFM*

Spin liquid *ubiquitous in Mott-Anderson Insulator ?*

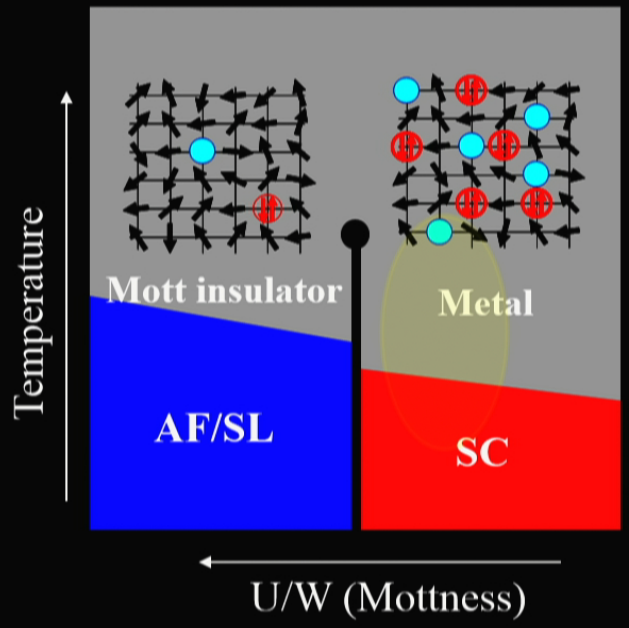


complicated interactions

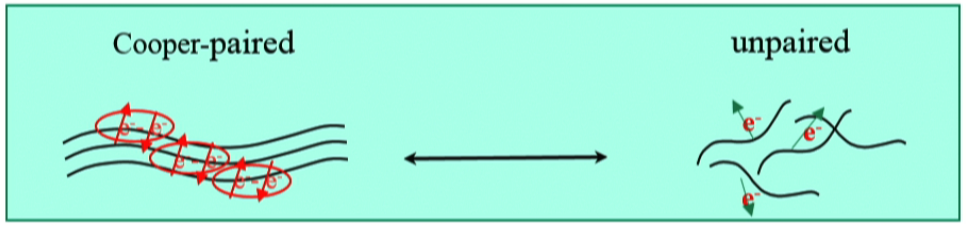
Spinon-deconfined chargeon-glass insulator ?

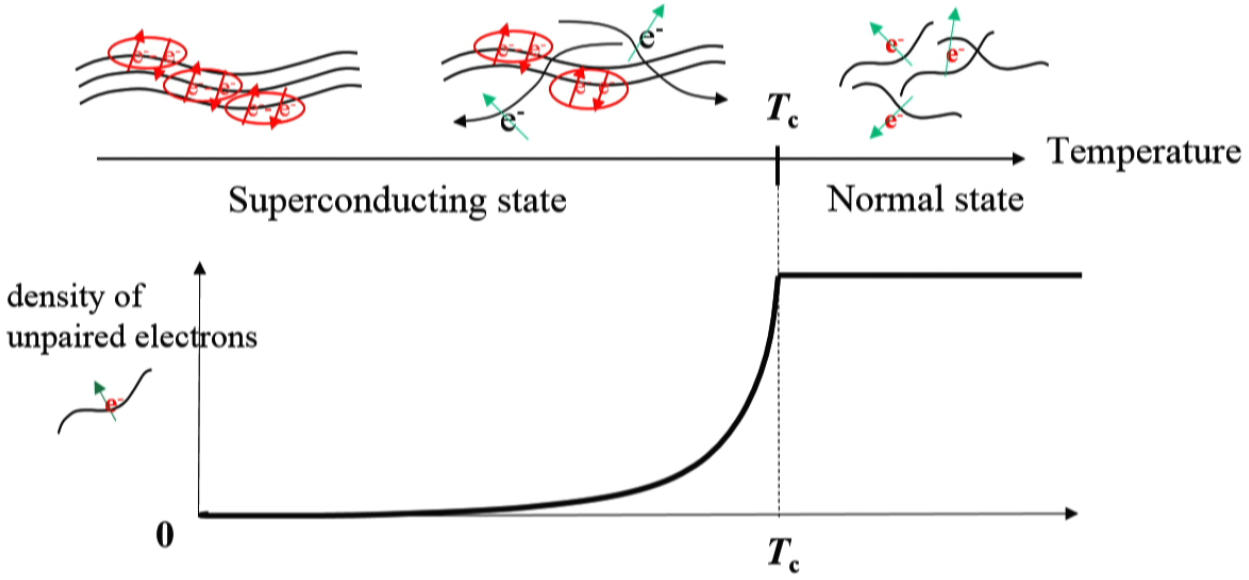
K.-S. Kim, *PRB* 73, 235115 (2006)
Senthil, *PRL* 109, 077205 (2012)

