Strong correlations in organic charge transfer salts: superconductors, Mott insulators, bad metals and spin liquids

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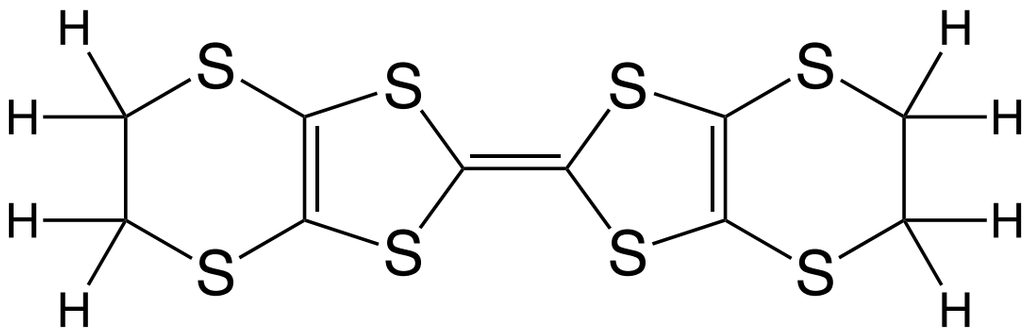
COPE

Some reasons to study organic molecular materials

- Fascinating range of strongly correlated q2d systems - I will limit myself to half filled systems, but quarter filled and non-stoichiometric salts also exist
  - Mott transition driven by bandwidth control & wide range of associated phenomena
- Clean systems
  - Typically stoichiometric
  - Quantum oscillations are readily seen (simple, well understood Fermi surfaces)
- Low energy scales
  - T_c may only be ~10 K [bad for applications]
  - But this also means "large" fields only means ~10 T [good for experimentalists]
- Chemical control
  - Organic chemists have can make subtle changes to the molecular structure, which allow them to tune the emergent physics

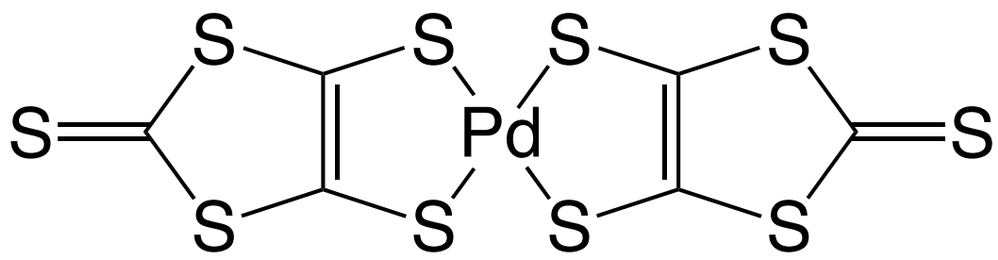
Overview

κ-(BEDT-TTF)$_2X$



- Structure and phase diagram
- Model Hamiltonian
- Metal-insulator transition
- Spin liquid
- Strongly correlated metal
- Nernst effect
- Superconductivity
- Parameters for the model Hamiltonian

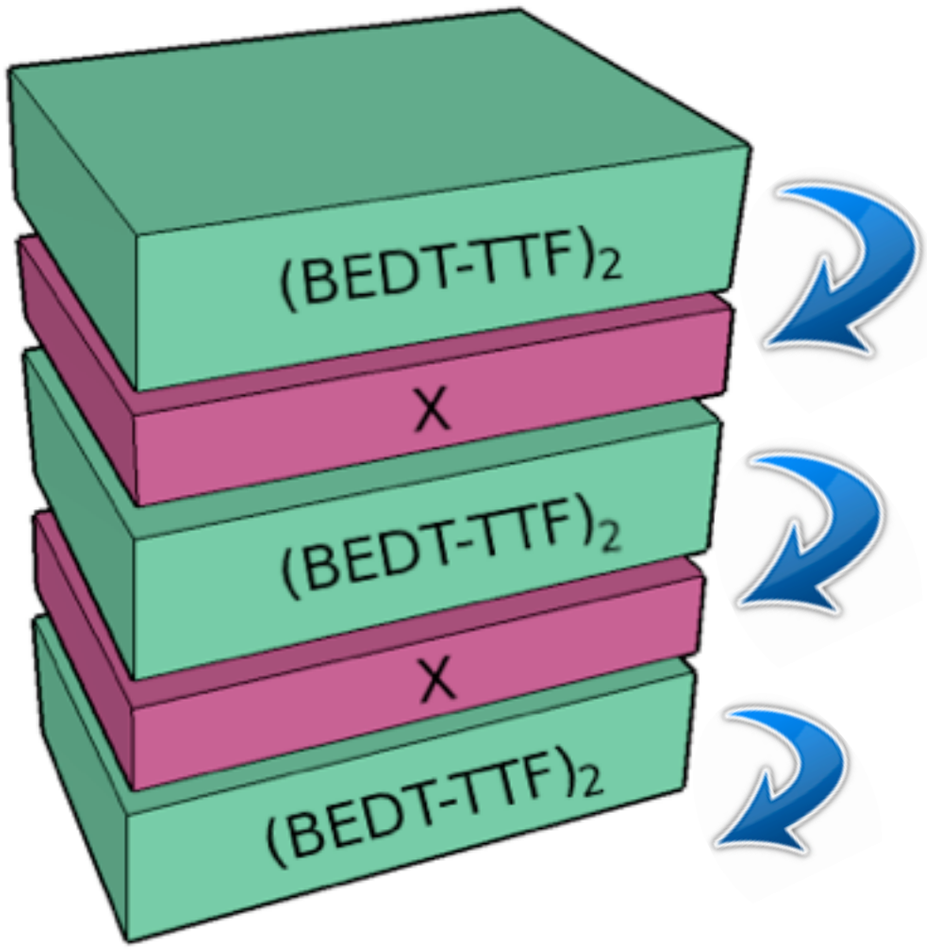
β'-Z[Pd(dmit)$_2$]



- Structure and phase diagram
- Model Hamiltonian
- Metal-insulator transition
- Spin liquid
- Valence bond solid
- Charge ordered insulator
- Superconductivity

Structure of κ-ET_2X (ET=BEDT-TTF)

For a review see BJP and McKenzie, JPCM **18**, R827 (2006)

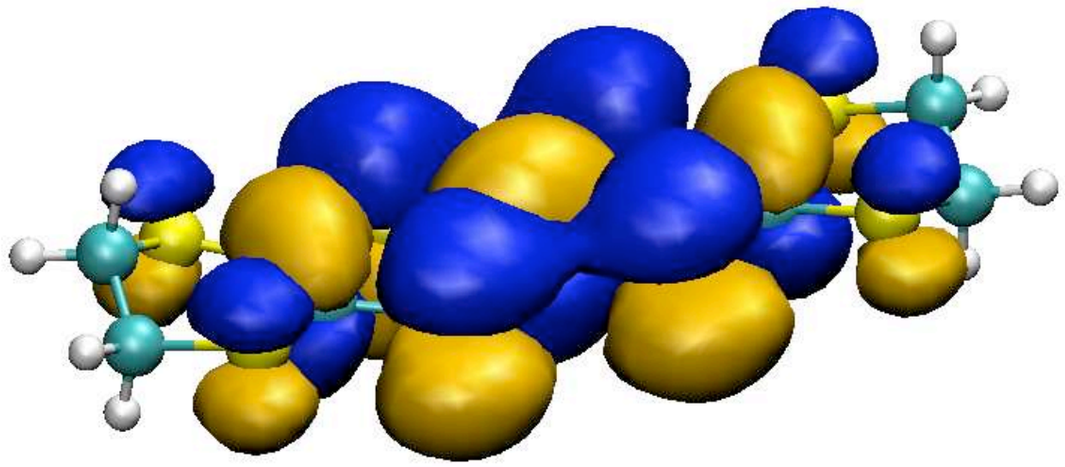


Charge transfer

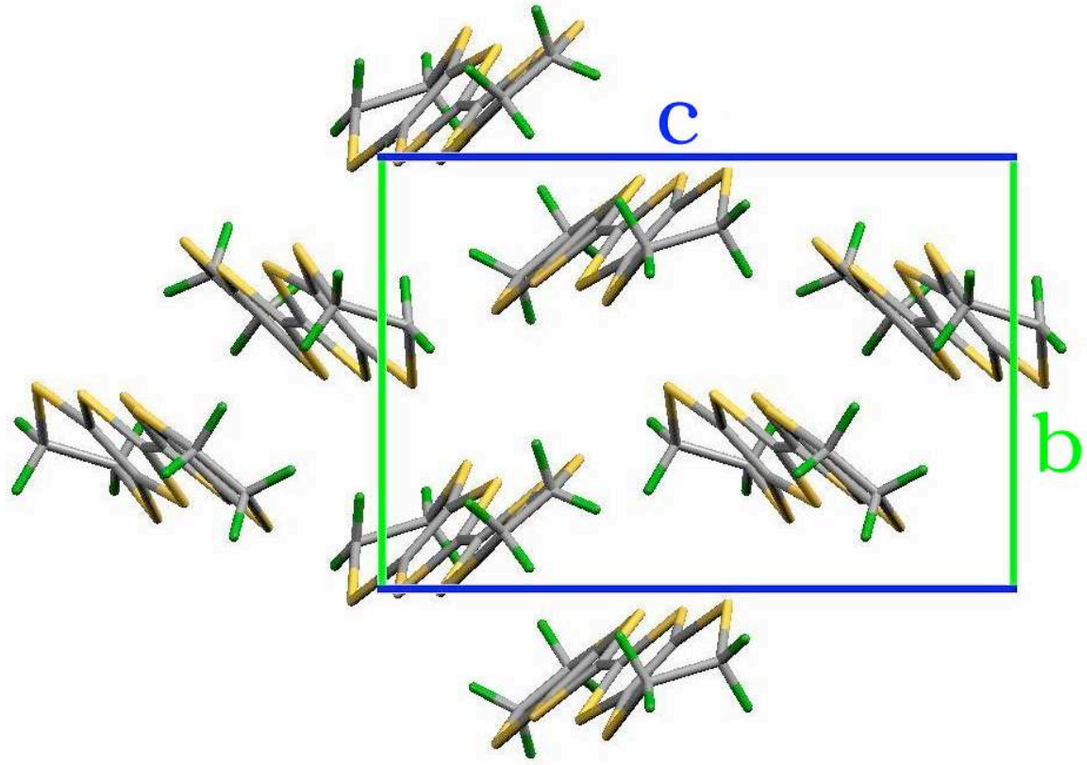
$$\kappa\text{-}(\mathrm{ET})_2^+ X^-$$

X is a monovalent anion, e.g., I_3, so the charge is localised in the anion layer, but the holes in the ET layer are not localised at a non-interacting level

Molecular orbitals



Highest occupied molecular orbital (HOMO) of a neutral monomer from DFT [Scriven and BJP, J. Chem. Phys. '09]



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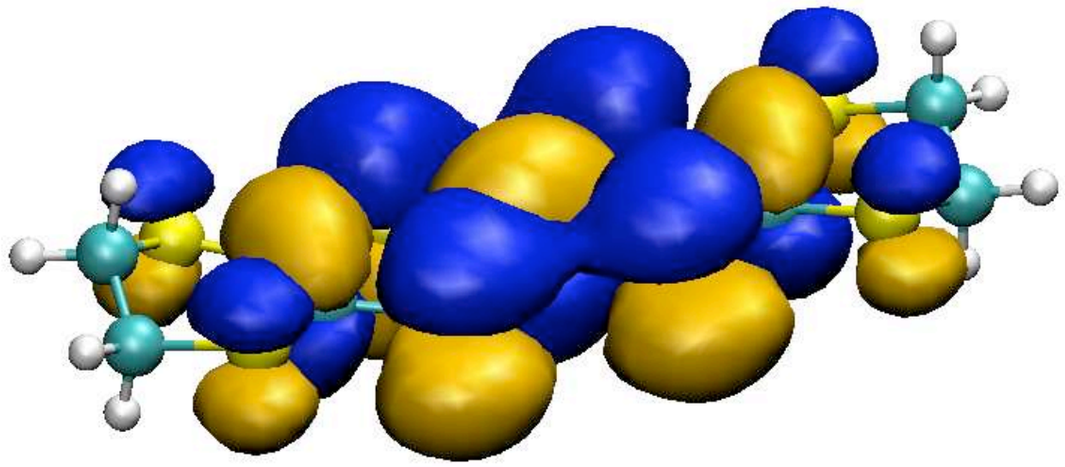

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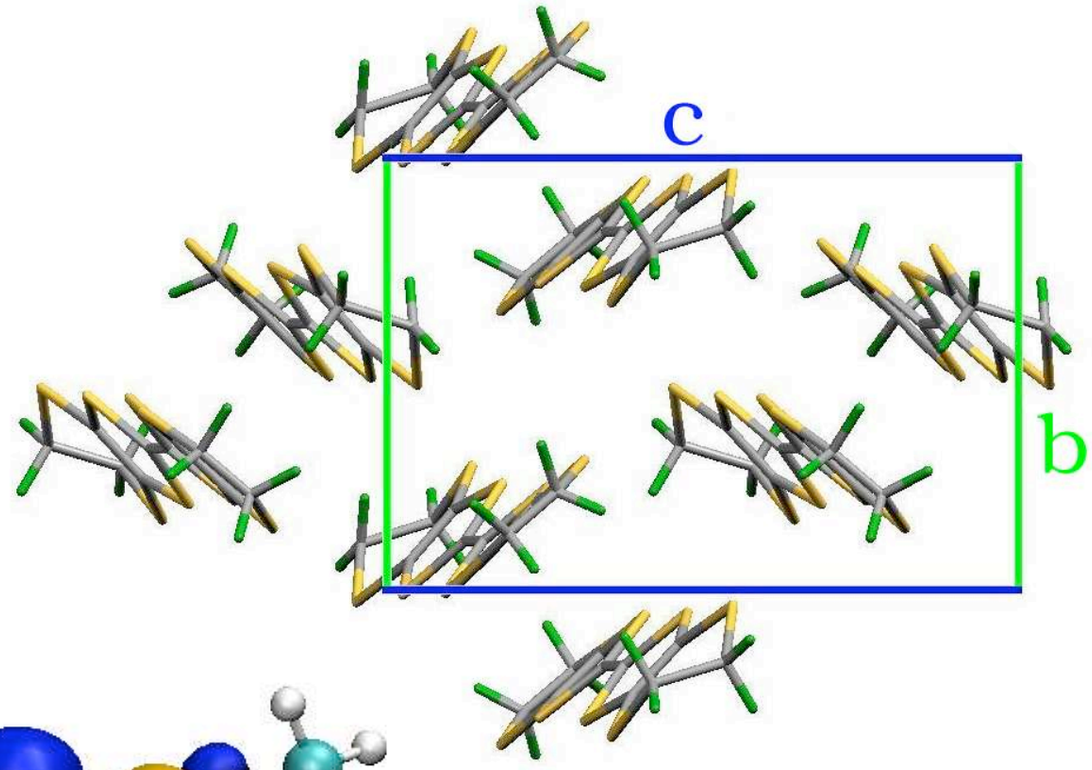

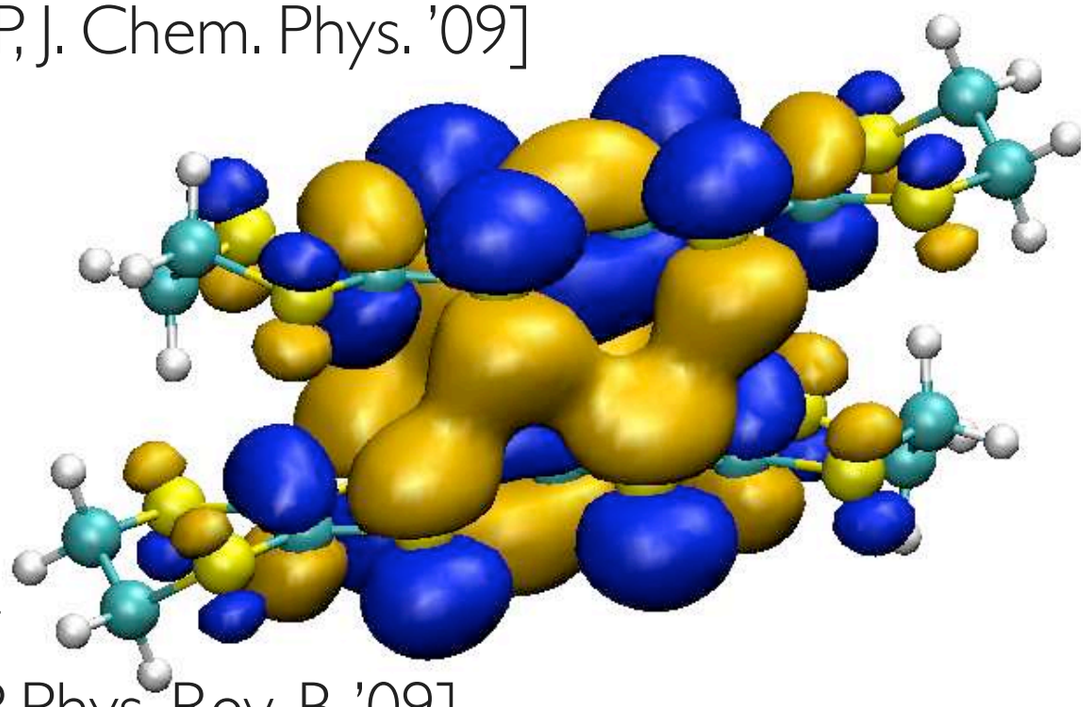

HOMO of ET_2^+
[Scriven and BJP, Phys. Rev. B '09]

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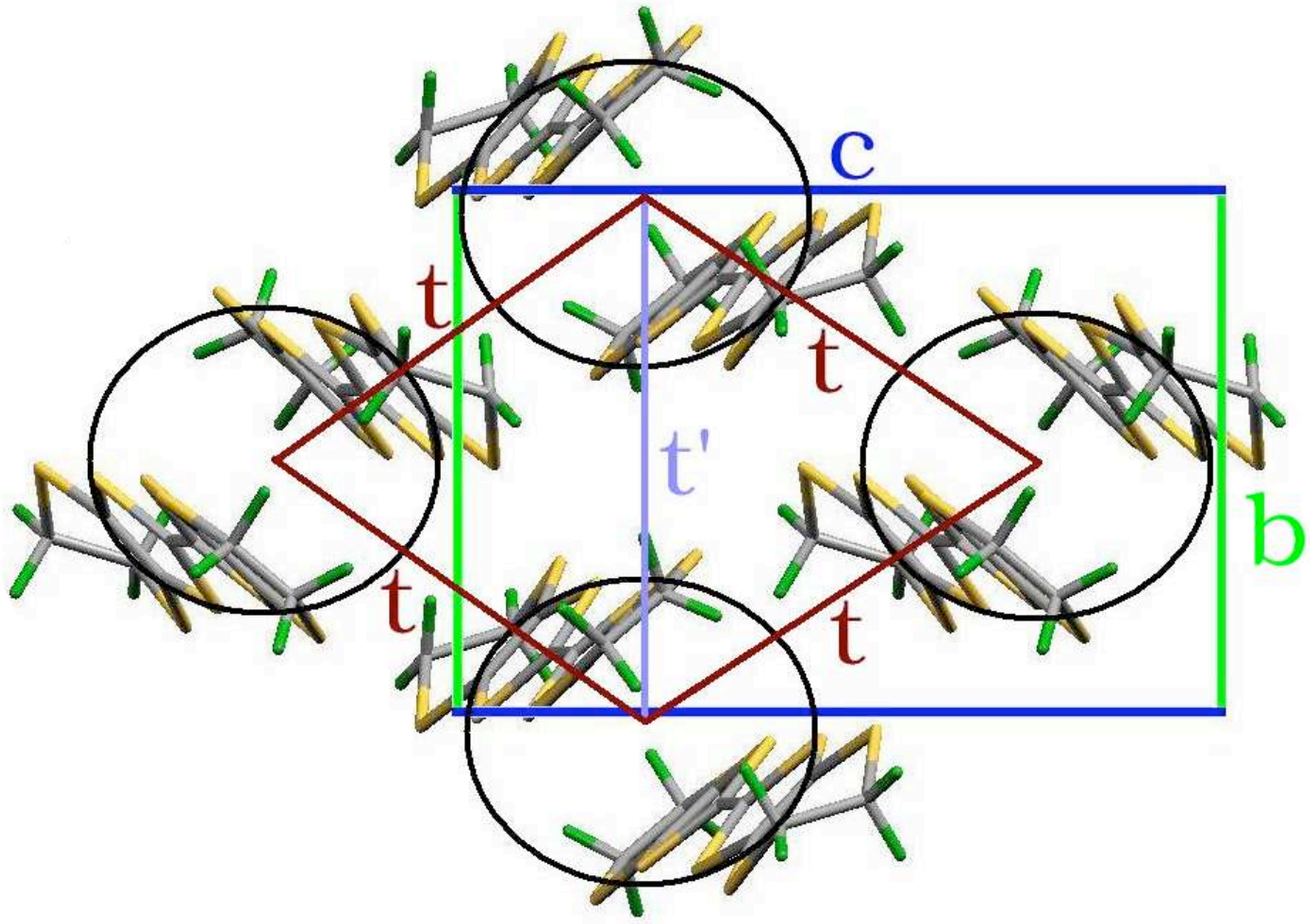
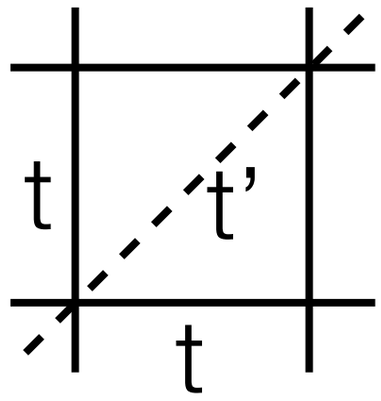


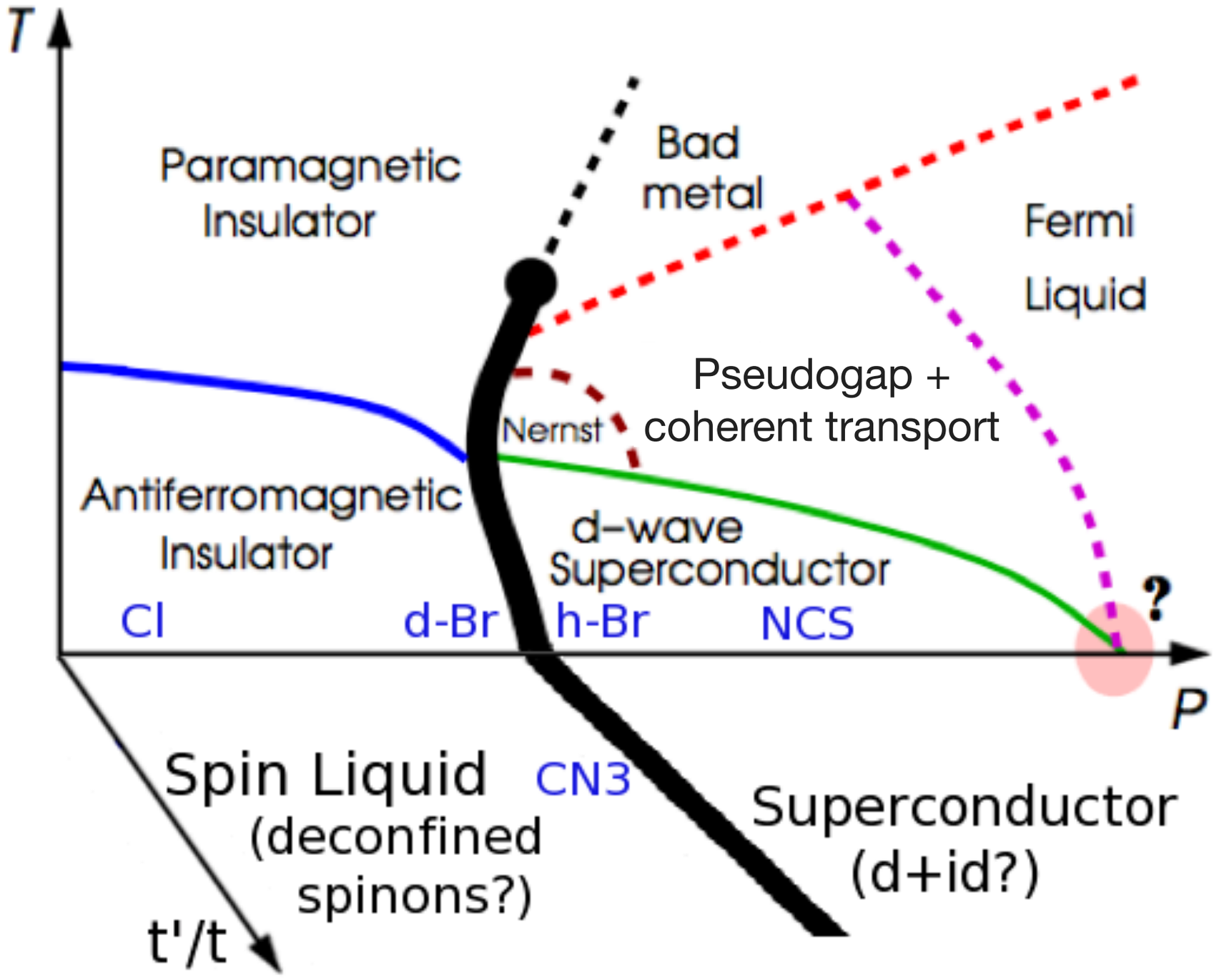


half filled

$$\hat{\mathcal{H}} = -t \sum_{\langle ij \rangle \sigma} \hat{c}^{\dagger}_{i\sigma} \hat{c}_{i\sigma} + U \sum_{i} \hat{n}_{i\sigma} \hat{n}_{i\sigma}$$

Experimental phase diagram

For a review see BJP and McKenzie, JPCM **18**, R827 (2006)



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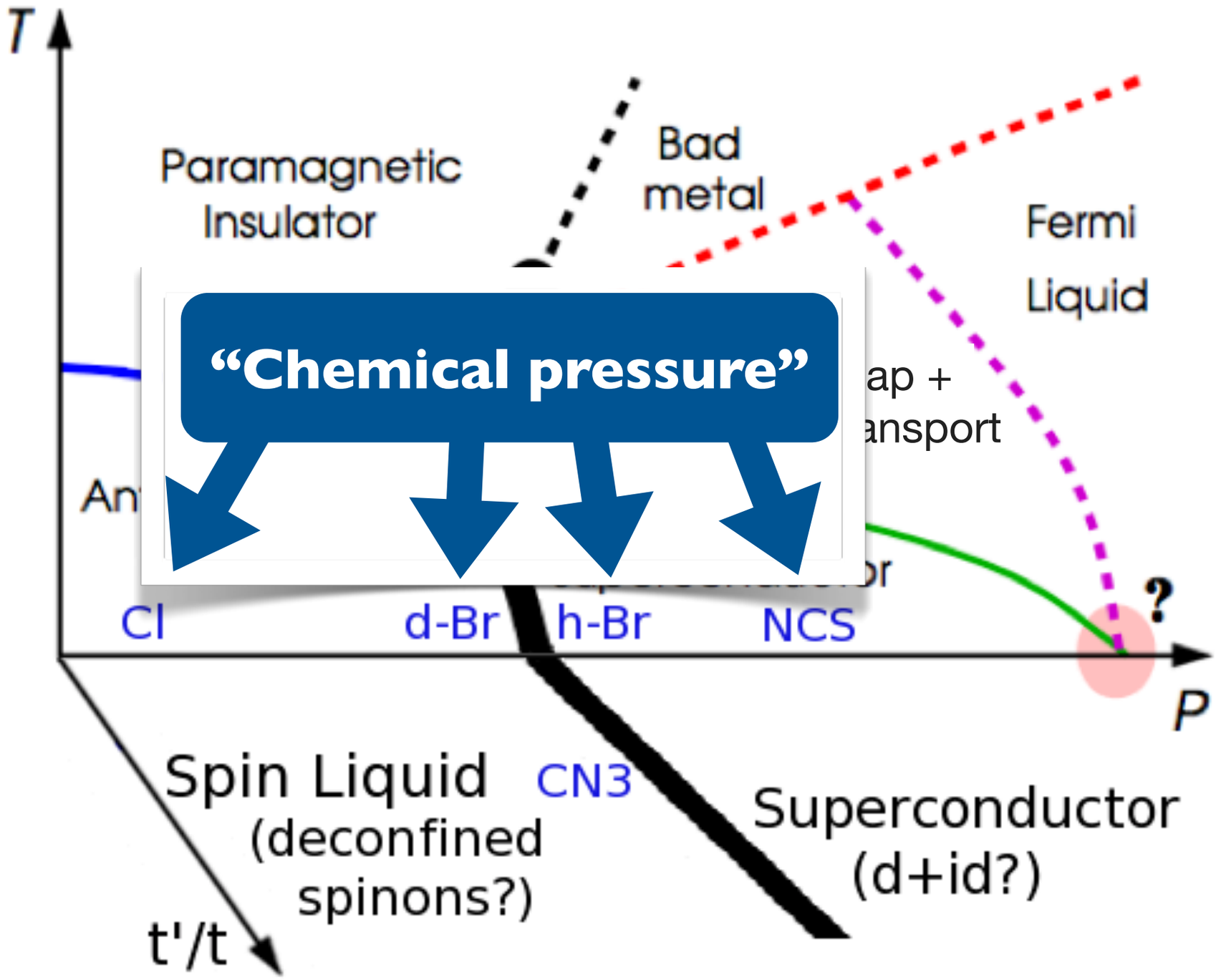

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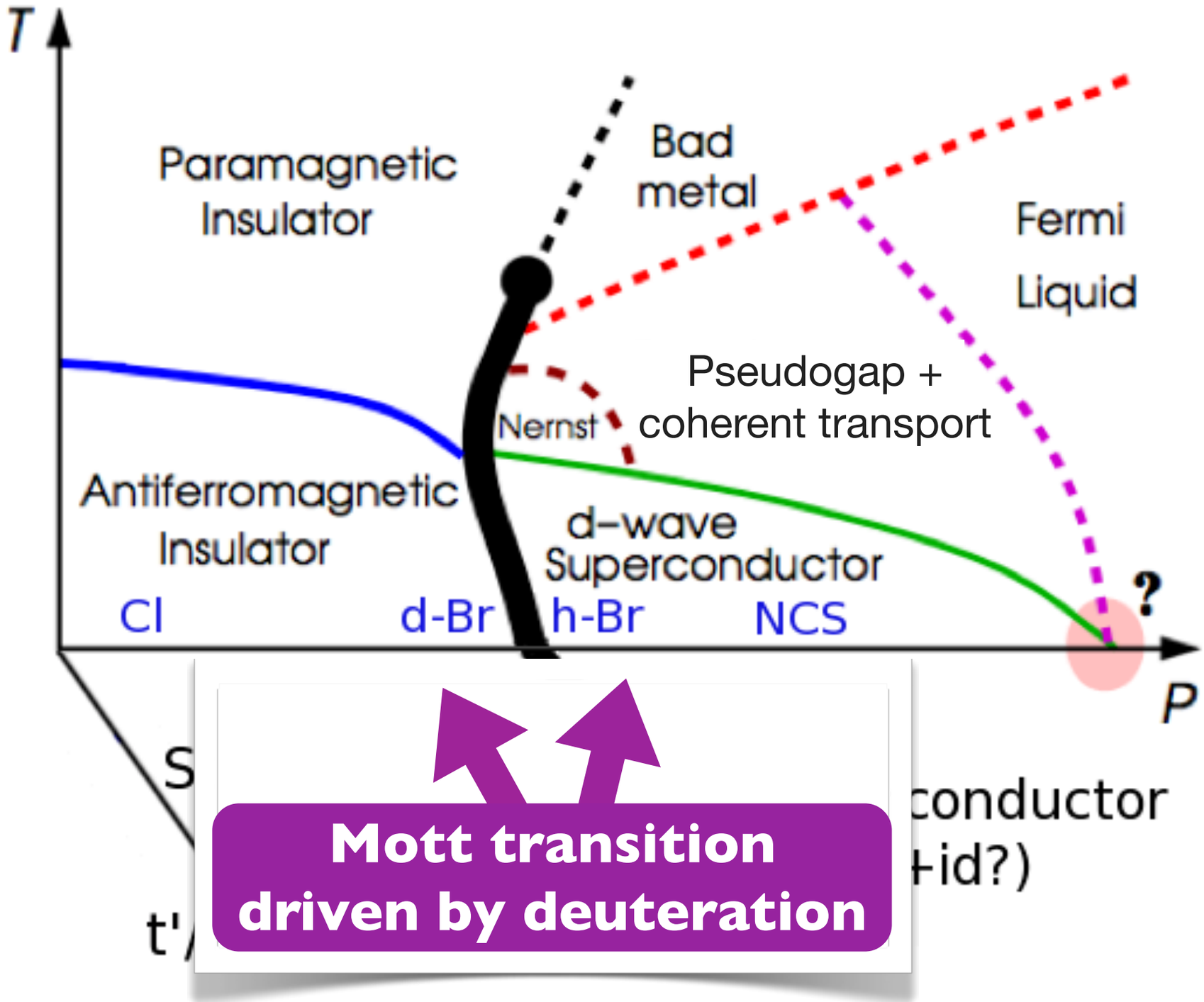
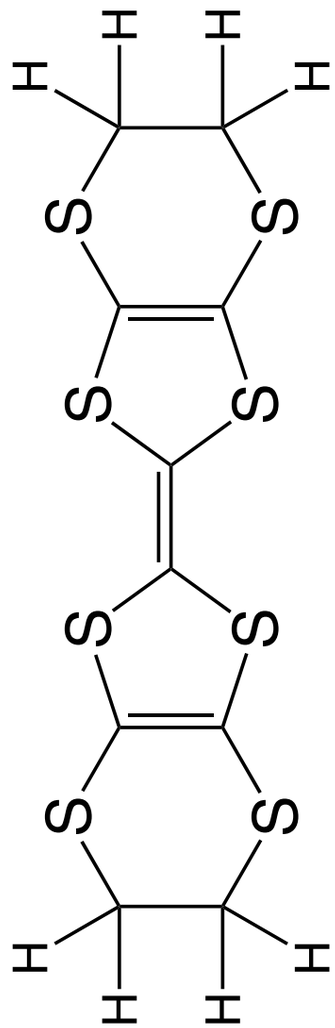
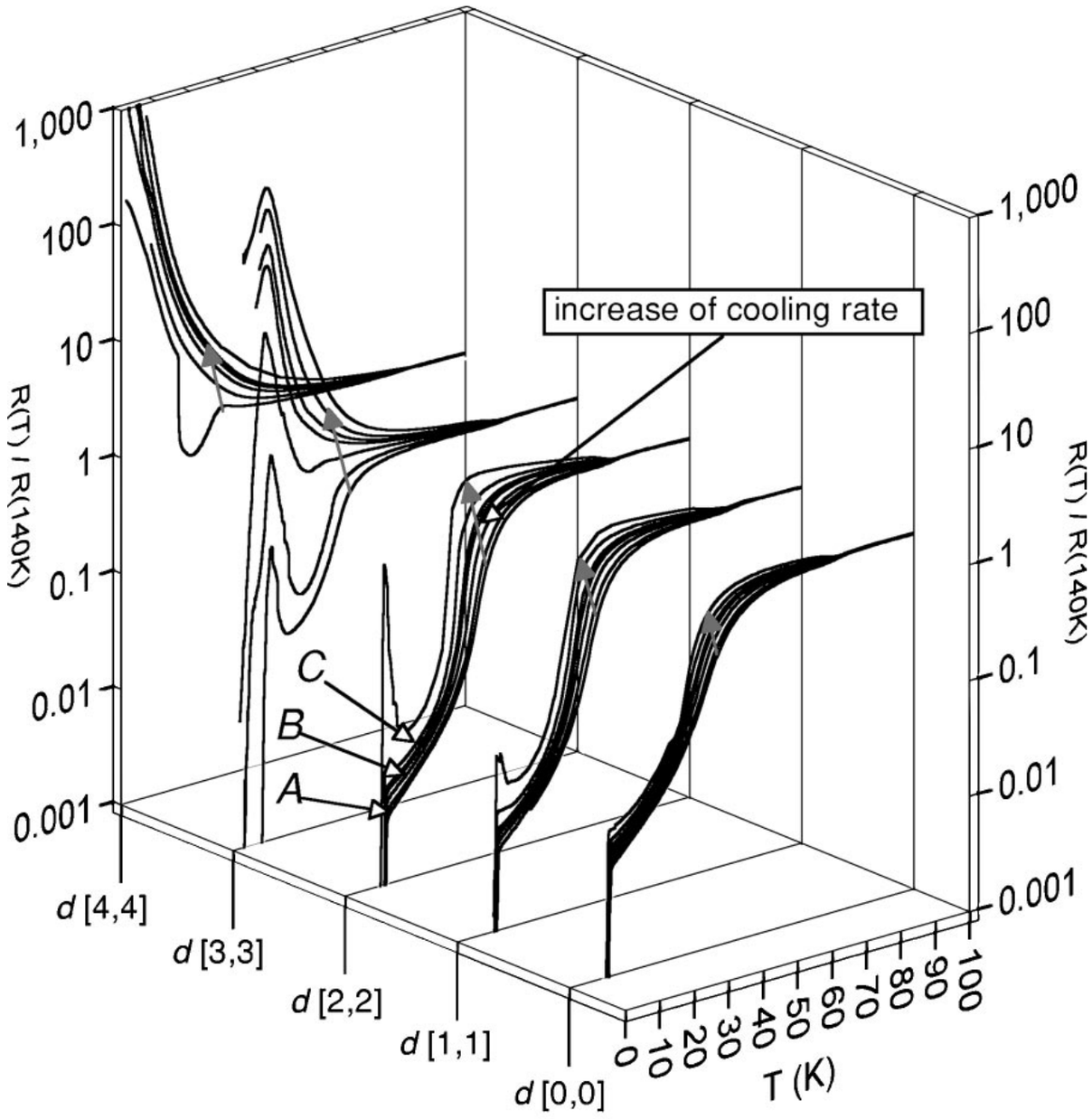
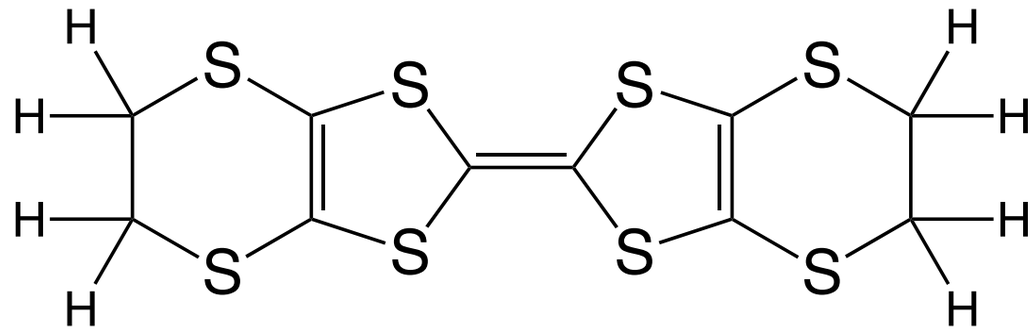




Metal insulator transition driven by deuteration!

Taniguchi et al. PRB ’03

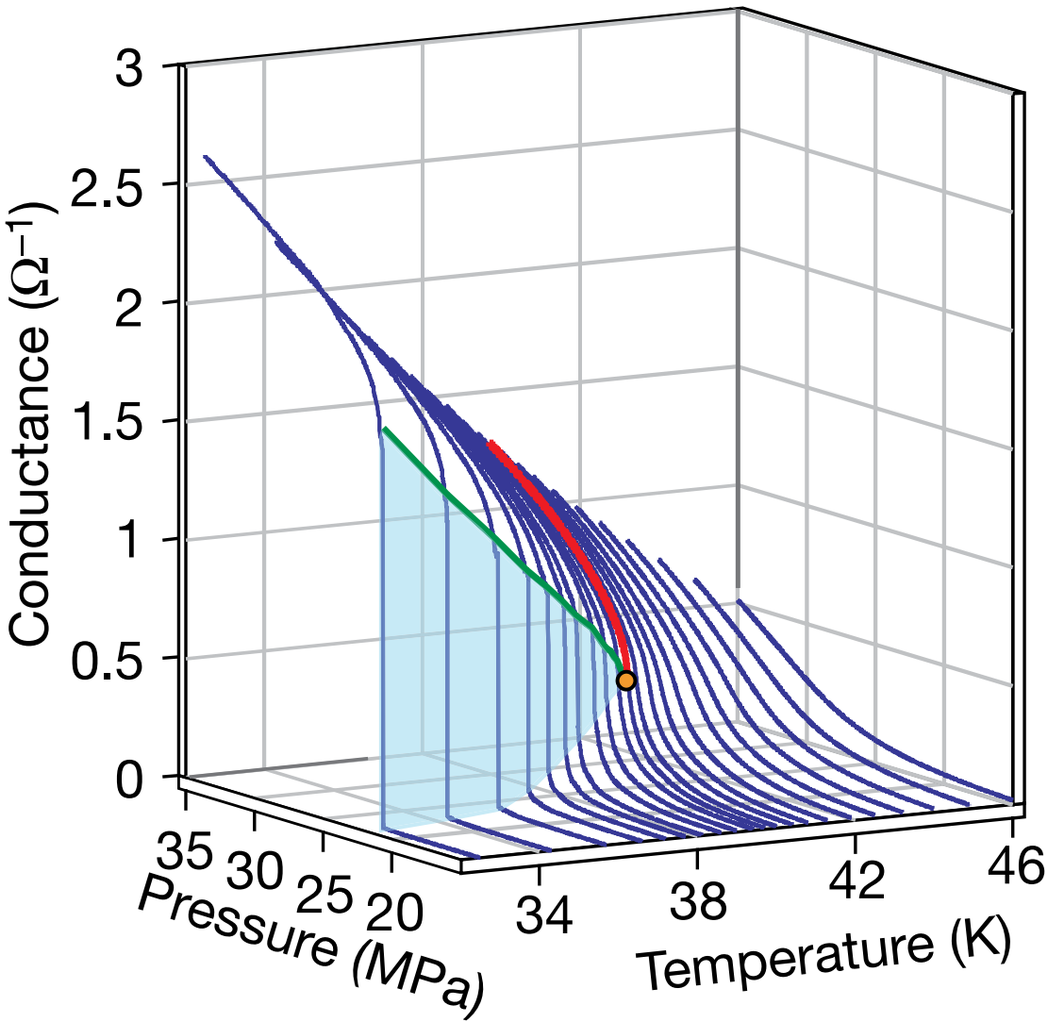




- This shows that molecular crystals can be controlled by subtle changes in the molecular chemistry
- This gives experimentalists an extra “dial”