Preformed pairs in Metallic phase

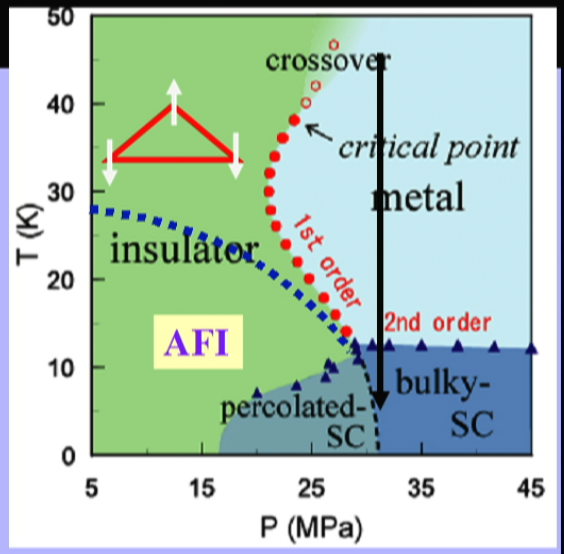


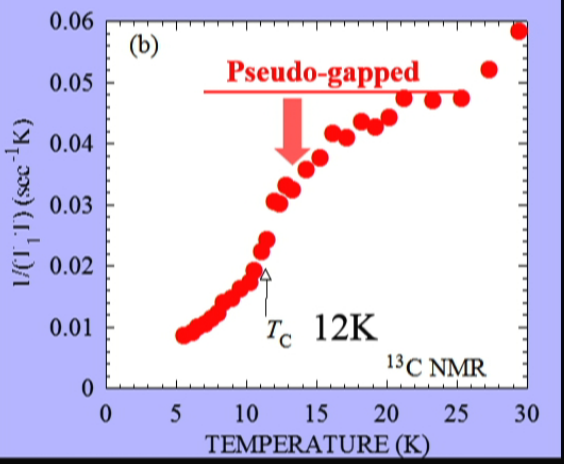
Superconductivity --- a sort of self-calalyzed electronic chemical reaction