Metal insulator transition driven by pressure

Kagawa et al. Nature ‘05; Nature Phys. ‘09



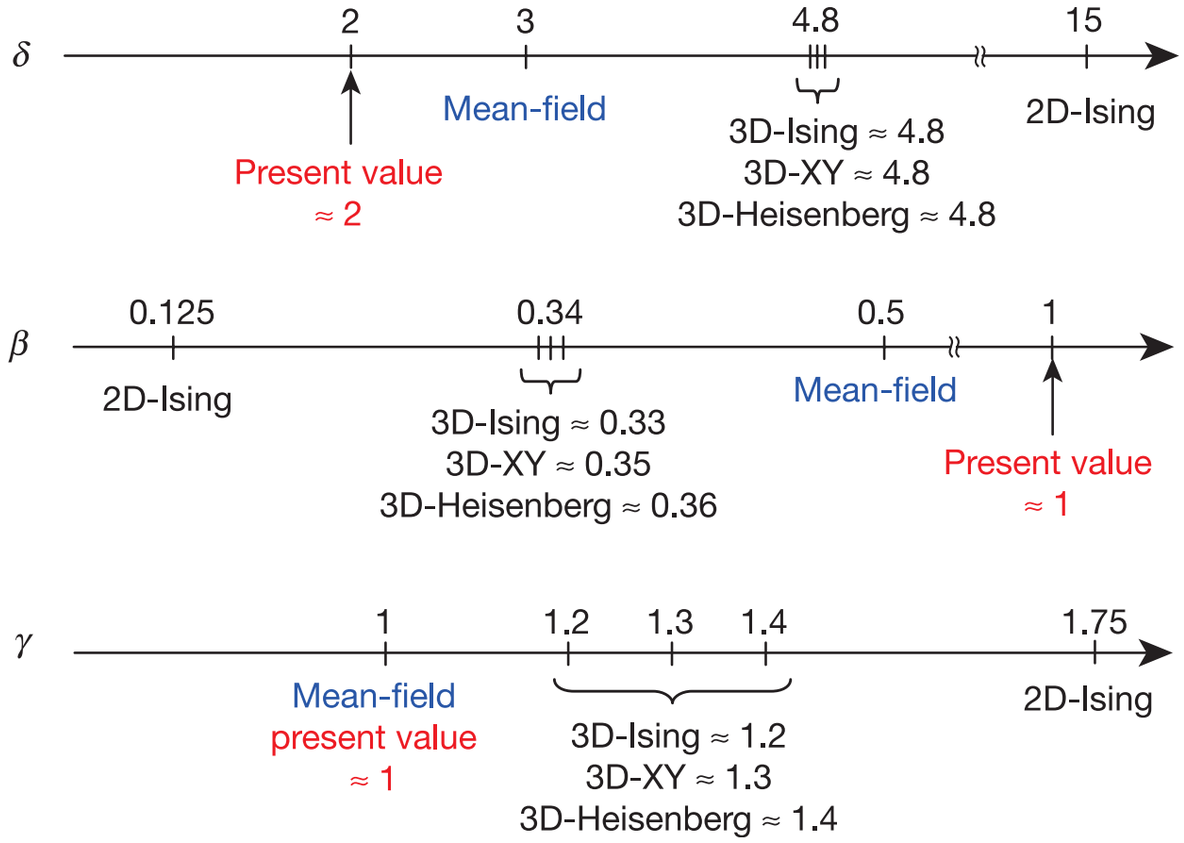
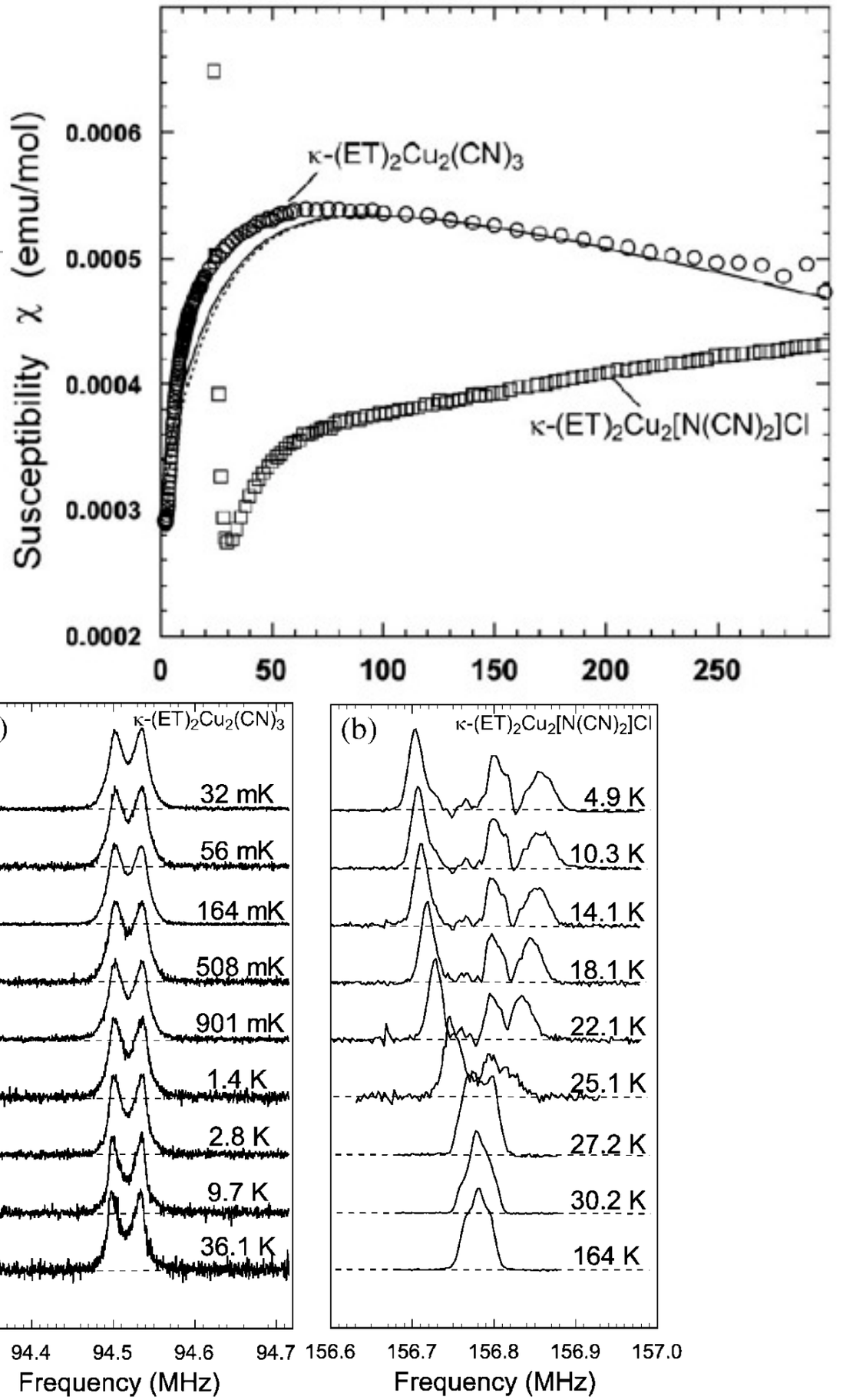


Figure 3 | Comparison of the critical exponents (δ, β, γ) of the present case with those of the known universality classes (mean-field, Ising model, XY model and Heisenberg model). The examples of phase transitions

- The observed critical exponents are not Ising like as in V_2O_3 and DMFT [cf. Limelette et al. Science ’03]
- Various theoretical proposals [e.g., Misawa et al. JPSJ ’06 - proximity to QCP; Papanikolaou et al. PRL ’08 - not deep enough into critical region]
- Same δ exponent seen in NMR experiments [Kagawa et al. Nature Phys. ‘09]

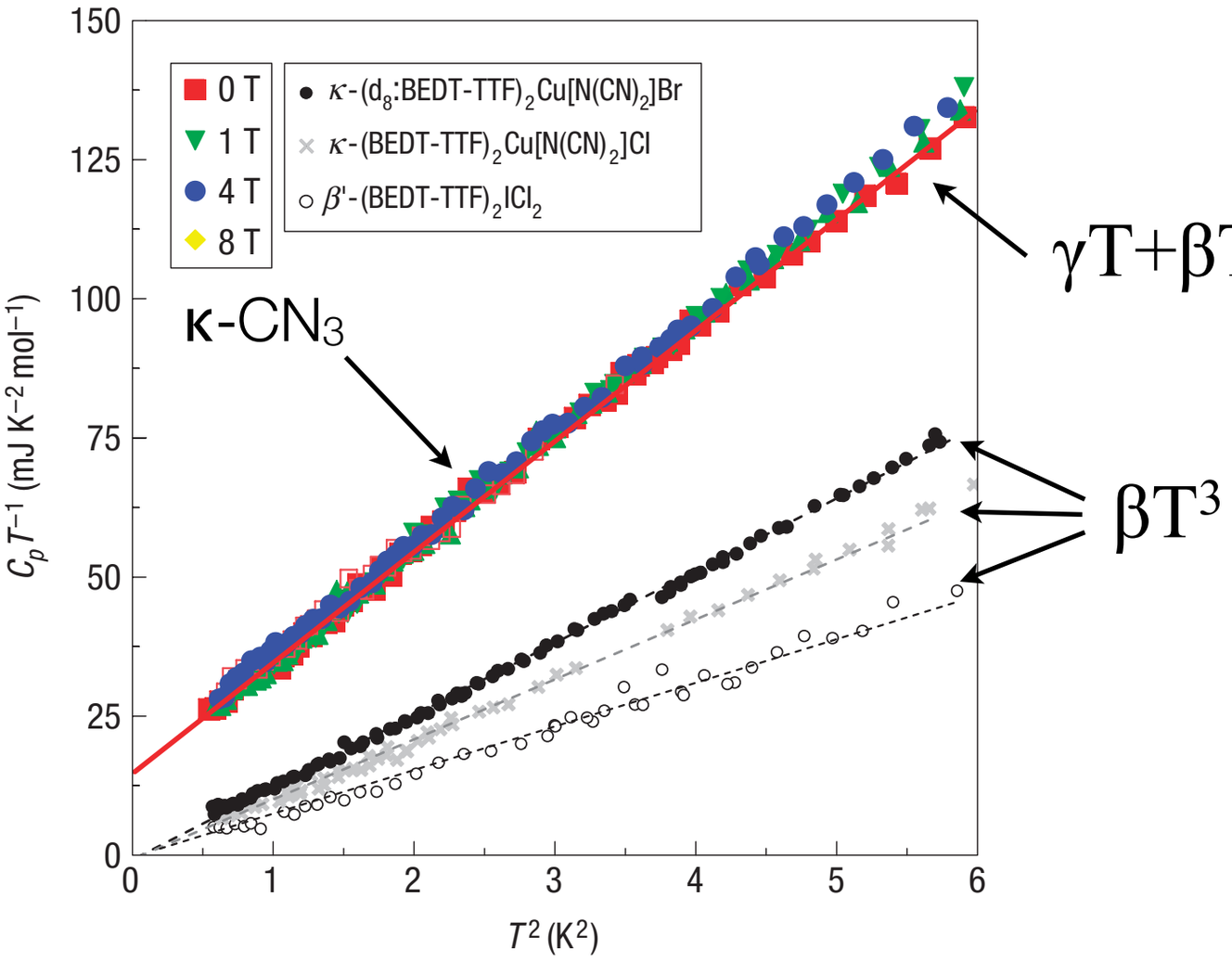
Spin liquid

- κ-$(ET)_2Cu[N(CN)_2]Cl$ (henceforth κ-Cl) has a antiferromagnetic ground state - there is a slight canting of the moments leading to a large effect in the static susceptibility
- κ-$(ET)_2Cu(CN)_3$ (henceforth κ-CN_3) has a spin-liquid ground state [Shimizu et al. PRL '03] – no long range order in magnetic ground state
- A splitting is observed in the NMR below T_N in κ-Cl - no such splitting is seen in κ-CN_3.
- [The line in the figure is a fit to high-T series expansions for the isotropic (J=J') triangular lattice Heisenberg model, which give J~250 K]



Gapped or gapless spin liquid?

S. Yamashita et al. Nature Phys. '08; M. Yamashita et al. Nature Phys. '09



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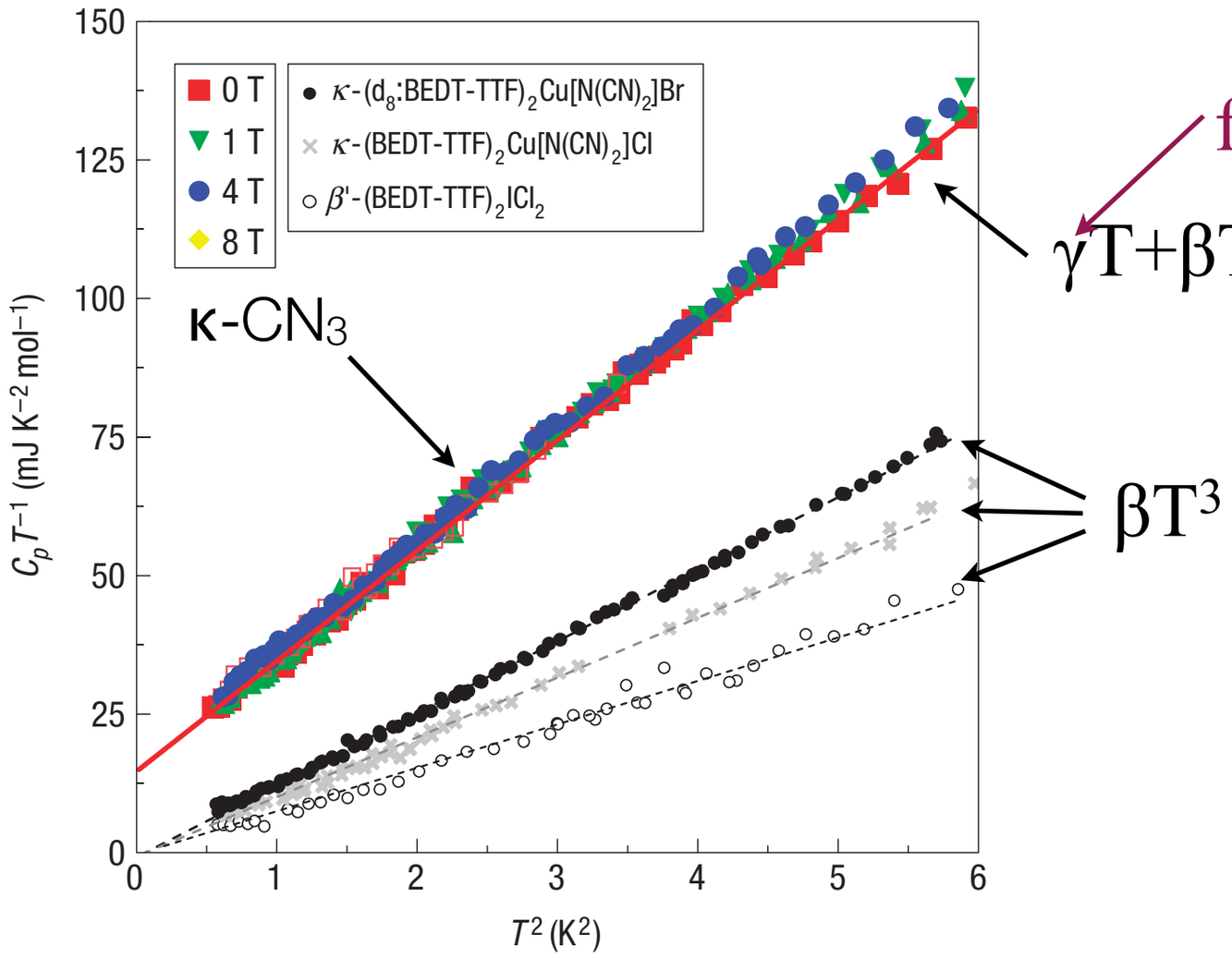

$\gamma = 12$ mJ K^{-2} mol^{-1}

fermions (gapless spinons?)

Gapped or gapless spin liquid?

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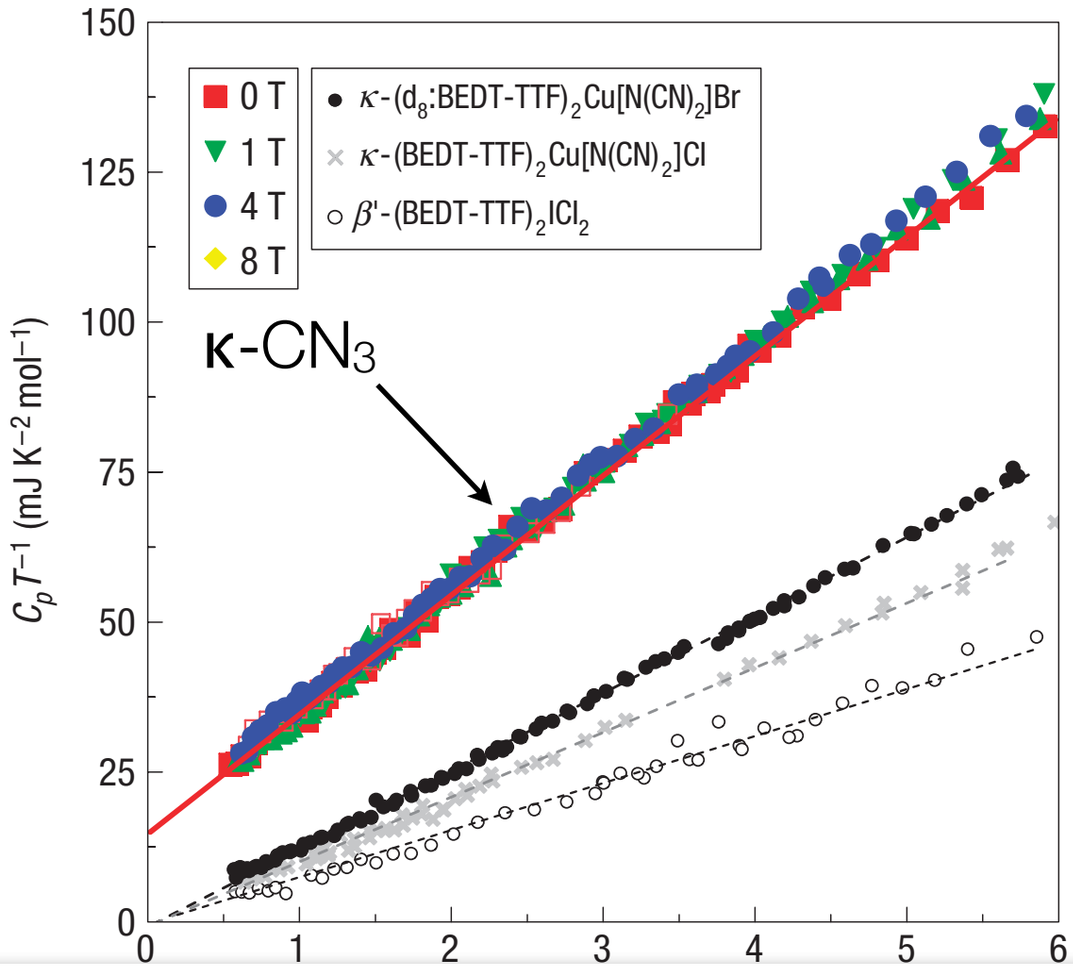
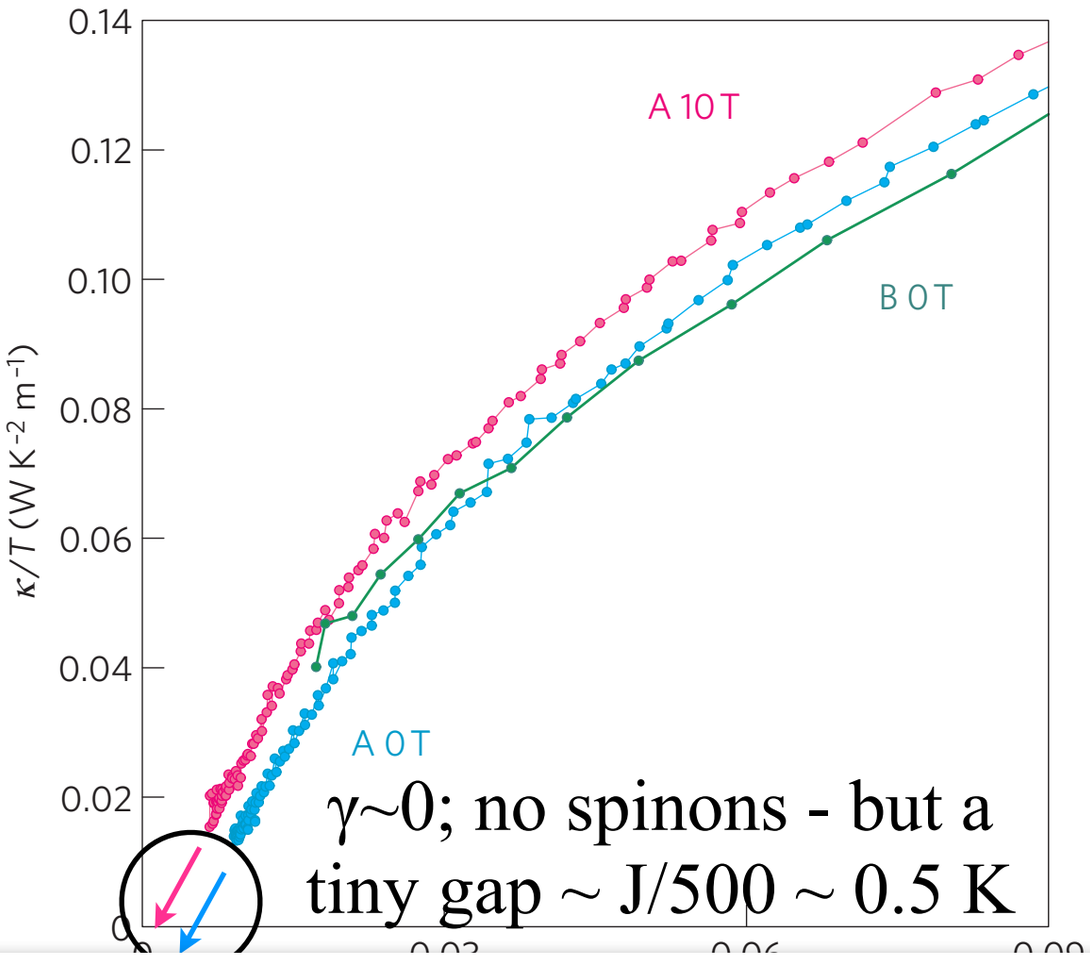
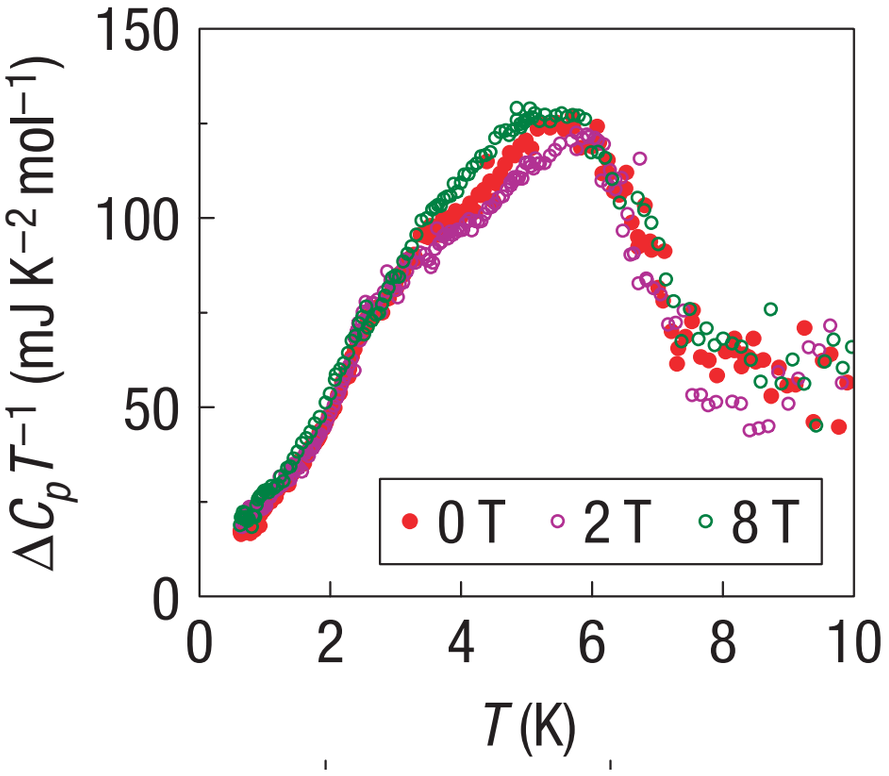