Pseudo-gapped nearby AFM





Deuterated κ-Br

Miyagawa *et al.*, PRL89 (2002) 017003

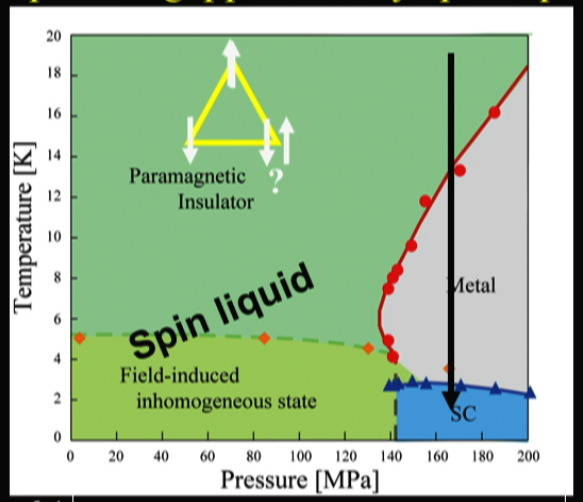
^{13}C NMR

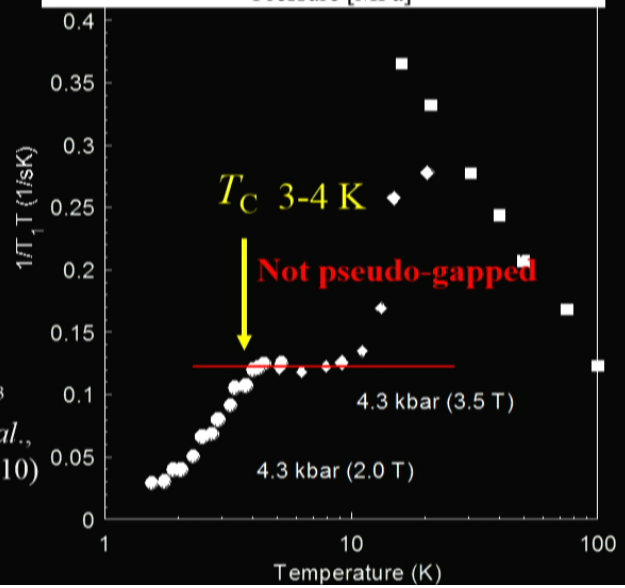
$1/T_1T$

κ-$Cu_2(CN)_3$

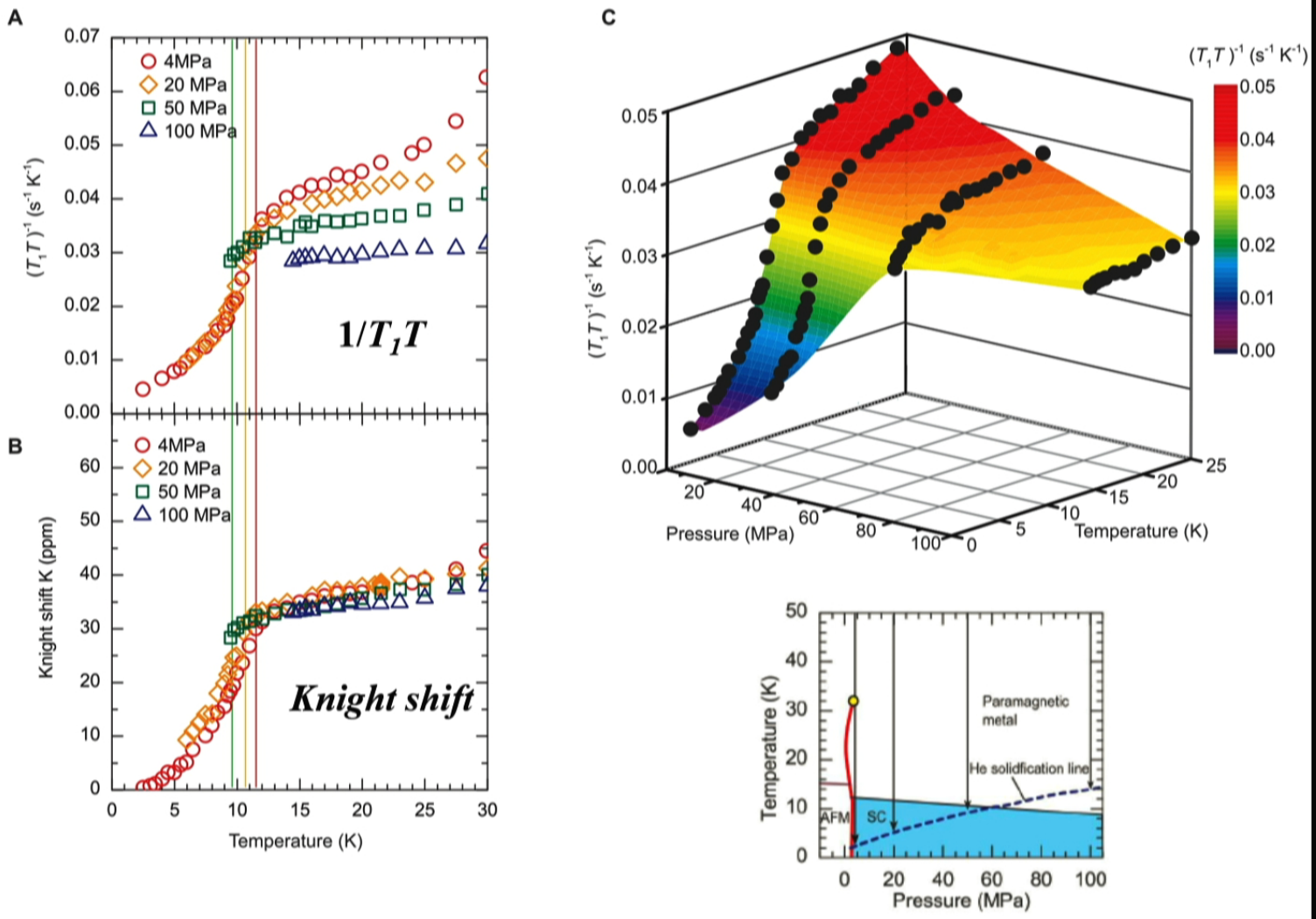
Shimizu *et al.*, PRB 81 (2010) 224508

Not pseudo-gapped nearby spin liq.

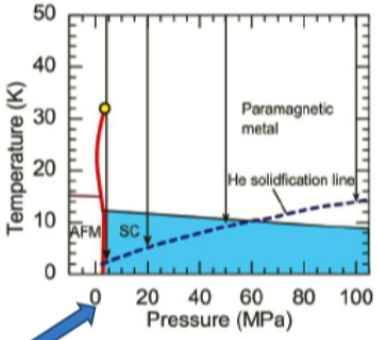




^{13}C NMR $1/T_1T$ and Knight shift near Mott boundary

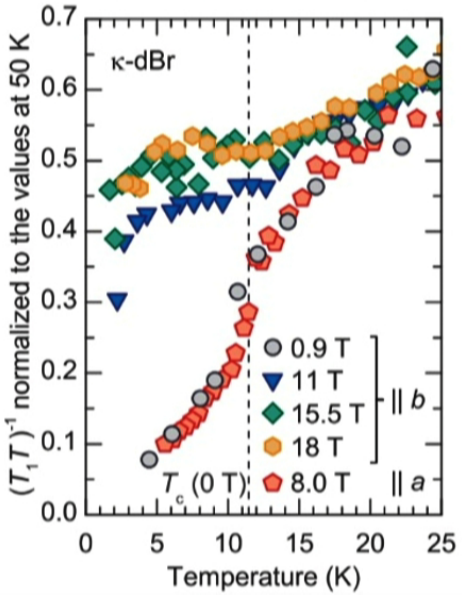


Pseudogap and SC suppressed simultaneously by magnetic field



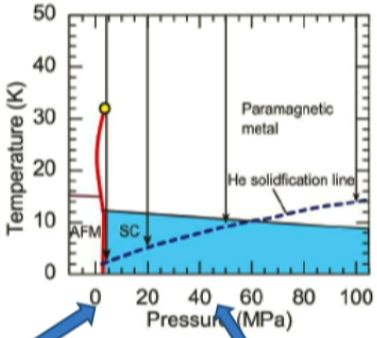
submitted

κ-(d[4,4], ET)$_2$Cu[N(CN)$_2$]Br



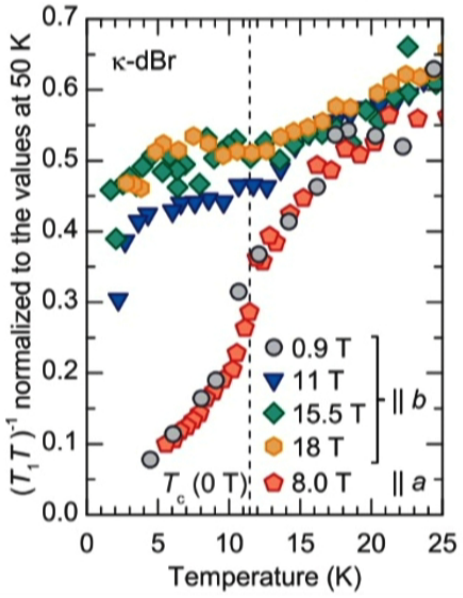
Pseudogap and SC suppressed simultaneously by magnetic field