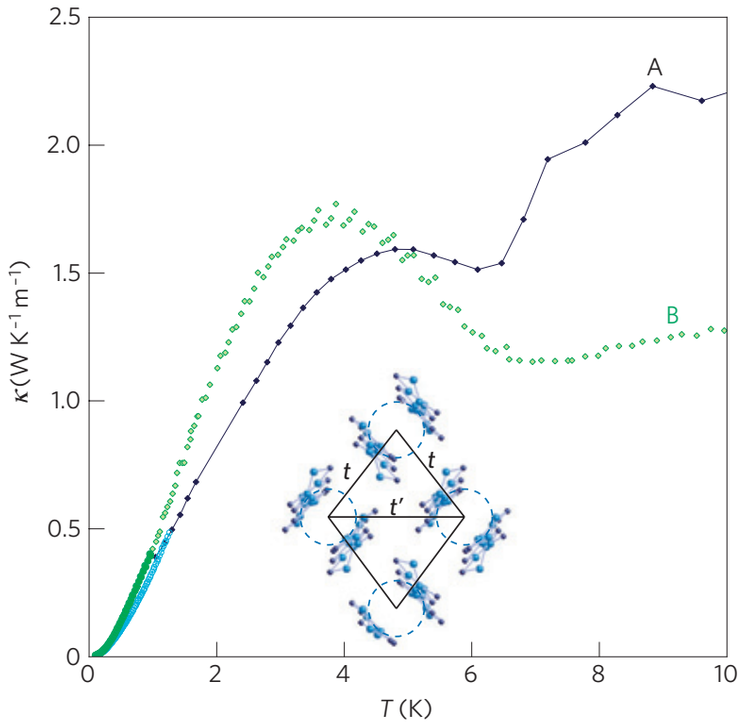


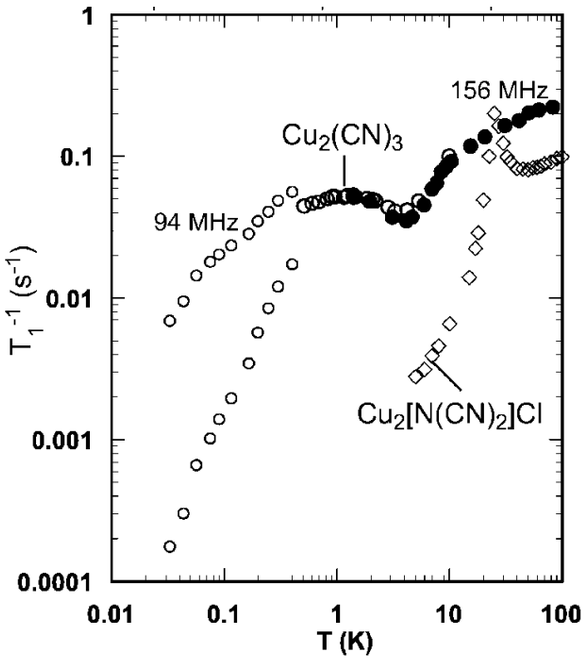
- Why the difference?
- M. Yamashita et al. argue it is because of the Schottky anomaly (from the Cu spins in the anion) in the anion affecting C_p
- Also see discussion (particularly the coments) at

  http://condensedconcepts.blogspot.com/2009/08/can-we-see-visons.html

6 K anomaly





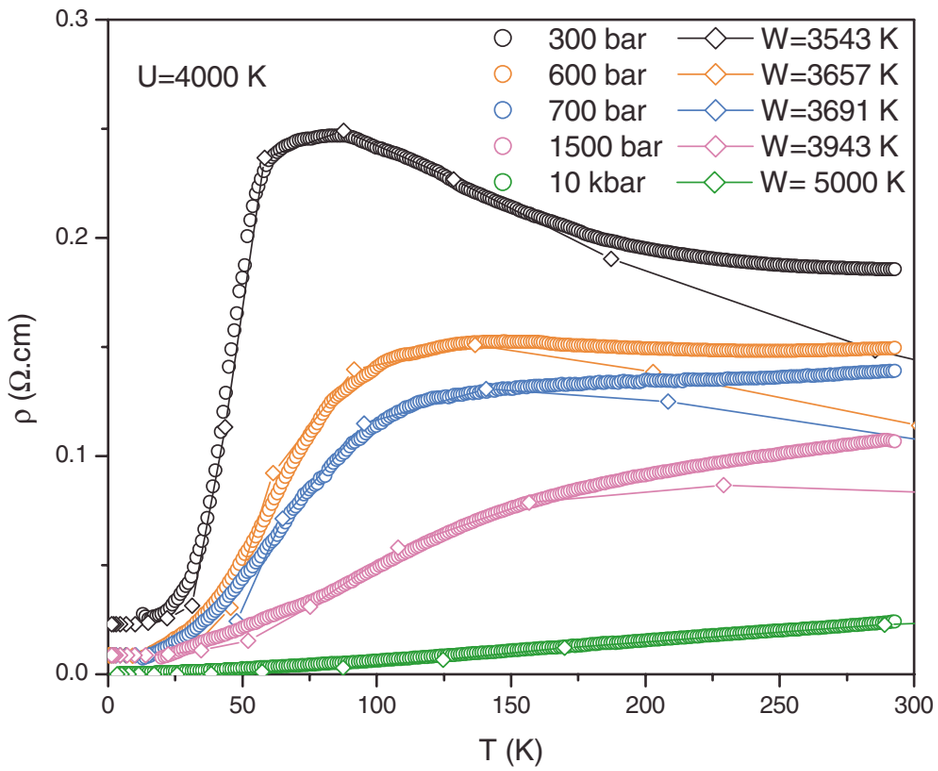


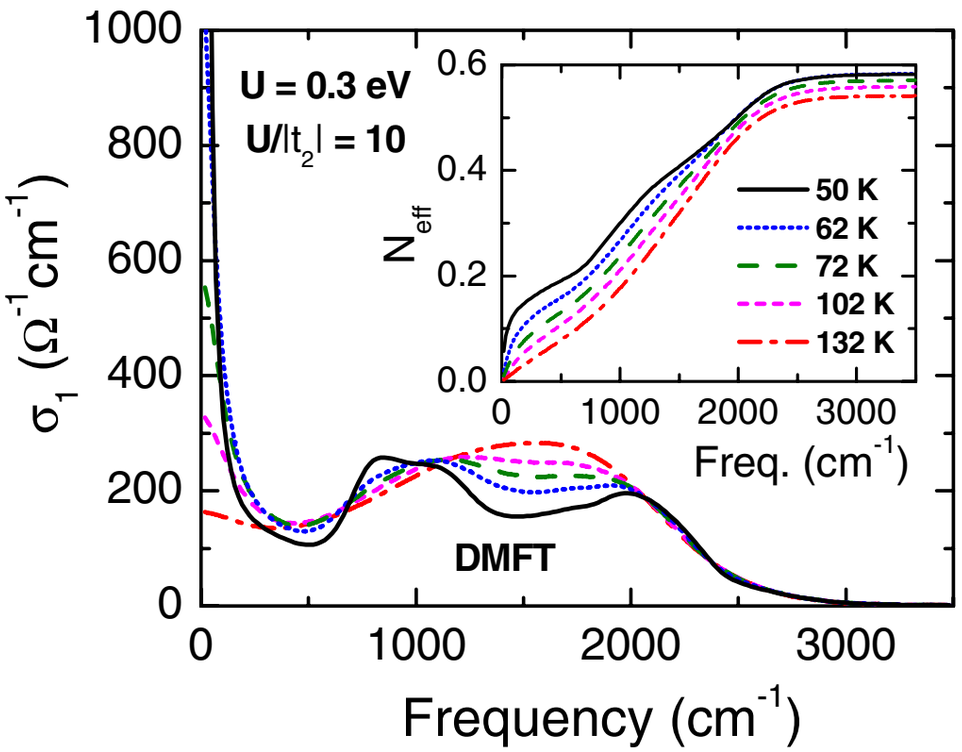
- A “bump” is seen below ~6 K in the heat capacity, thermal conductivity, and spin-lattice relaxation rate
- Many possible explanations have been proposed including: visons (vortices in a Z_2 spin liquid) [Qi et al. PRL ‘09], crossover to spin liquid [Yamashita et al. NP ‘08], “Amperean pairing of spinons [Lee et al. PRL ‘07], spin-chirality ordering [Baskaran PRL ‘89], excition condensation [Qi & Sachdev PRB ‘08],...

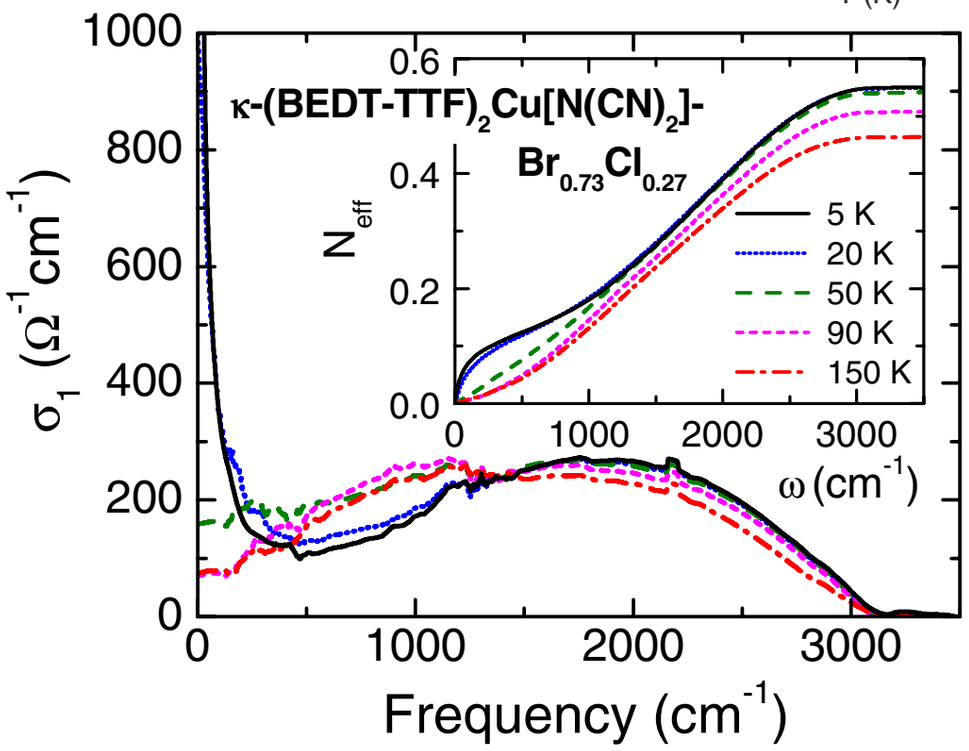
Bad metal

Merino & McKenzie, PRB 00, Limelette et al. PRL 03, Merino et al. PRL 08

- Many of the experiments on the normal state are quantitatively consistent with the “bad metal” phase predicted by DMFT
  - Non-monotonic temperature dependence of thermopower, resistivity [top fig.: Limelette et al. PRL 03] and Hall coefficient
  - Resistivity values above the Mott-Ioffe-Regal limit
  - Absence of Drude peak in the high-T optical conductivity [lower figs.: Merino et al. PRL 08]







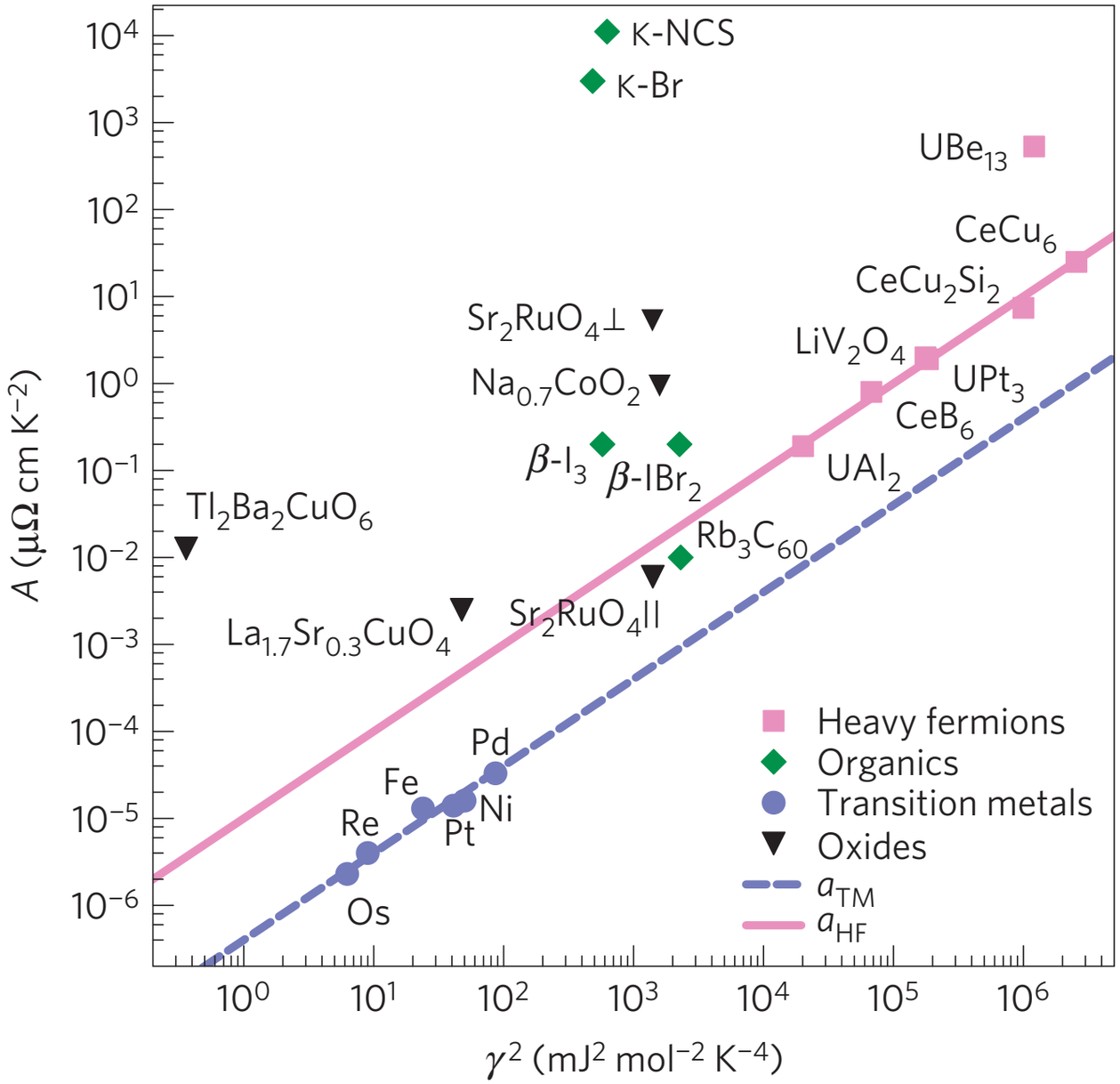
Kadowaki-Woods ratio (A/γ^2)

Jacko, Fjaerestad, and BJP, Nature Phys. **5**, 422 (2009)

$$\rho(T) = \rho(0) + AT^2$$

$$C_v = \gamma T + \beta T^3$$

- Dressel, Wosnitza and others have noted that A/γ^2 is very large in the organics
- Miyake et al. [SSC **71**, 1149 ('89)] argued that the heavy fermion materials have a large KWR because $\partial\Sigma/\partial\omega$ is large (strongly correlated) and that the KWR is much smaller in the transition metals because $\partial\Sigma/\partial\omega$ is much smaller.
- Hussey [JPSJ 74, 1107 ('05)] proposed plotting γ in volumetric units for oxides etc.
- Does the same physics give rise to the mass enhancement (γ) and A?



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Jacko, Fjaerestad, and BJP, Nature Phys. **5**, 422 (2009)

- Following Miyake, Matsuura, and Varma, [Solid State Commun. **71**, 1149 ('89)], we study a phenomenological local Fermi liquid theory where the imaginary part of the self energy is given by

$$\begin{aligned}\Sigma''(\omega,T) &= -\frac{\hbar}{2\tau_0} - \frac{2n}{3\pi D_0}\frac{\omega^2+(\pi k_B T)^2}{\omega^{*2}} && \text{for } \left|\omega^2+(\pi T)^2\right| < \omega^{*2} \\ &= -\left(\frac{\hbar}{2\tau_0}+\frac{2n}{3\pi D_0}\right) F\left(\sqrt{\frac{\omega^2+(\pi k_B T)^2}{\omega^{*2}}}\right) && \text{for } \left|\omega^2+(\pi T)^2\right| > \omega^{*2}\end{aligned}$$

- $F(1)=1$, $F(\infty)=0$, $F(y)$ is an unspecified monotonic function.
- Relate A to γ via the Kramers-Kronig transform for the self energy

$$A = \frac{16nk_B^2}{\pi\hbar e^2\langle v_{0x}^2\rangle D_0^2\omega^{*2}}; \qquad \gamma = \gamma_0\left(1-\frac{\partial\Sigma'}{\partial\omega}\right) \simeq \frac{8nk_B^2\xi}{9\omega^*}$$

$$\frac{A}{\gamma} = \frac{81}{4\pi\hbar k_B^2 e^2}\frac{1}{f_{dx}(n)}$$

where $f_{dx}(n) \equiv nD_0^2\langle v_{0x}^2\rangle\xi^2$

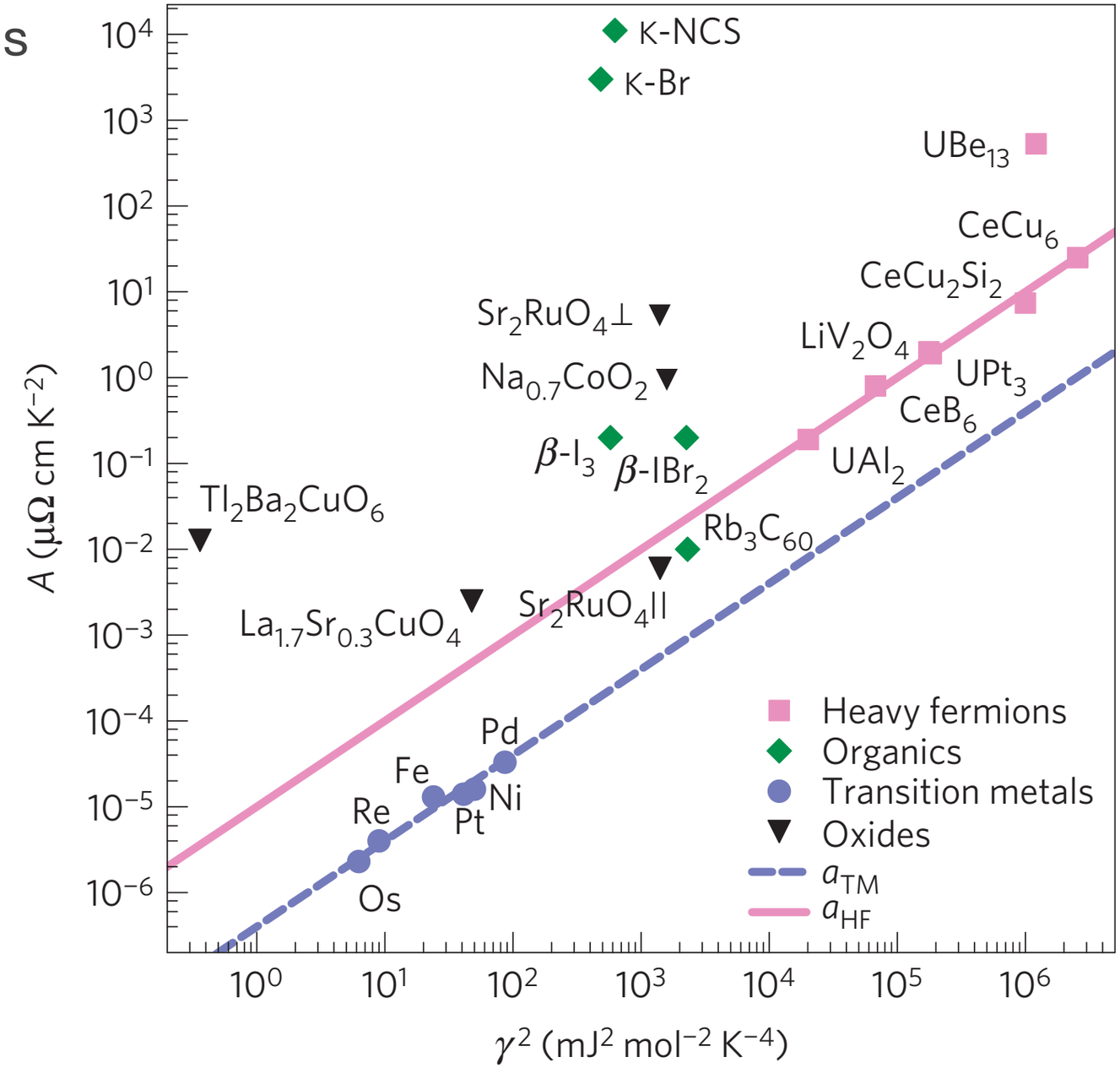
Modified Kadowaki-Woods ratio

Jacko, Fjaerestad, and BJP, Nature Phys. **5**, 422 (2009)

- This suggests that a more natural ratio is

$$\frac{A f_{dx}(n)}{\gamma^2} = \frac{81}{4\pi\hbar k_B^2 e^2}$$

- Assume simple model band structures to calculate $f_{dx} \equiv n D_0^2 \langle v_{0x}^2 \rangle \xi^2$
  - Spherical Fermi surfaces for 3D materials
  - Cylindrical Fermi surfaces for quasi-2D materials



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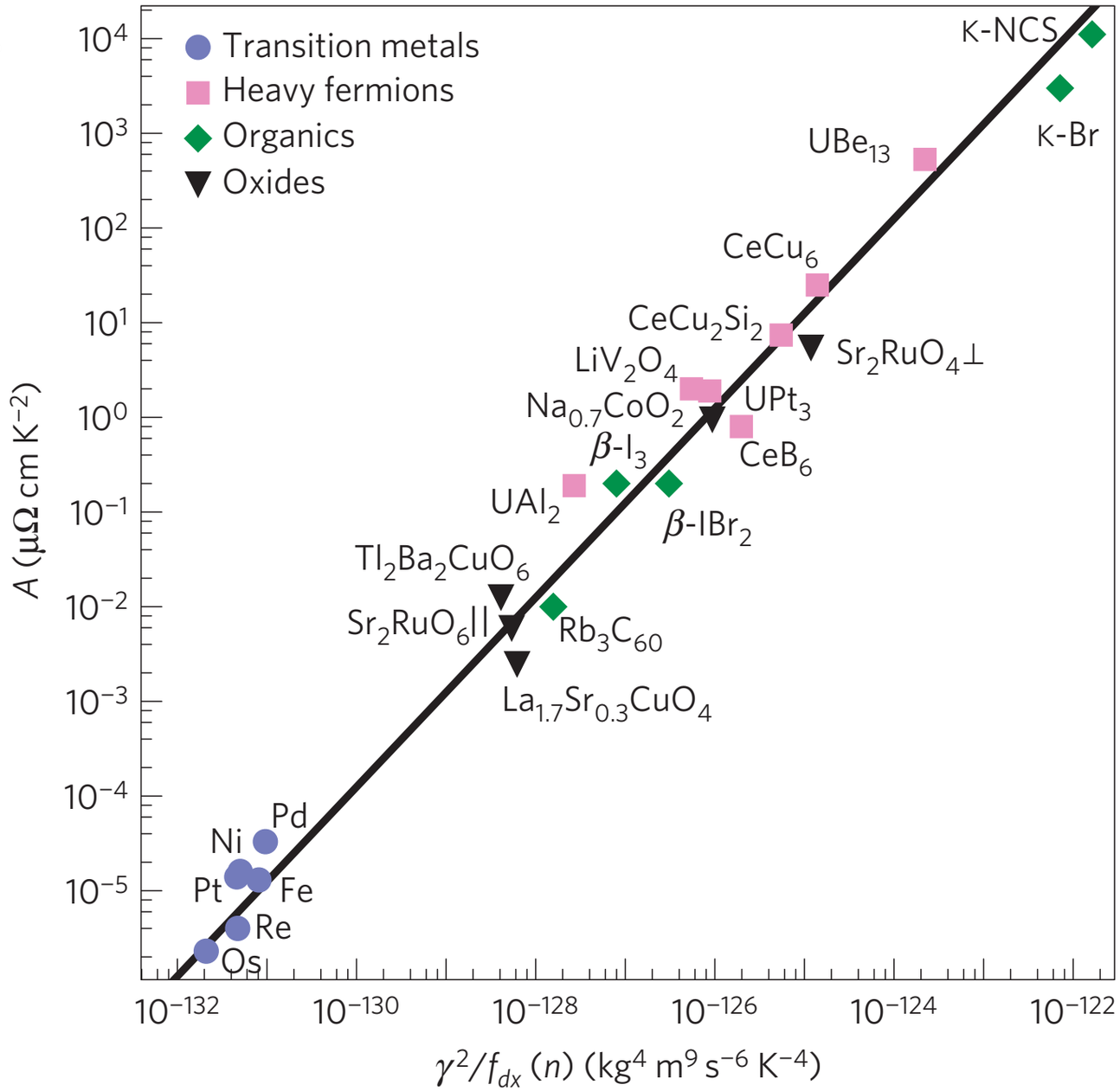
  - Spherical Fermi surfaces for 3D materials
  - Cylindrical Fermi surfaces for quasi-2D materials
- We find excellent agreement with data from a broad range of strongly correlated materials.
- This shows that the main difference between the heavy fermions and the transition metals are due to band structure [$f_{dx}(n)$], rather than correlations.
- The same correlations cause A and γ in the organics



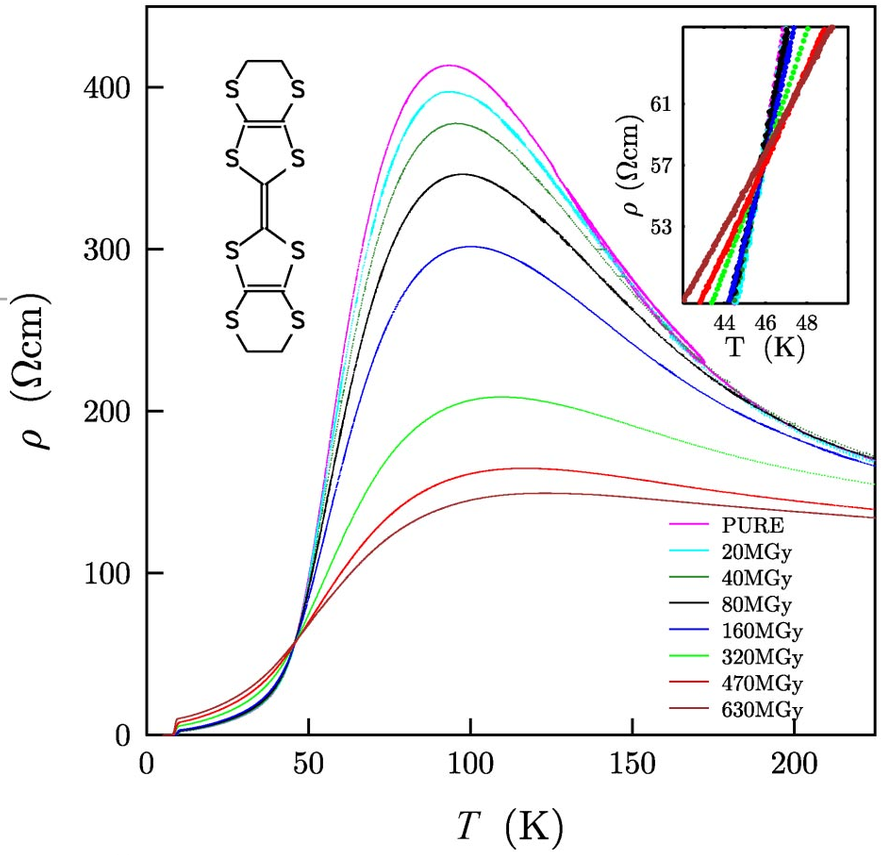
Disorder and transport

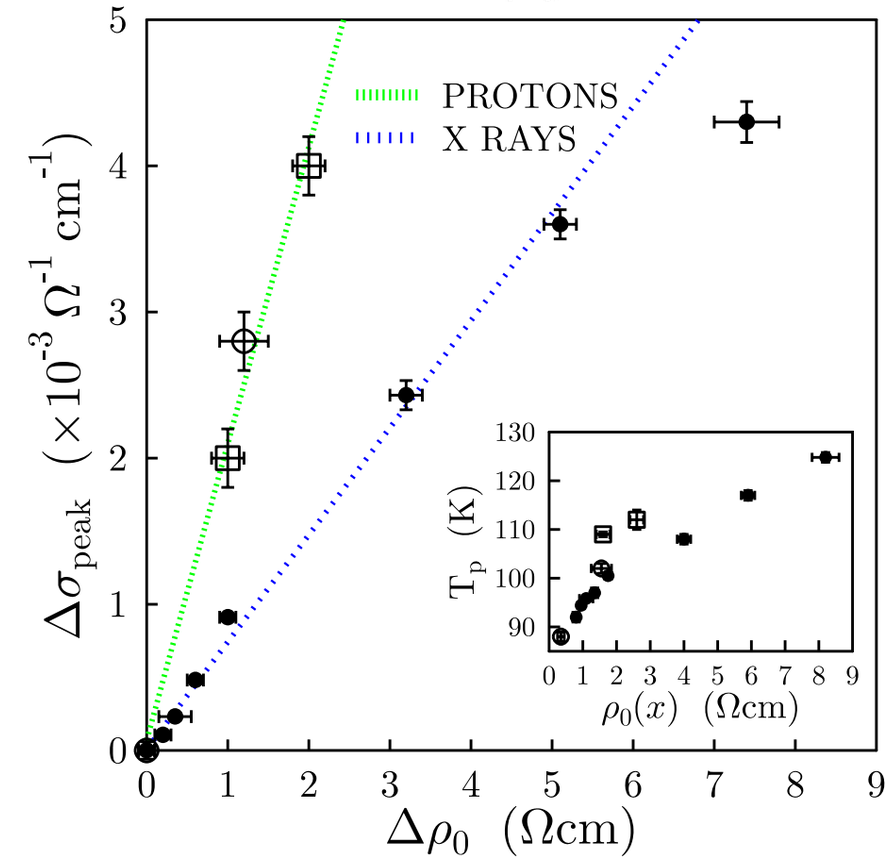
Analytis, BJP et al., PRL **96**, 177002 (2006)

- Defects induced into samples by x-ray and proton irradiation
- Matthiessen's rule obey at low T, but strongly violated at high T
- Resistivity independent of disorder at $T=T_{cross}\sim 46$ K
- Can be explained if we assume that the impurities have two effects
  1. Scattering in the usual way
  2. Act to assist interlayer tunnelling [Graf et al., PRB 93; Rojo et al., PRB 93, etc.]

$$\sigma(x,T) = \frac{1}{\rho_{clean} + x\rho_{imp}} + x\sigma_{\perp}$$

- This leads to the prediction that the residual resistivity is proportional to the peak conductivity, which is observed





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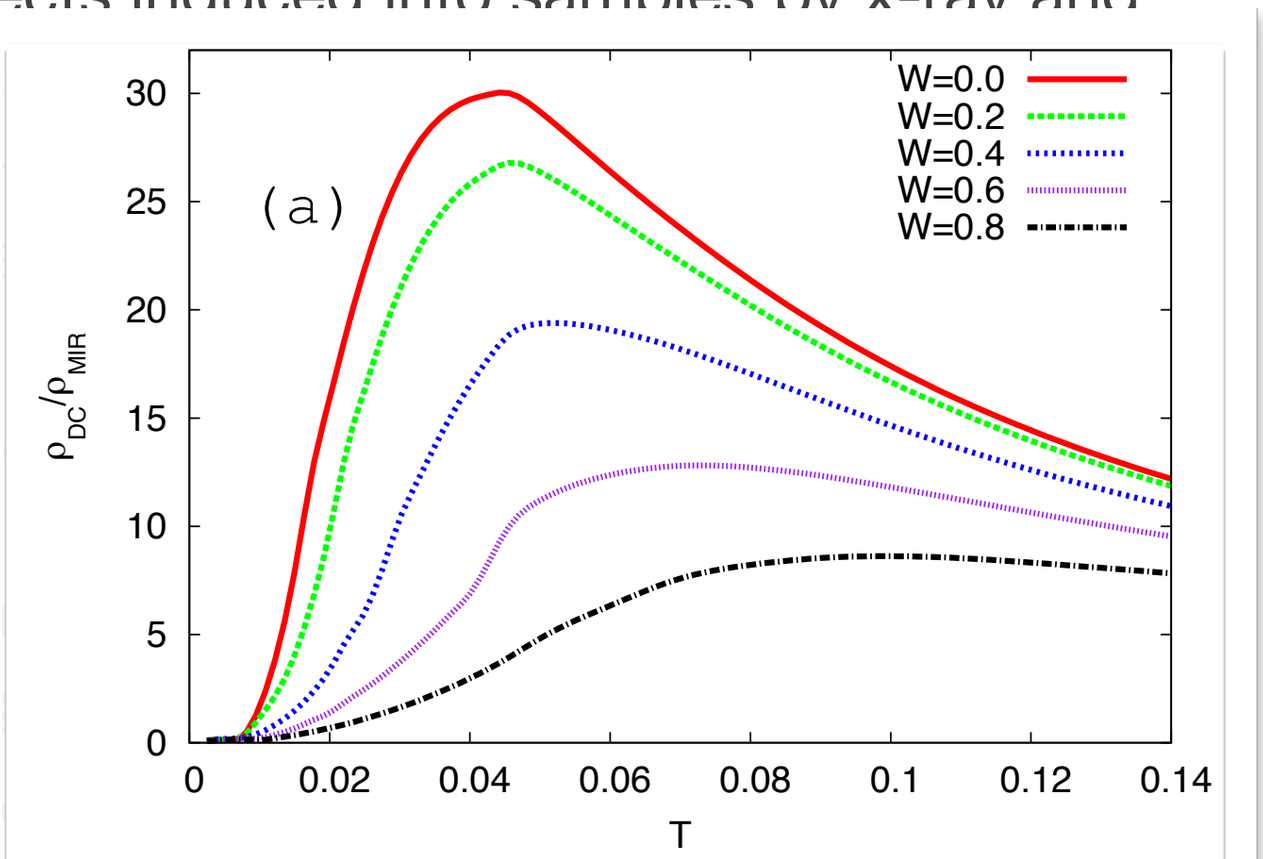
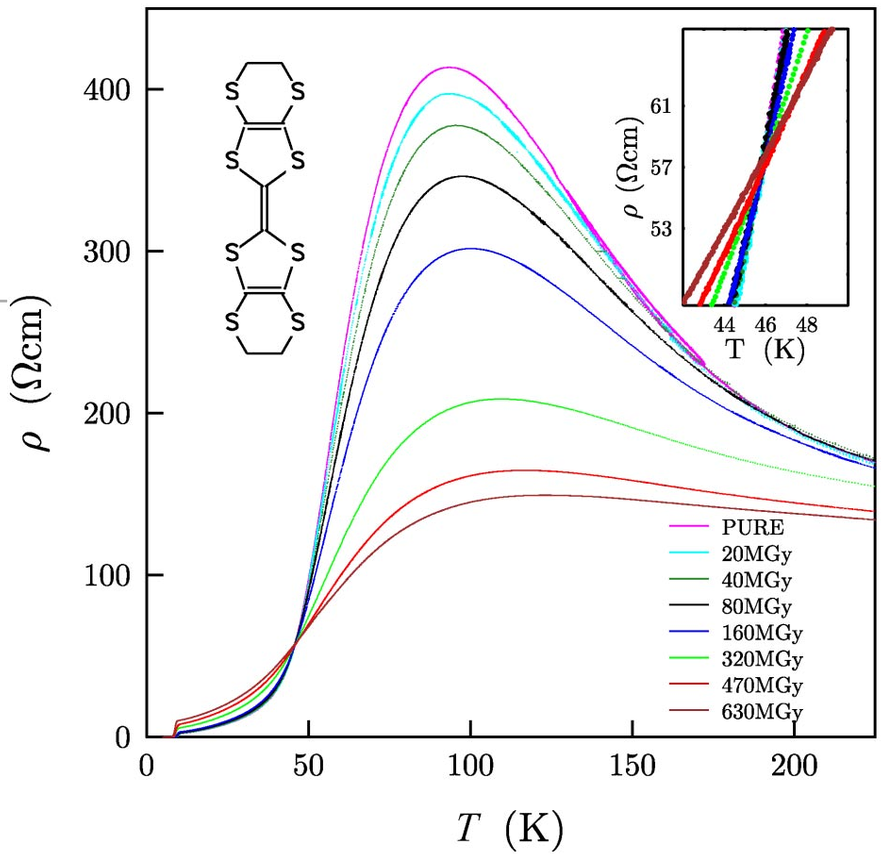
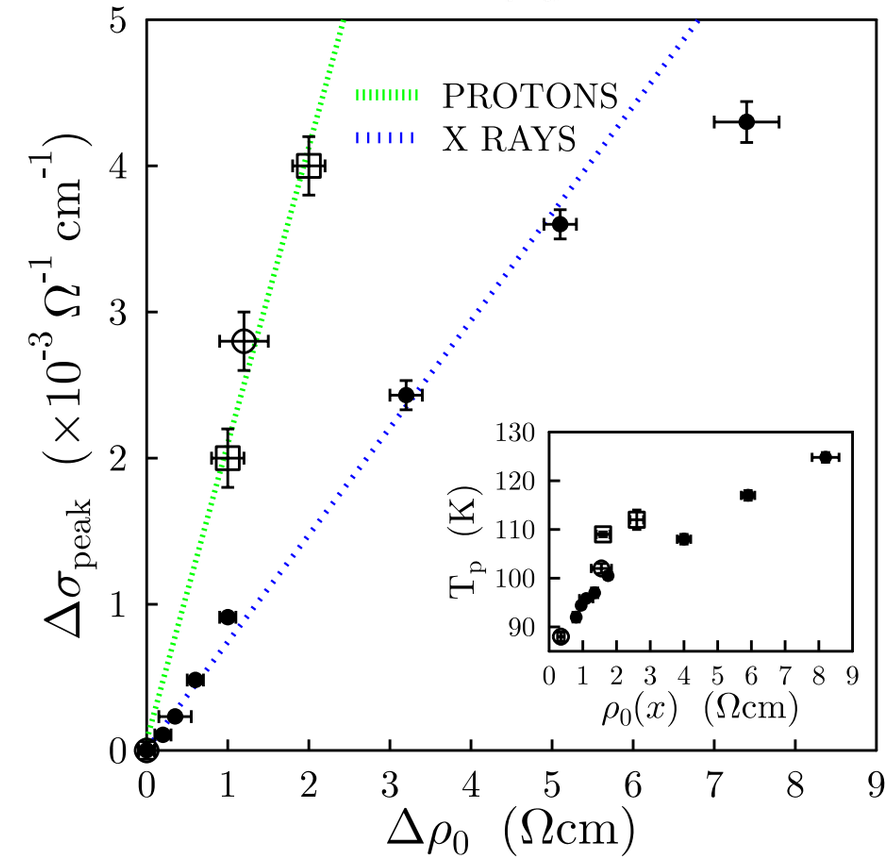


Disordered Hubbard model (DMFT)

Radonjić et al. arXiv:0910.5100

- This leads to the prediction that the residual resistivity is proportional to the peak conductivity, which is observed





Pseudogap?