Preformed Cooper pairs

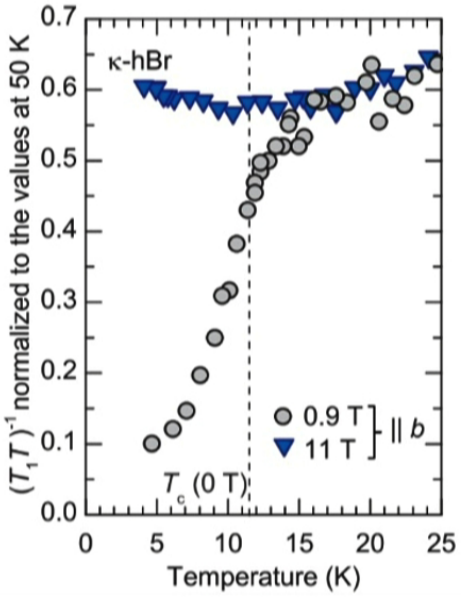


submitted

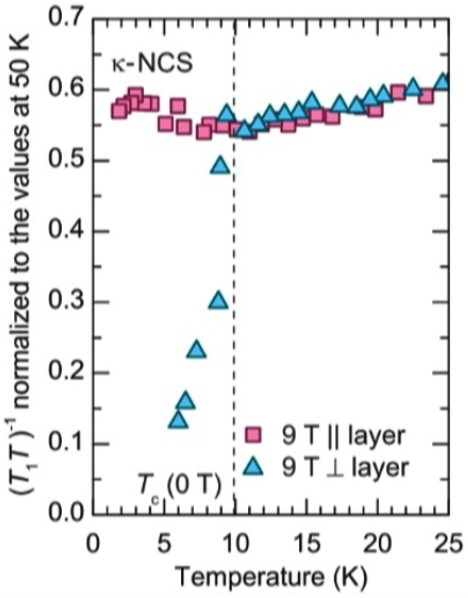
κ-(d[4,4], ET)$_2$Cu[N(CN)$_2$]Br

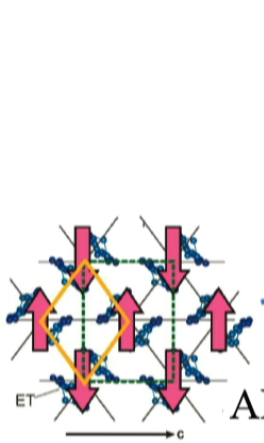


κ-(d[0,0], ET)$_2$Cu[N(CN)$_2$]Br

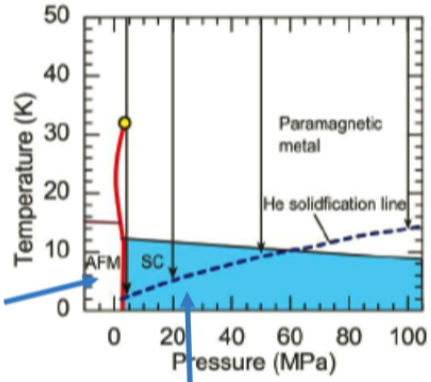


κ-(ET)$_2$Cu(NCS)$_2$

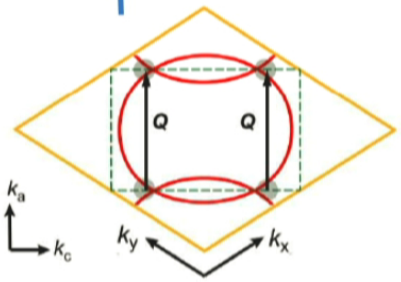




AFM



Fermi surface



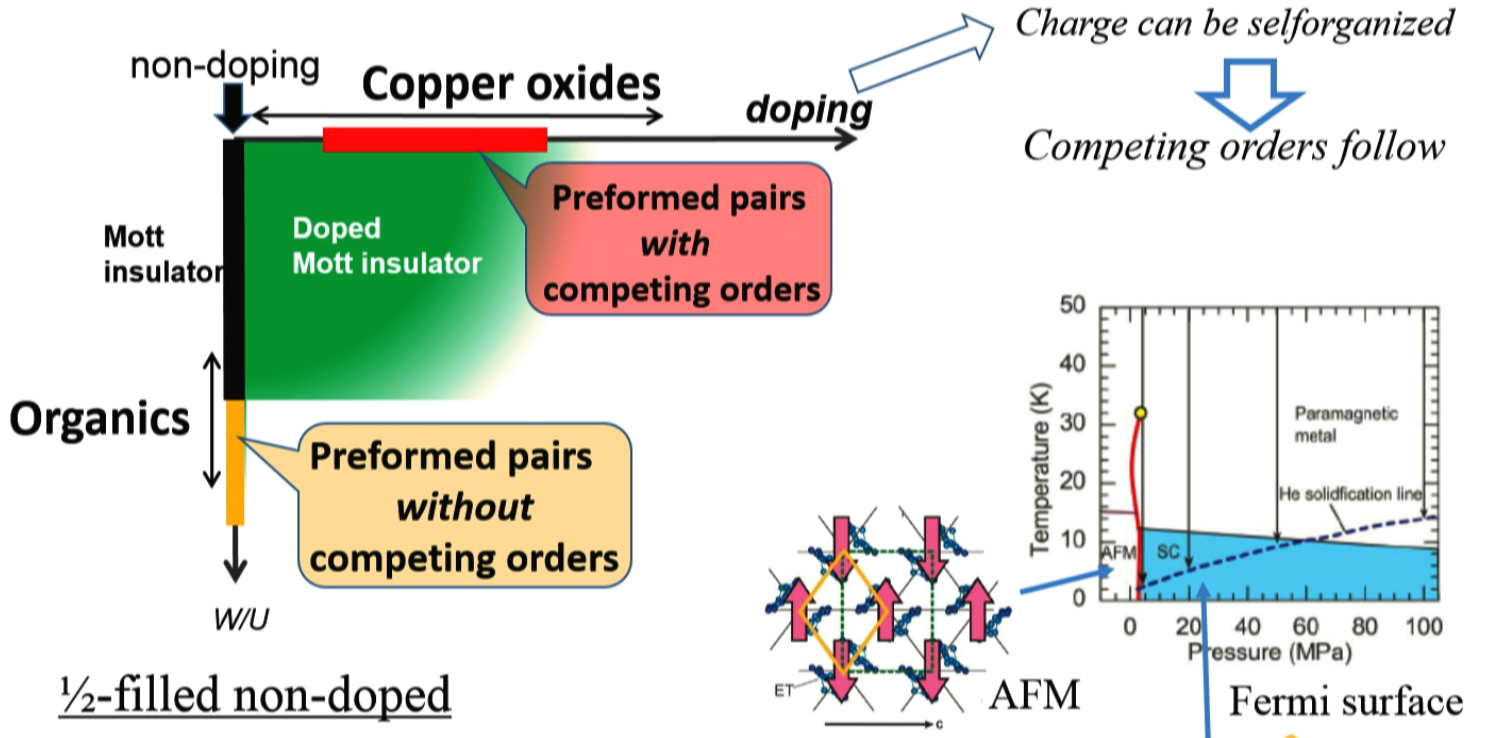
½-filled non-doped

Toward Mott localization, sites more singly occupied

Spin → more localized

phase → more uncertain

*Nernst effect; M.-S. Nam, Nature **449** (2007) 584*



½-filled non-doped

Toward Mott localization, sites more singly occupied