BJP, Yusuf & McKenzie, PRB **80**, 054505 (2009)

<u>Pseudogap + coherent transport</u>

$\rho(T) \sim T^2$

SdH and dHvA oscillations

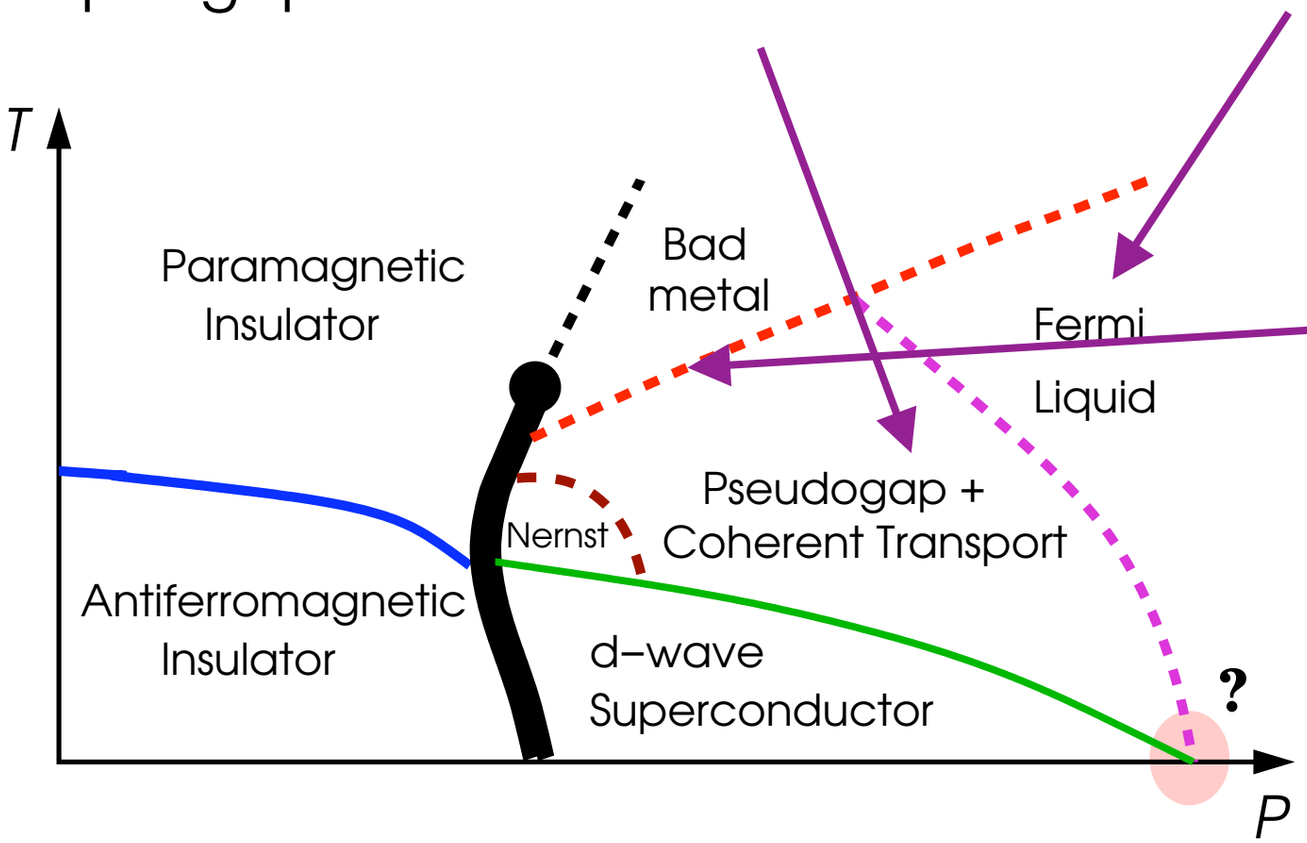
Spin gap observed in NMR

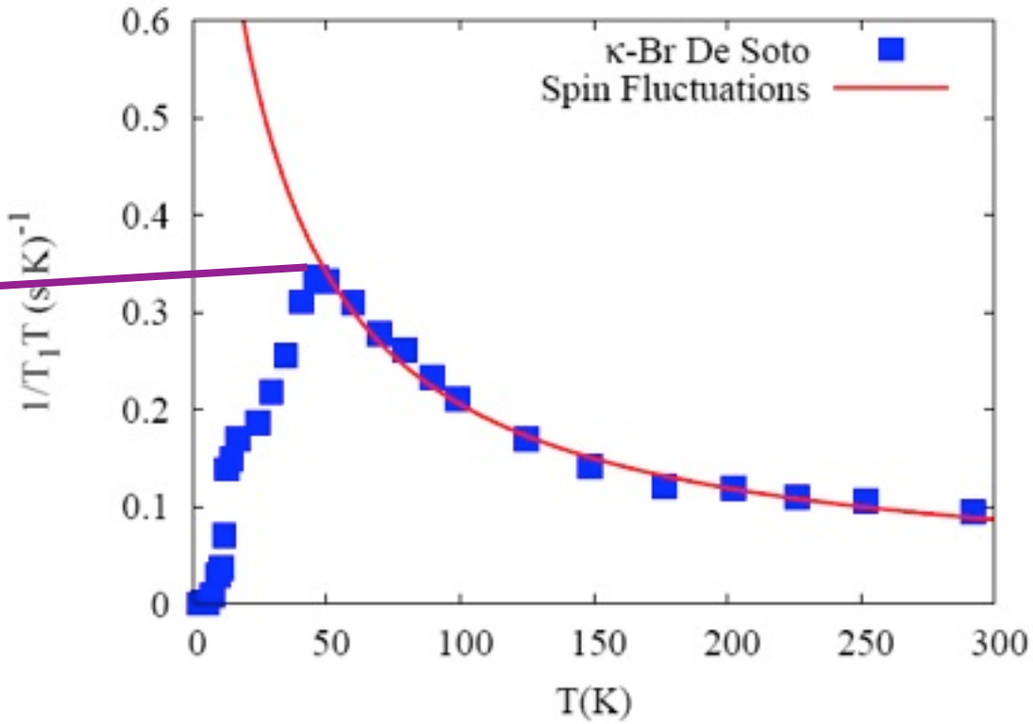
<u>Fermi Liquid</u>

$\rho(T) \sim T^2$

SdH and dHvA oscillations

No gap observed in NMR



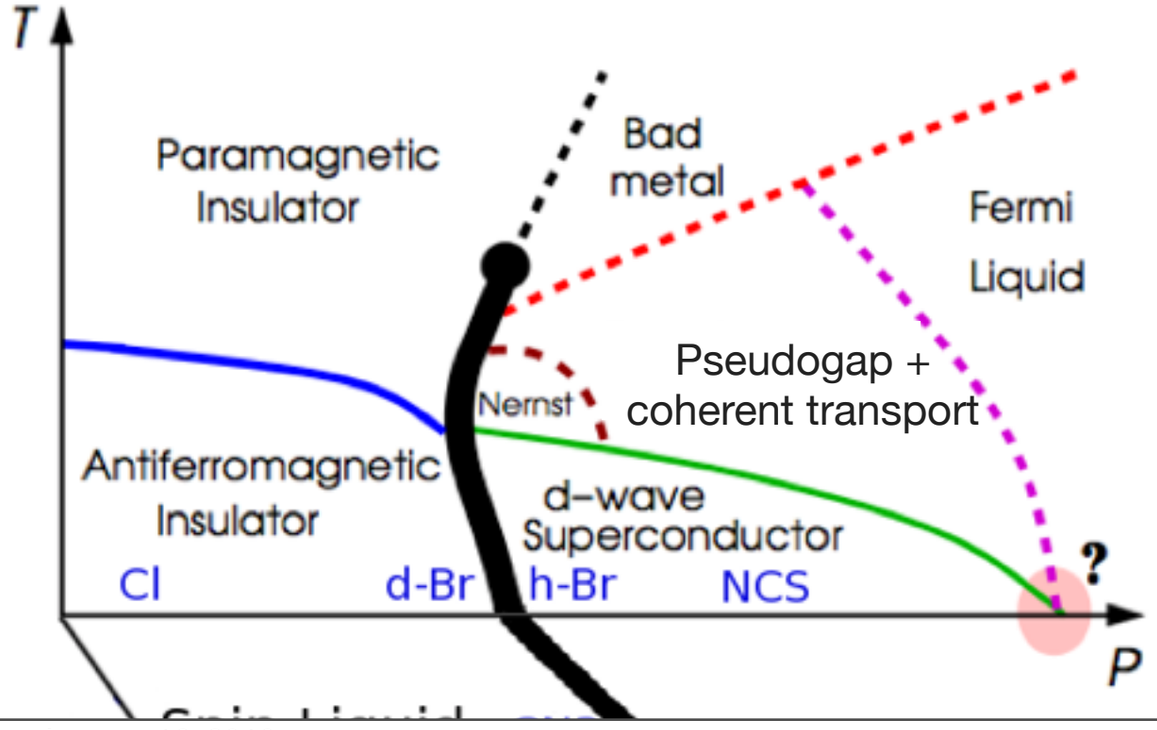


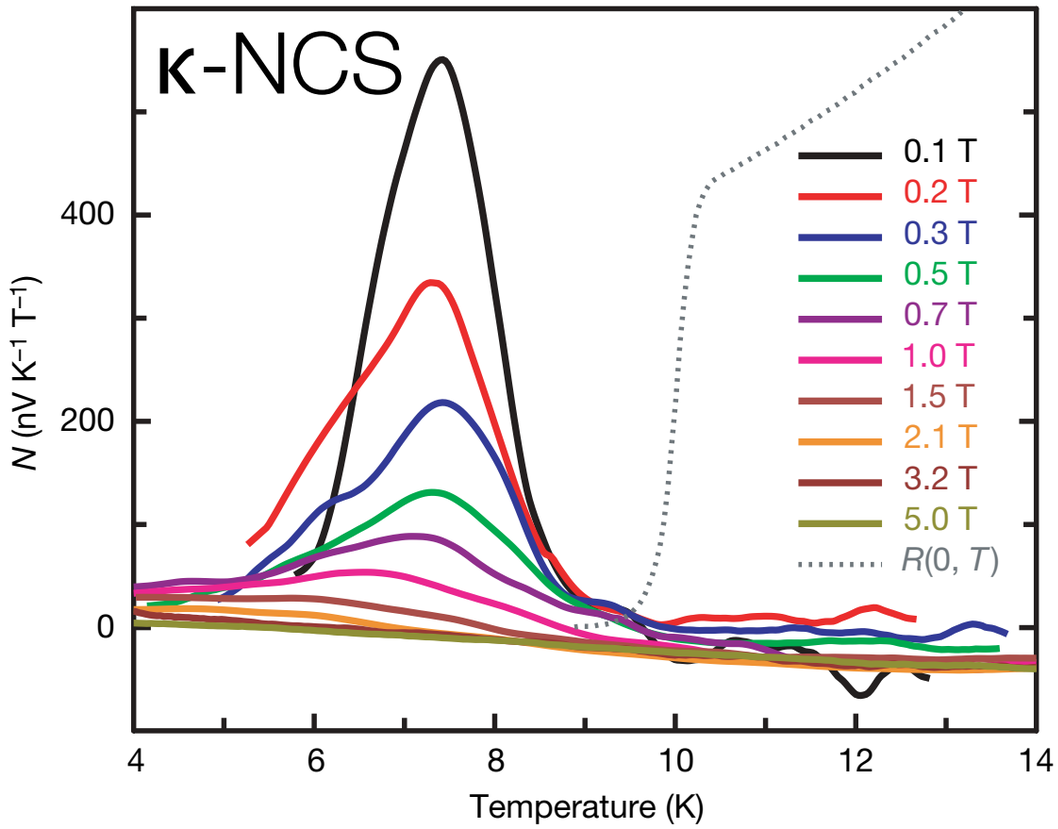
De Soto et. al., Phys. Rev. B 52, 10364 (1995); Mayaffre, et al., EPL, 25, 208 (1994); etc.

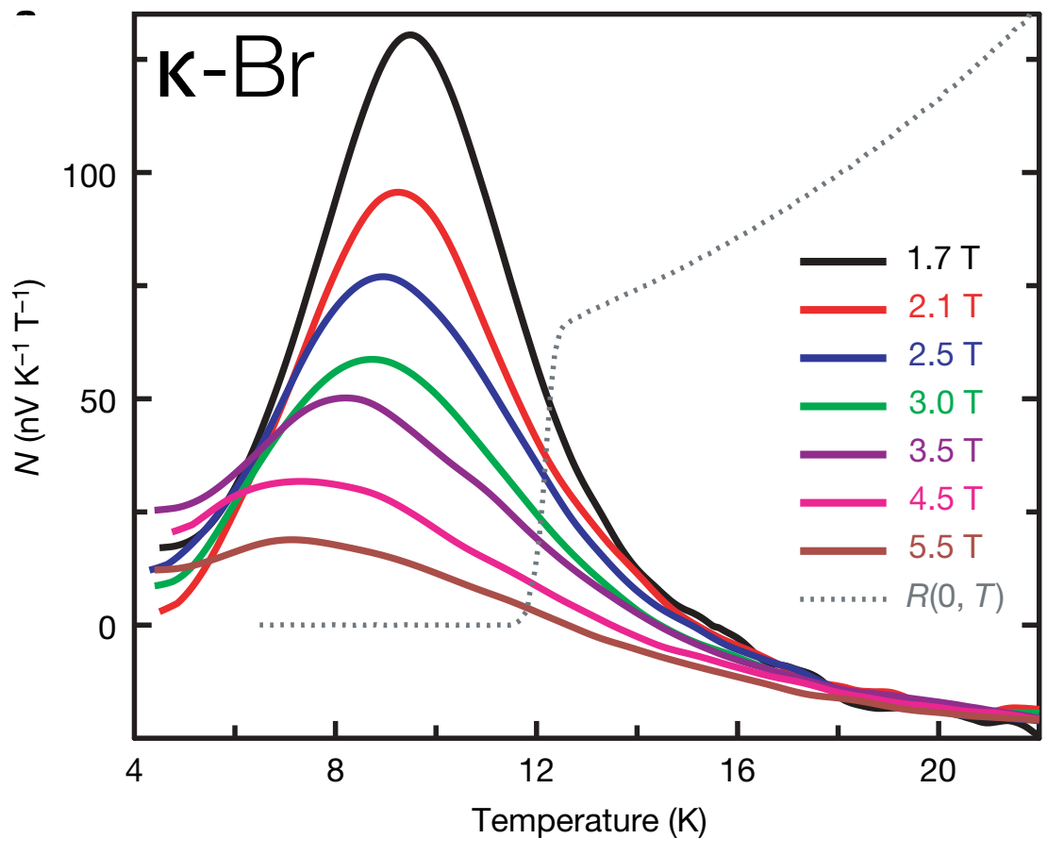
Nernst effect near the Mott insulator

[Nam et al. Nature 07]

- In κ-NCS one sees a small Nernst effect in the normal state, and a large vortex Nernst below T_c
- In κ-Br Nernst signal is large in a significant region about T_c
- κ-Br is very close to being a Mott insulator, whereas κ-NCS is at a higher "chemical pressure"
- This is reminiscent of what is seen in the underdoped cuprates



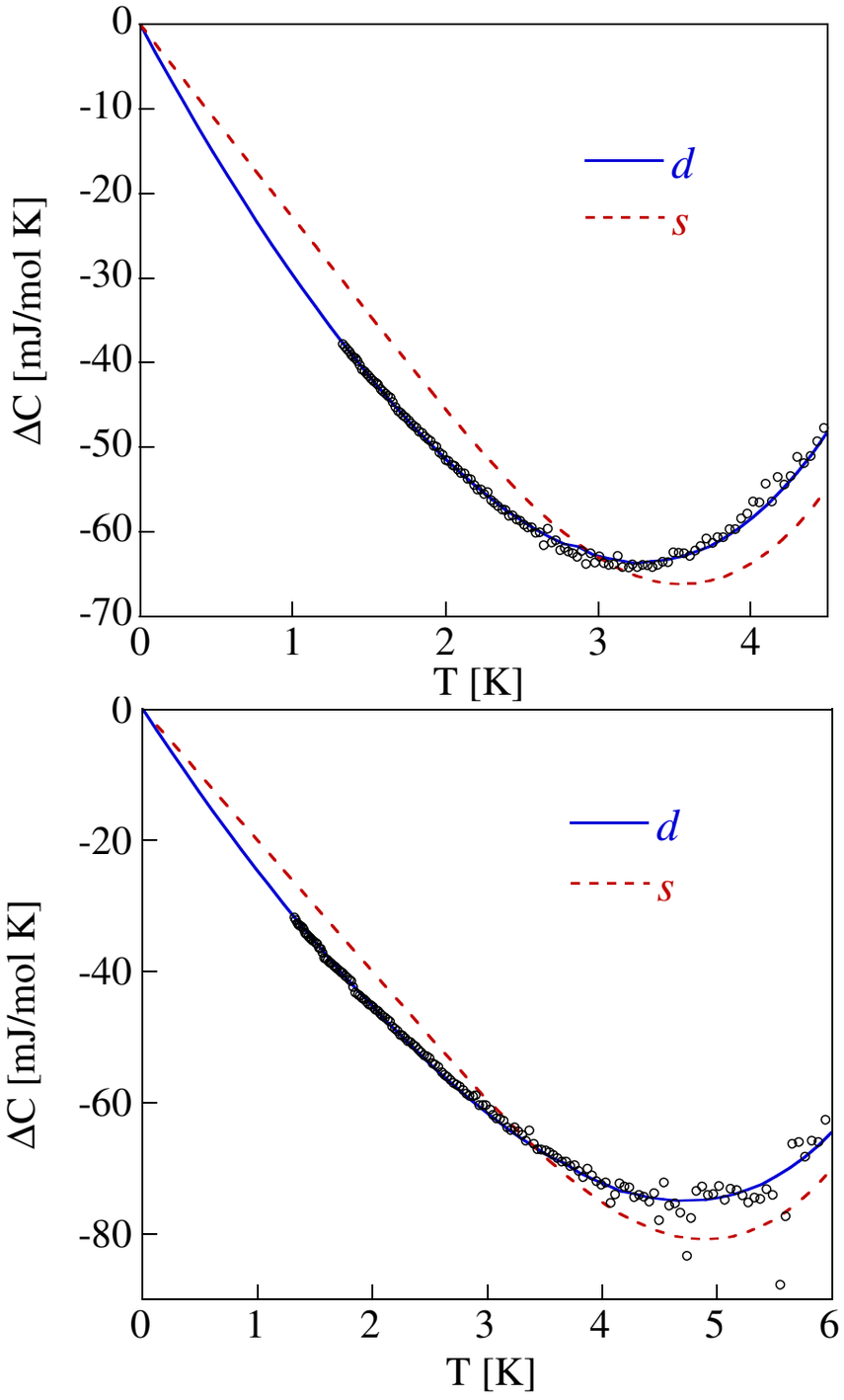




d-wave superconductivity in κ-Br and κ-NCS

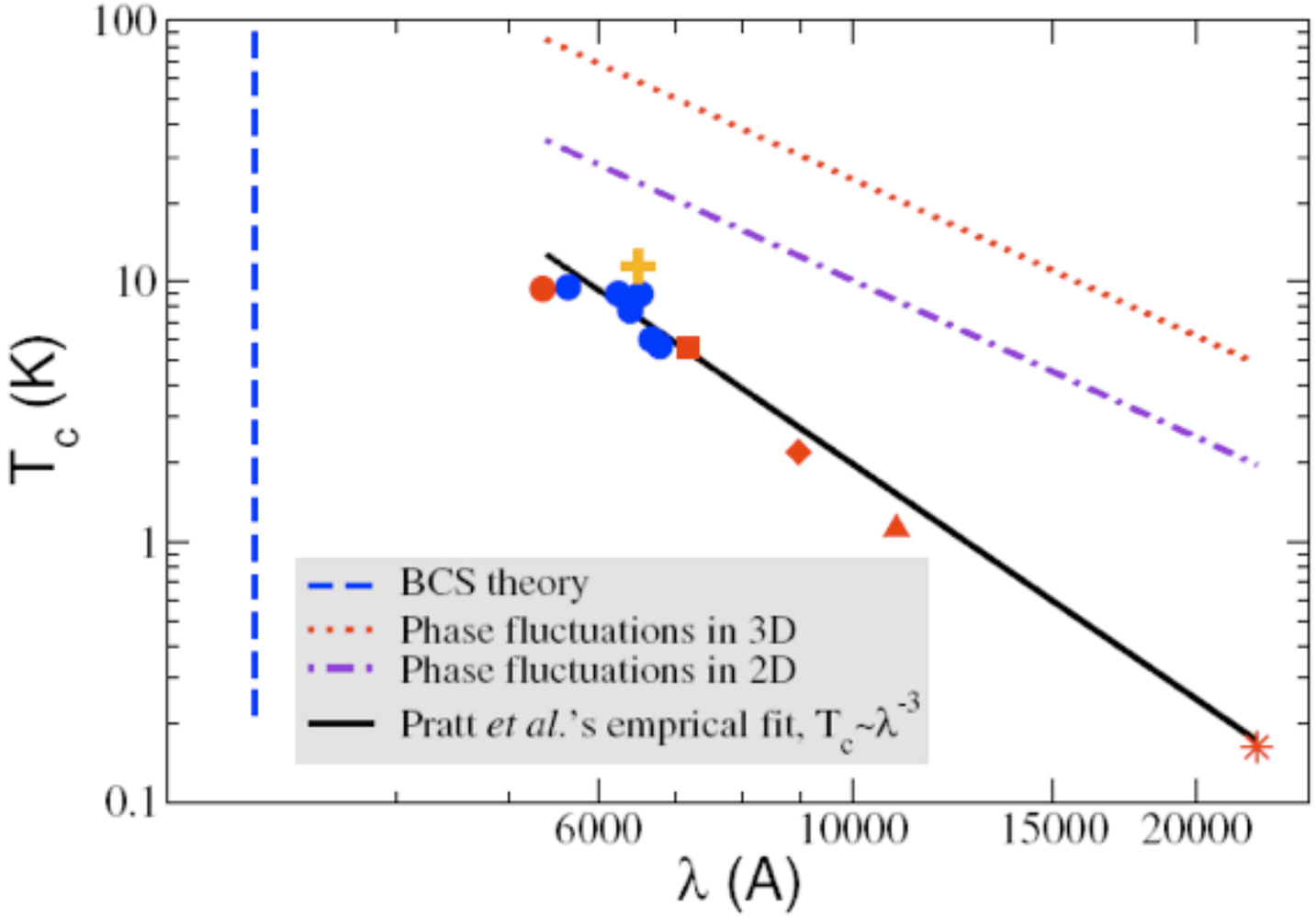
For a review see BJP and McKenzie, JPCM **18**, R827 (2006)

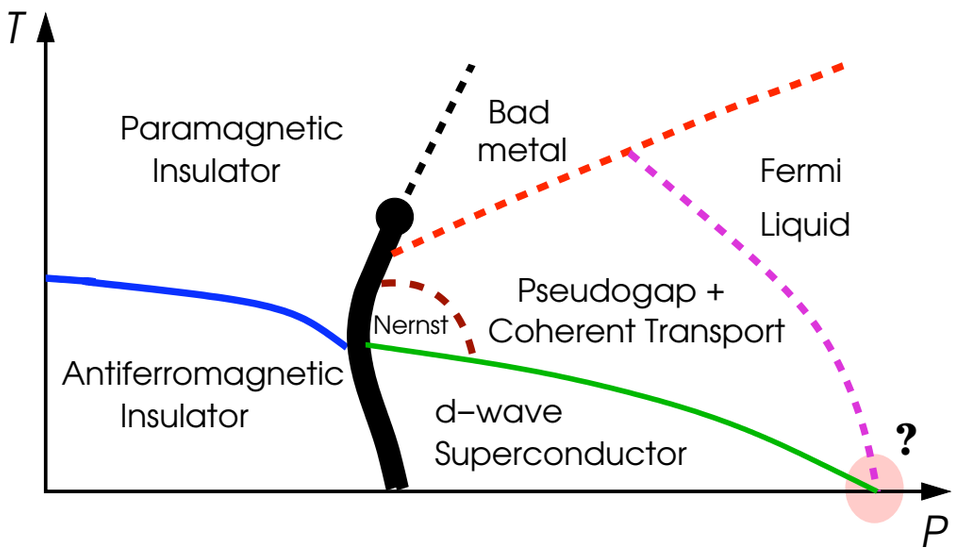
- There has been a long debate about the pairing symmetry
- My view is that the most likely answer is d-wave but others would still argue for s-wave (everyone agrees it is singlet)
  - Disorder suppresses T_c [BJP & McKenzie, PRB 04] - but story is more complicated than it appeared at first sight [Analytis, BJP et al. PRL 06]
  - Power laws in low temperature heat capacity [left: Taylor et al. PRL 07] and NMR [Kanoda et al. PRB 96]
  - Absence of Hebel-Slichter peek in NMR



Small superfluid stiffness

BJP & McKenzie, JPCM **16**, 367 ('04)





$$D_s \propto \frac{1}{\lambda^2}$$

Data from Pratt et al., Polyhedron ('03), Lang et al. PRB ('92) and Larkin et al. PRB ('01) for a variety of organic superconductors (different shapes denote different anions). Also see Pratt & Blundell PRL ('05).

Note that the superfluid stiffness is smallest far from the Mott transition

Gossamer-RVB and organics

BJP & McKenzie; Gan et al.; Liu et al. [all PRL '05]

- First theory of organics to be able to study the competition between the superconducting and insulating phases
- We take a partially Gutzwiller projected BCS wavefunction – solve for the fraction of doubly occupied sites as a variational parameter simultaneously with the BCS variational problem.

$$|\text{Gossamer-RVB}\rangle = \prod_i (1 - \alpha \hat{n}_{i\uparrow}\hat{n}_{i\downarrow})|\text{BCS}\rangle$$

- cf. the "plain vanilla" RVB theory where

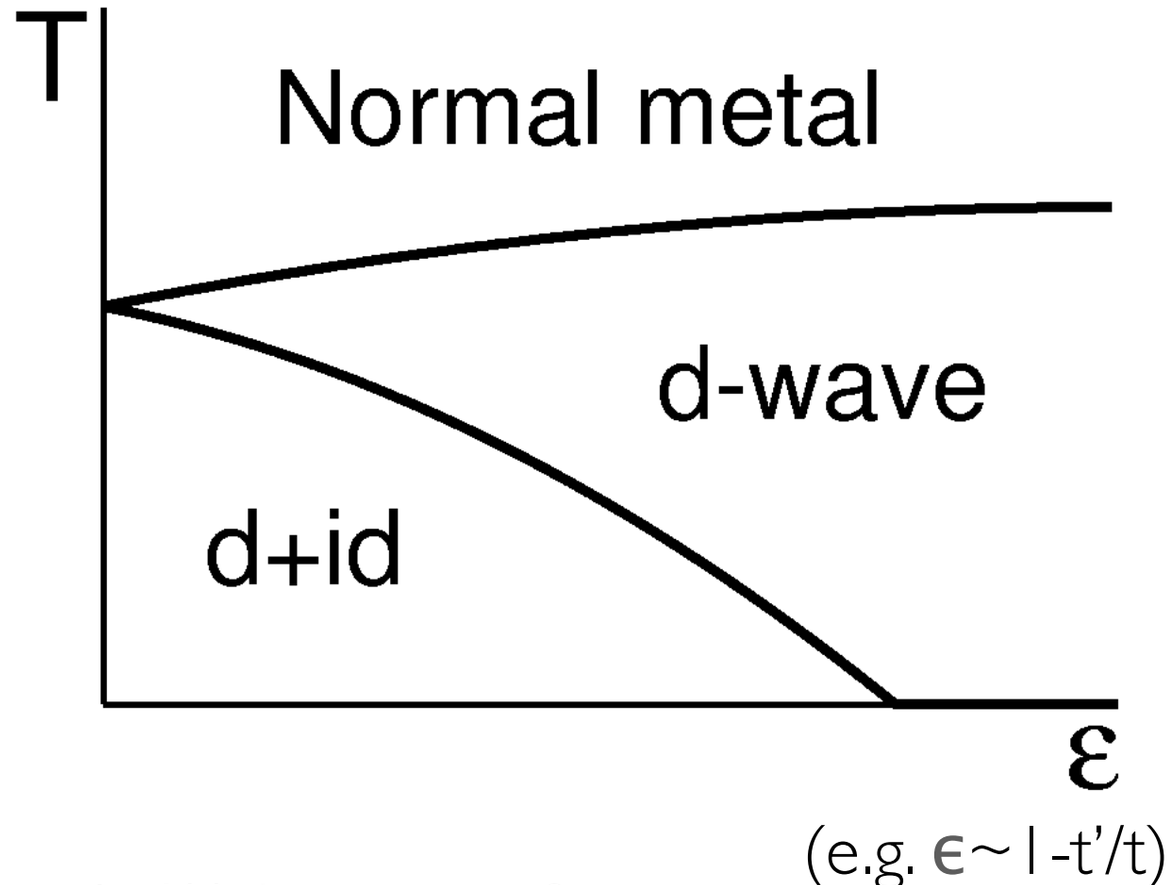
$$|\text{RVB}\rangle = \prod_i (1 - \hat{n}_{i\uparrow}\hat{n}_{i\downarrow})|\text{BCS}\rangle$$

- In qualitative agreement with many experiments [BJP & McKenzie, PRL '05] and CDMFT [Kyung & Tremblay, PRL '06], variational cluster perturbation theory calculations [Sahebsara & D. Sénéchal, PRL '06] and VMC [Watanabe et al. JPSJ '06]
- But does not explain the vanishing superfluid stiffness at high pressures (yet)

Double superconducting phase transition

BJP, JPCM **18**, L575 (2006)

- On the isotropic triangular lattice a group theoretical analysis suggests that it is natural for $d_{x^2-y^2}+id_{xy}$ superconductivity to be realised.
- This occurs because they transform according to the different bases of a 2d irrep.
- But as we break the symmetry we regain either $d_{x^2-y^2}$ or d_{xy} superconductivity



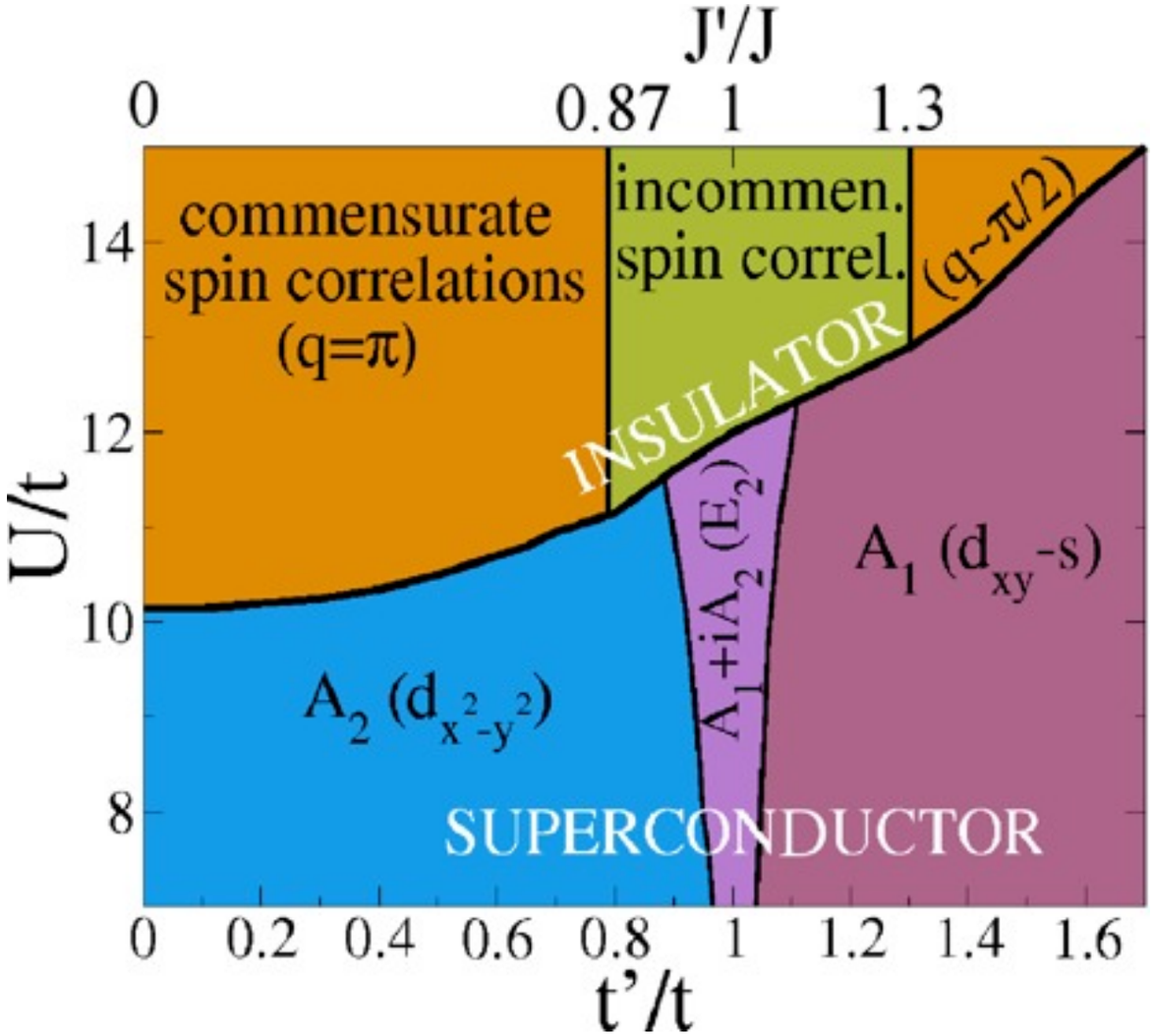
(e.g. $\epsilon \sim 1-t'/t$)

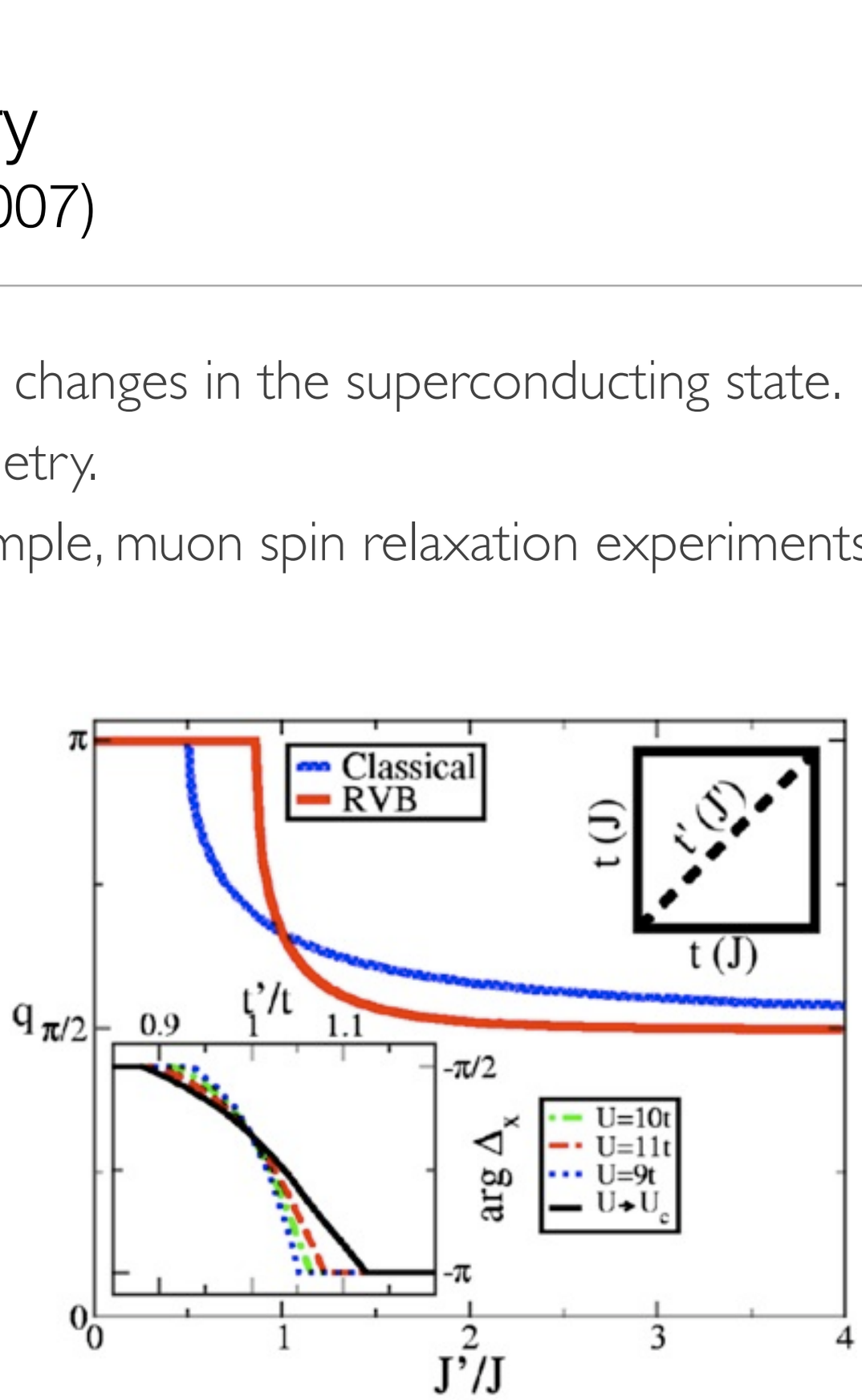
- ϵ is a symmetry breaking parameter (e.g. $\epsilon \sim 1-t'/t$) because of the low crystal symmetry we always have $\epsilon \neq 0$.
- β'-*Pn*$Me_{4-n}Et_n[Pd(dmit)_2]_2$ seem a particularly promising class of systems to look for this double transition in.

Broken time reversal symmetry

BJP & McKenzie, PRL **98**, 027005 (2007)

- As the spin correlations change this drives changes in the superconducting state.
- The d+id state breaks time reversal symmetry.
- This could be directly detected in, for example, muon spin relaxation experiments.

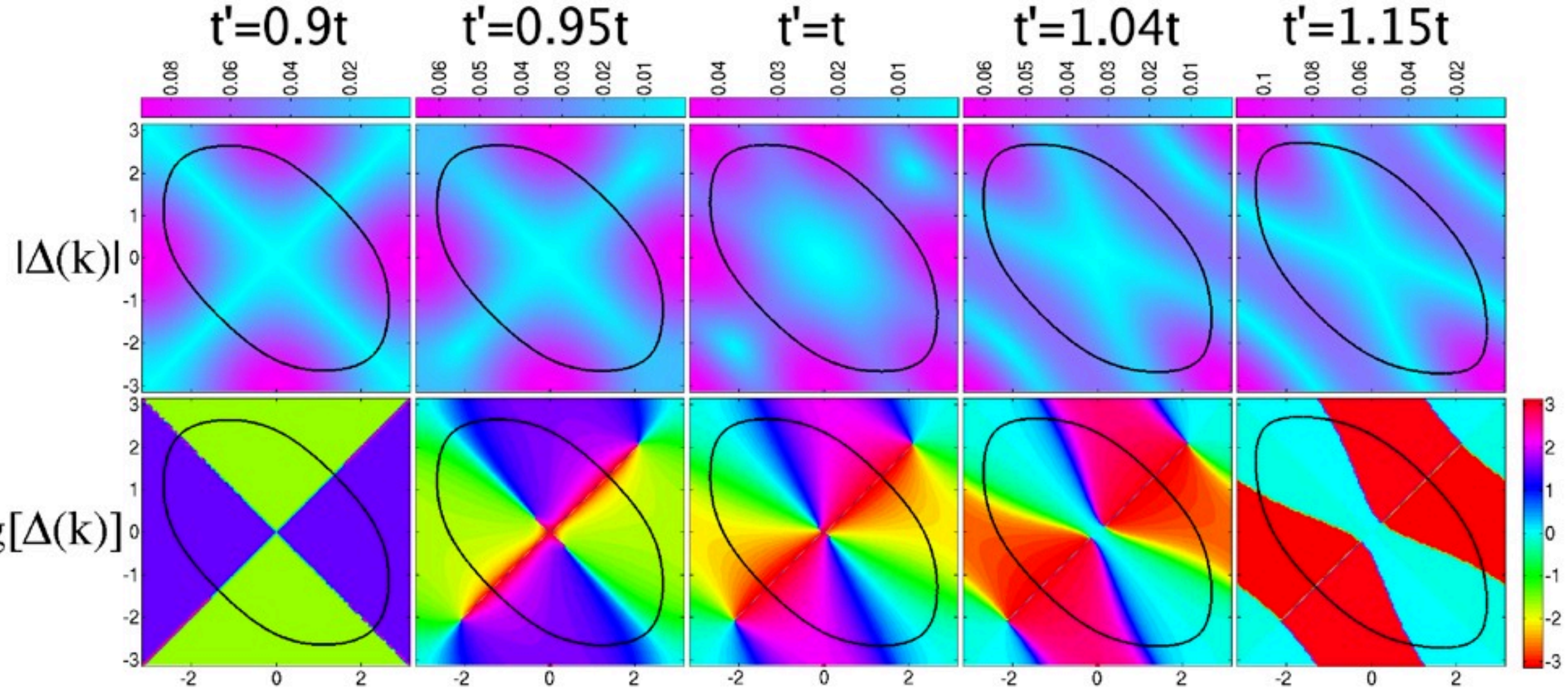




What is the structure of the order parameter?

BJP & McKenzie, PRL **98**, 027005 (2007)

- The d+id state breaks time reversal symmetry.
- This could be directly detected in, for example, muon spin relaxation experiments.



Parameterisation of Hubbard models: band-structure

Nakamura et al., JPSJ '09; Kandpal et al., PRL '09

- Most band structure calculations for BEDT-TTF and $Pd(dmit)_2$ salts have historically been based on the Huckel approximation (a parameterised tight-binding method)
- More recent DFT calculations seem to confirm one's fears that these are not accurate
- For example for κ-$(BEDT\text{-}TTF)_2Cu(CN)_3$ Huckel gives $t'/t \sim 1$, i.e. an (nearly) isotropic triangular lattice - but the triangular lattice Heisenberg model has 120° order (ring exchange [Motrunich PRB '05, '06]?)

Phase diagram of the Heisenberg model on an anisotropic triangular lattice after Weihong *et al*., PRB **59**, 14367 (1999).