Spin → more localized → $Q=(\pi,\pi)$ AF fluctuations

phase → more uncertain → preformed pairs

Intertwined

Nernst effect; M.-S. Nam, Nature ***449*** *(2007) 584*

Doping a spin liquid

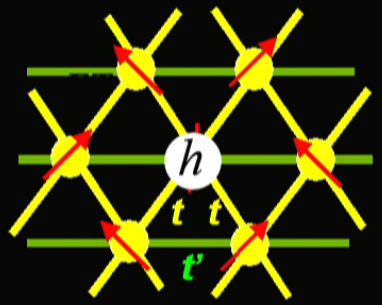
A doped triangular lattice

κ-$(ET)_4Hg_{2.89}Br_8$

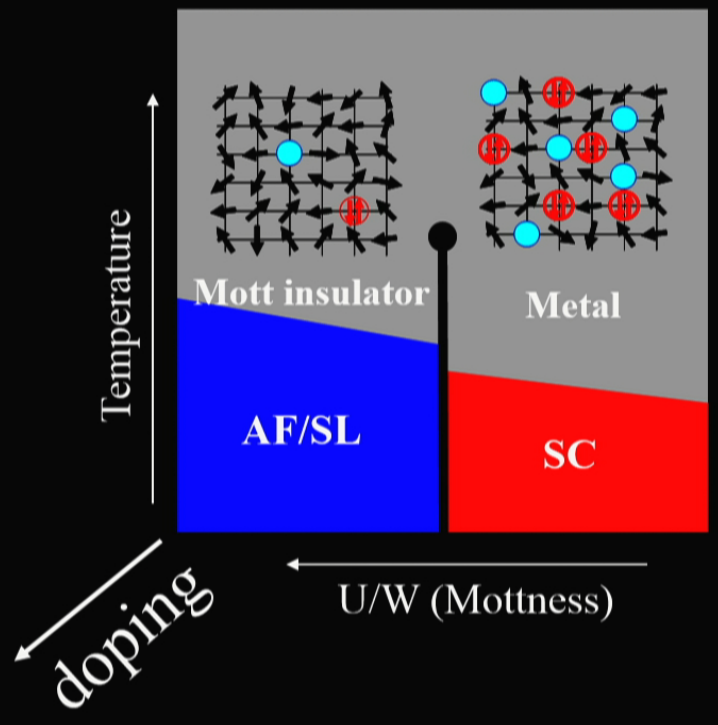
3-δ

hole doping (11%)

t'/t =1.02



Lyubovskaya et al. (1987)



Doping a spin liquid

A doped triangular lattice

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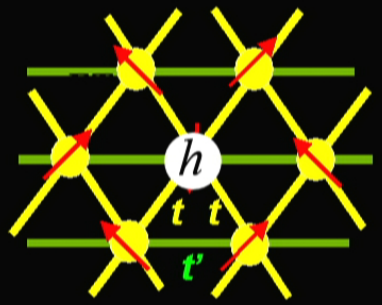
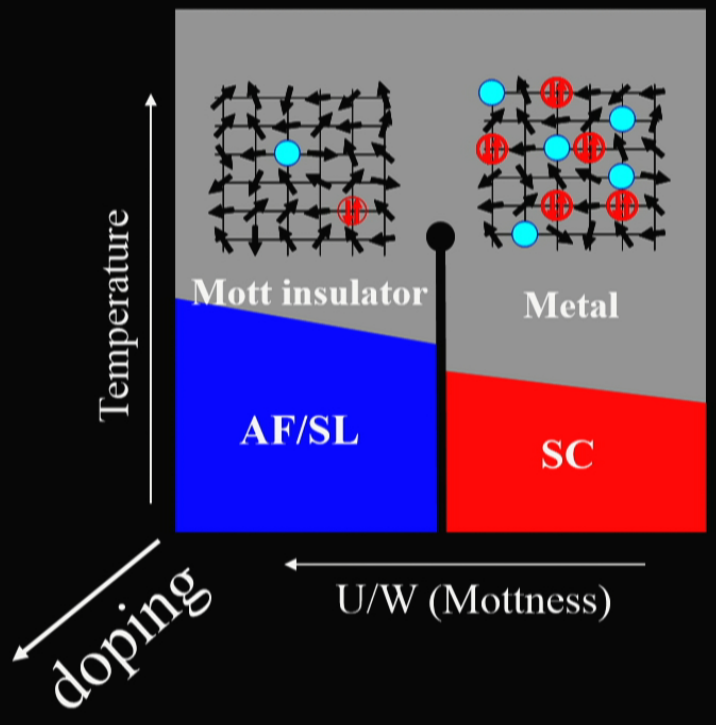


Lyubovskaya et al. (1987)



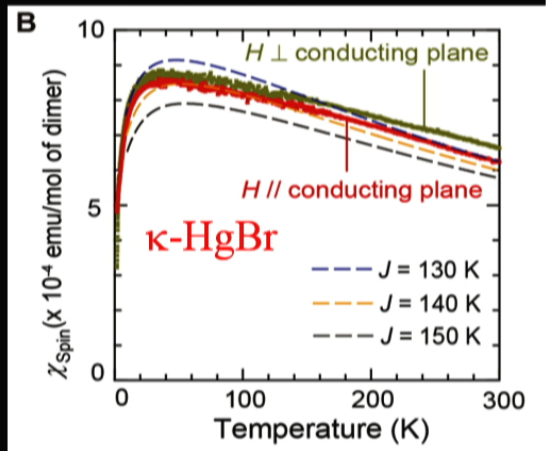
κ-$(ET)_4Hg_{2.89}Br_8$ *a doped triangular lattice (11% hole doping)*

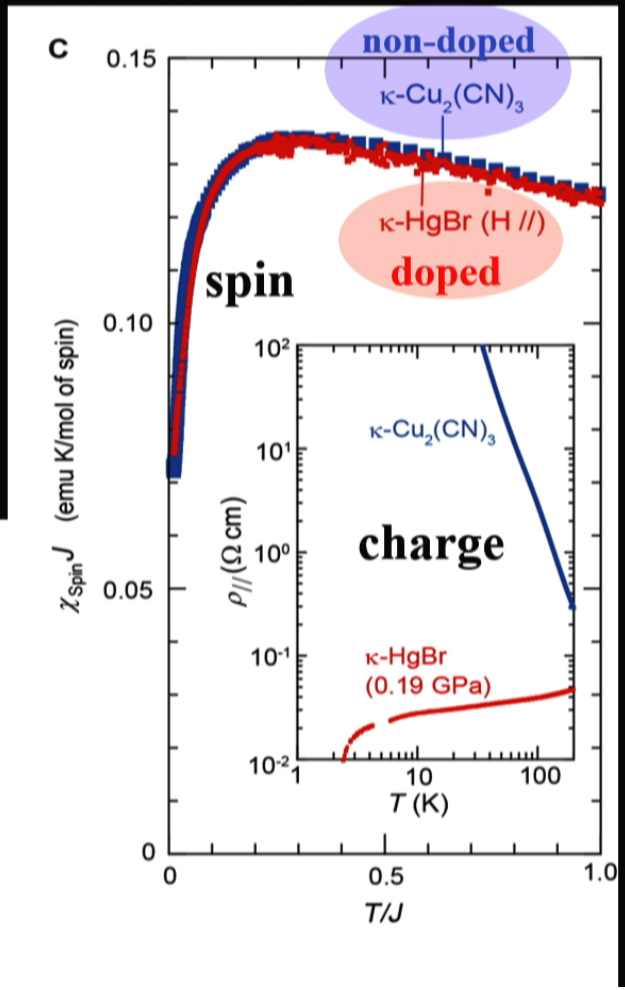
submitted

Spin liquid nature !

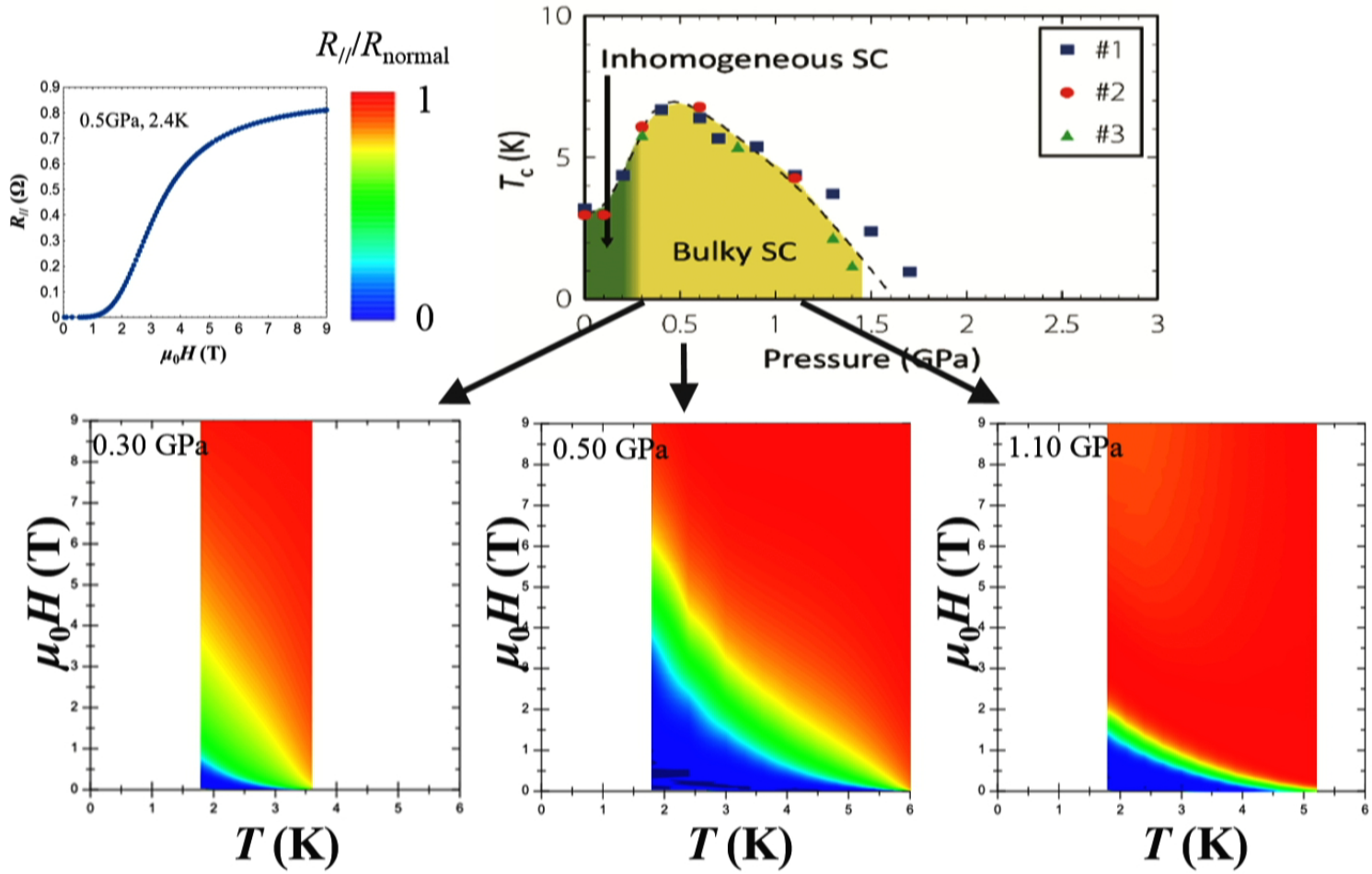
Spin-charge separation !

Triangular-lattice Heisenbeg model
$J = 140$ K





Upper critical field H_{C2}

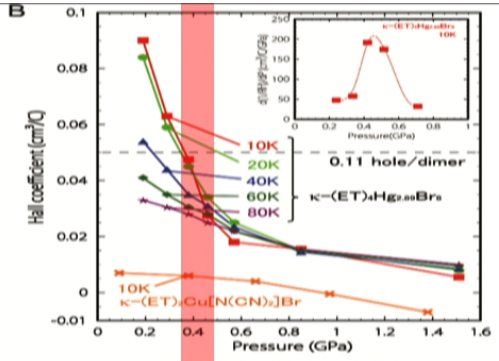


Doped spin liquid

Correlated metal

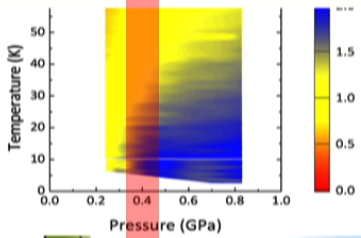
low carrier density

high carrier density



non-Fermi liquid

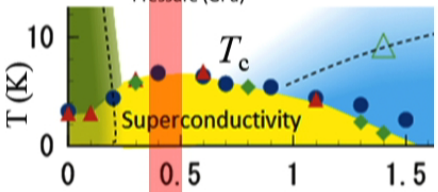
$\rho \sim T$

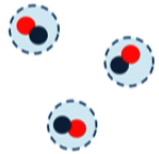


Fermi liquid

$\rho \sim T^2$

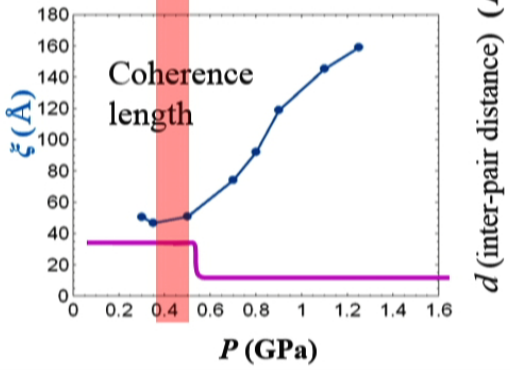
SC dome

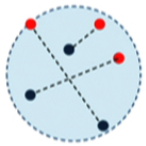




$d \sim \xi$
BEC like

$k_F \xi \sim 1$





$d << \xi$
BCS like

$k_F \xi \sim 10$

conclusion

Non-doped Mott systems κ-(ET)$_2$X

Similarity at high temperatures
Quantum critical behavior

Variety at low temperatures
AF/SL, SC, PG, strong/weak Mott transitions

Doped triangular lattice κ-(ET)$_4$Hg$_{2.89}$Br$_8$

Realization of a doped spin liquid

Deconfined non-Fermi liquid with spin-charge entanglement