- But two recent tight-binding parameterisations of DFT band-structures [Nakamura *et al*., JPSJ '09; Kandpal *et al*., PRL '09] find that $t'/t=0.8$ for κ-$(BEDT\text{-}TTF)_2Cu(CN)_3$
- Does this resolve the conflict with the 120°-state?
- But, high-T series expansions for the isotropic triangular lattice Heisenberg model seem to fit well with the magnetic susceptibility data [Zheng et al. PRB '05]

Parameterisation of Hubbard models: Hubbard *U*

Scriven & BJP, JCP **130**, 105408 ('09); PRB **80**, 205107 (2009).

$$U_d = E_d(0) + E_d(+2) - 2E_d(+1)$$

where $E_d(q)$ is the energy of a $(BEDT\text{-}TTF)_2$ dimer of charge q

- Previous approach has been to treat that dimer as a two site Hubbard model, where each site is a monomer

$$\mathcal{H} = t_m \sum_\sigma \hat{c}^\dagger_{1\sigma}\hat{c}_{2\sigma} + \text{h.c.} + U_m \sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow} + V_m \hat{n}_1 \hat{n}_2$$

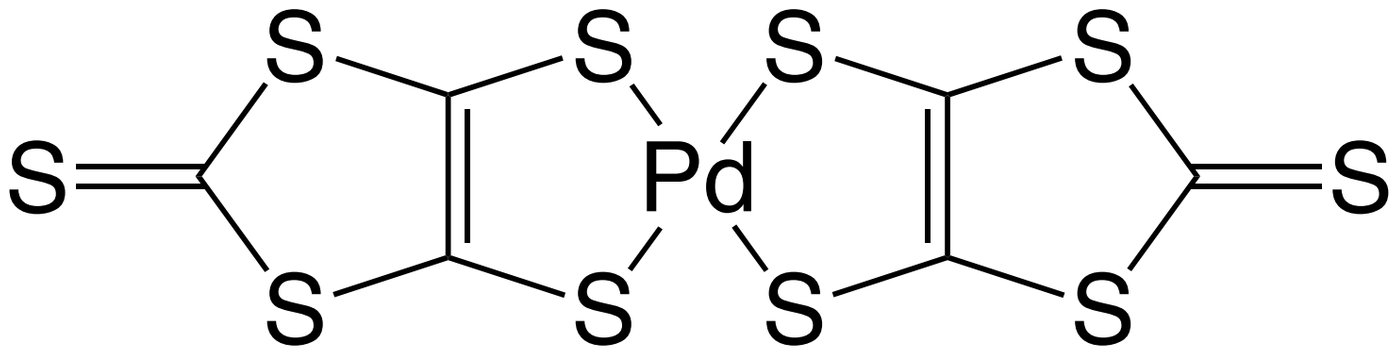
- For $V_m=0$ and $U_m >> t_m$ one finds that $U_d=|2t_m|$ - therefore U_d=0.2-2 eV (variation both between groups and between materials) estimated from Huckel calculations
- DFT calculations of $E_d(q)$ give **U_d=3.2 eV** - for a wide range of **κ** and **β** phase BEDT-TTF salts
- Further we find that $U_m \sim V_m >> t_m$, which leads to $U_d = \frac{1}{2}(U_m+V_m) >> |2t_m|$
- Thus we expect a U_d to be reduced by the polarisability of the crystalline environment, hence

$$U_d^{\text{eff}} = U_d - \delta U_d$$

- **δ**U calculated in other molecular crystals (A_3C_{60}, TTF-TCNQ, oligoacene, thiopenes, etc.), but it is complicated in the BEDT-TTF salts by the polymeric anions, geometry, etc. [Merino et al.]
- However, **δ**U_d may well be quite sensitive to hydrostatic and chemical pressure, and may, therefore, be important for properly explaining the pressure dependence of these materials
- **U_d^{eff} = 0.8 eV** from DFT + constrained-RPA [Nakamura et al., JPSJ '09]
- **U_d^{eff} = 0.3 eV** from comparison of DFMT to optical conductivity [Merino et al., PRL '08]

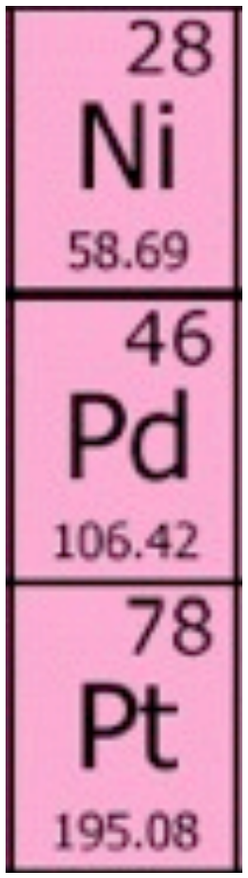
β'-*Z*[Pd(dmit)$_2$]

Review: BJP & McKenzie - in preparation

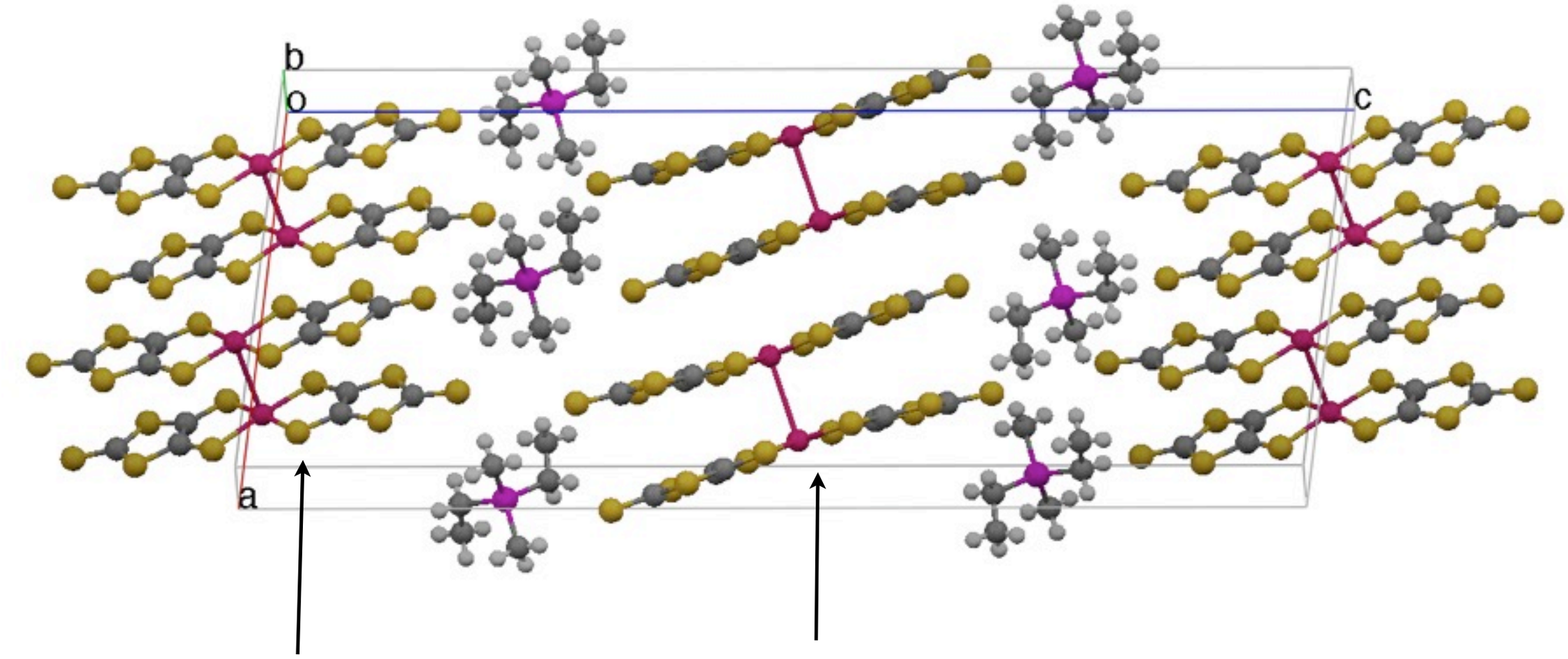


Reizo Kato

- dmit = 1,3-dithiol-2-thione-4,5-dithiolate
- Pd(dmit)$_2$ is a member of a larger class of molecules *M*(dmit)$_2$, where *M* is a transition metal
- Another interesting molecule is Ni(dmit)$_2$, which forms a similar set of charge transfer salts.
  - The Ni salts seem to be quite one-dimensional, but I will not discuss them much today



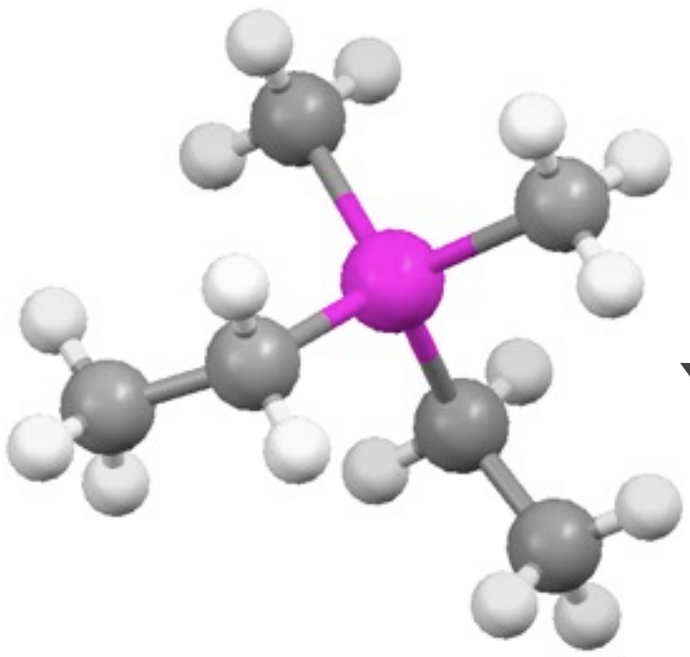
Structure of β'-$Et_2Me_2As[Pd(dmit)_2]_2$



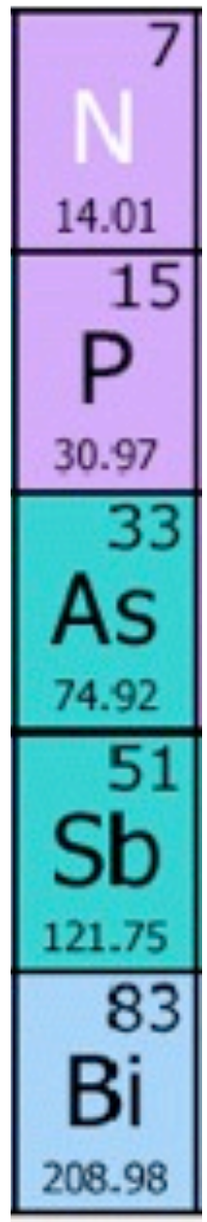
In alternating layers the dimers stack along different directions (a+b and a-b) this is known as the "solid crossing" structure

Cations

- We will focus on cations of the form $Et_nMe_{(4-n)}V$, where *V* is a pnictogen (group V element) and *n* is an integer.
- We will introduce a shorthand notation to *V*-*n* to represent β'-$Et_nMe_{(4-n)}V[Pd(dmit)_2]_2$.
  - e.g., As-3 = $Et_3MeAs[Pd(dmit)_2]_2$
- The pnictogen has to give up one electron in order to form the four bonds - this bond is donated to

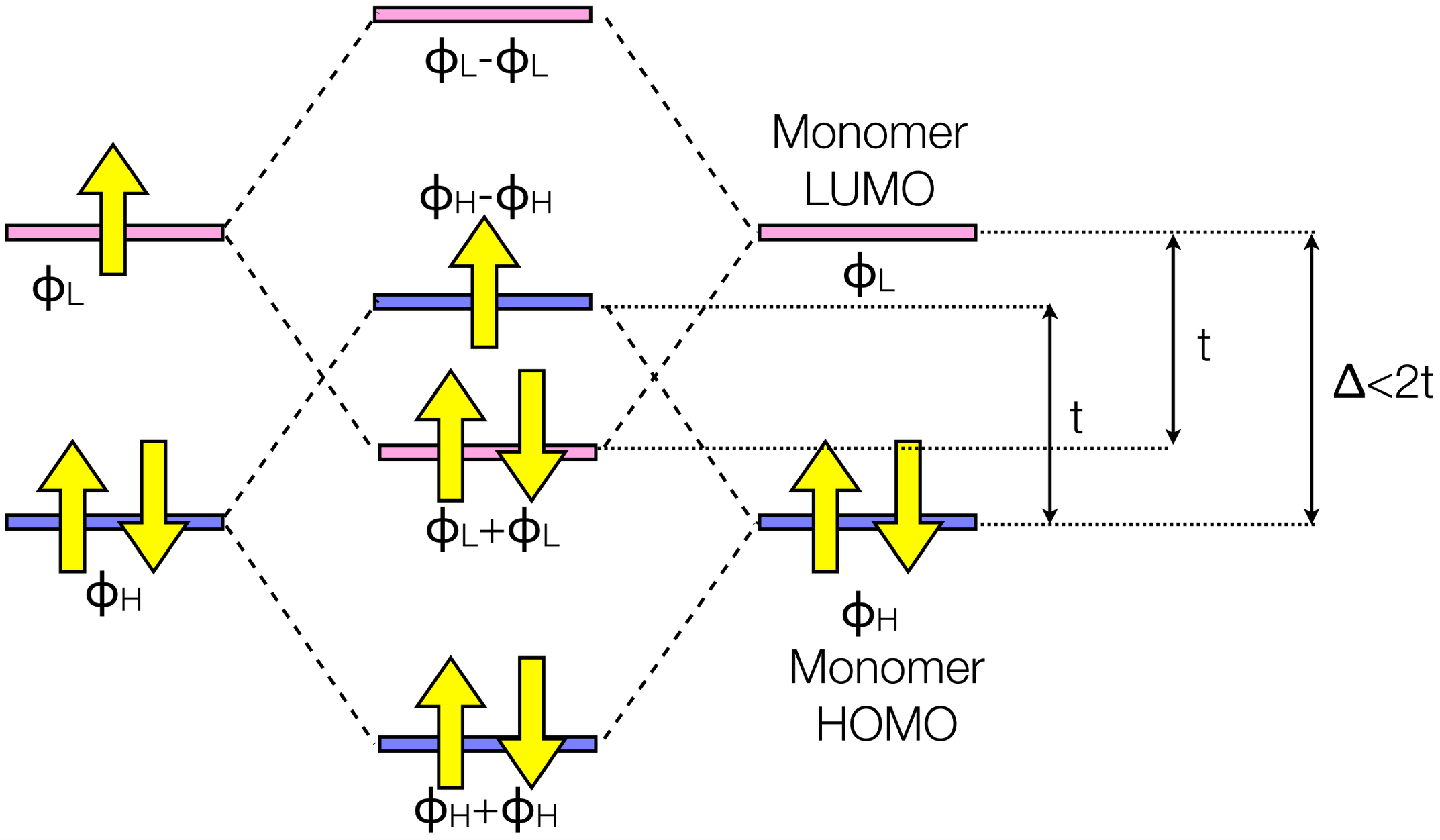


Et_2Me_2As - the cation in As-2



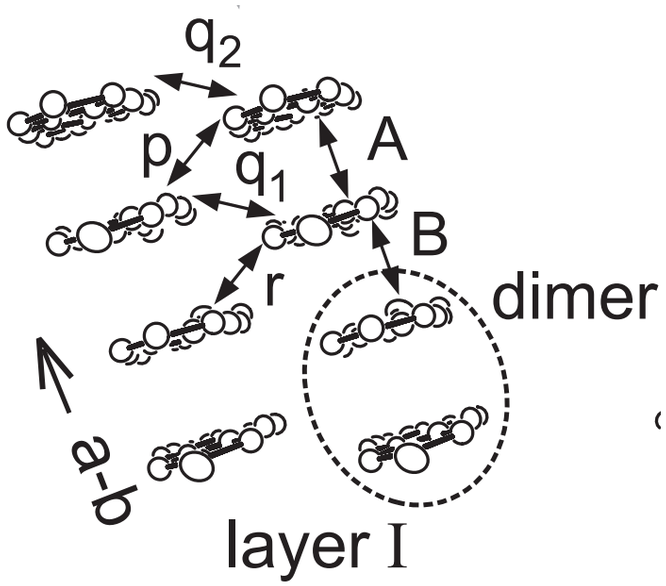
(Non-interacting) electronic structure of the $[Pd(dmit)_2]_2^-$ dimer

- Picture from Huckel (confirmed by DFT [Miyazaki & Ohno, PRB '99])
- The HOMO-LUMO splitting, $\Delta<2t$ (or, more accurately, t_H+t_L)

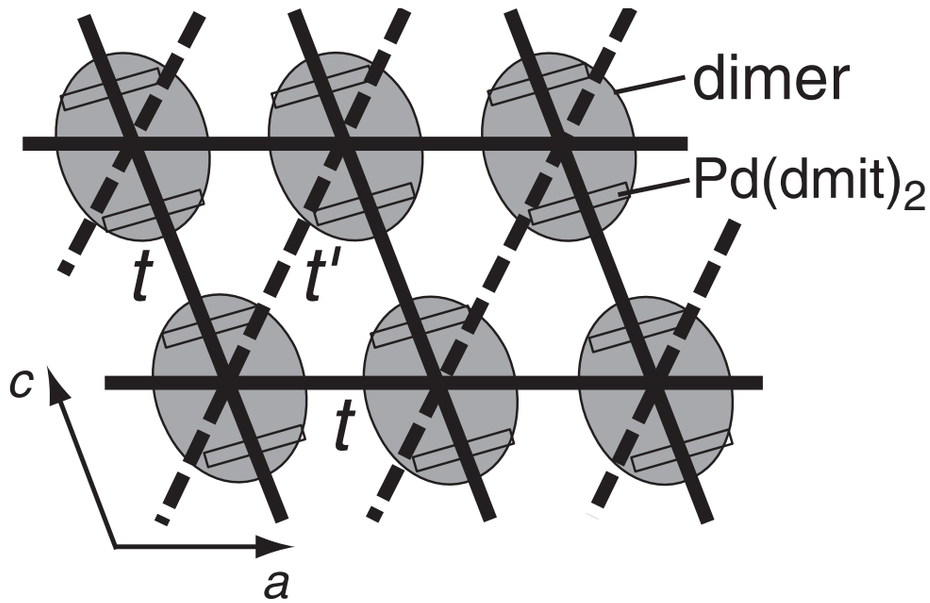


Band structure (extended Huckel-tight binding)

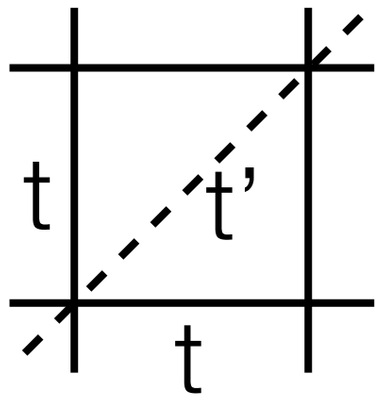
Miyazaki & Ohno, PRB **59**, R5269 (1999)



effective dimer model

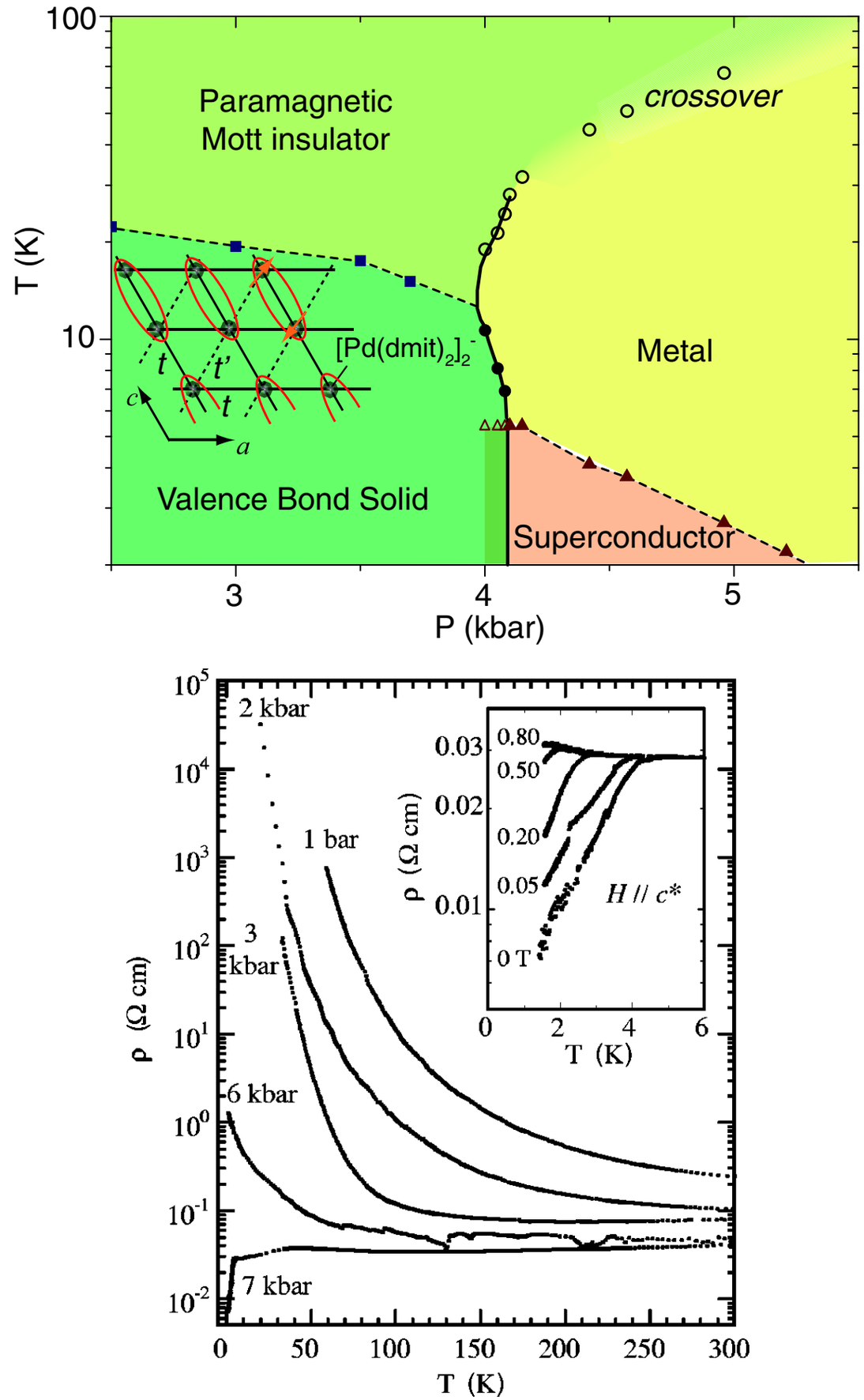


topologically equivalent



Metal-insulator transition

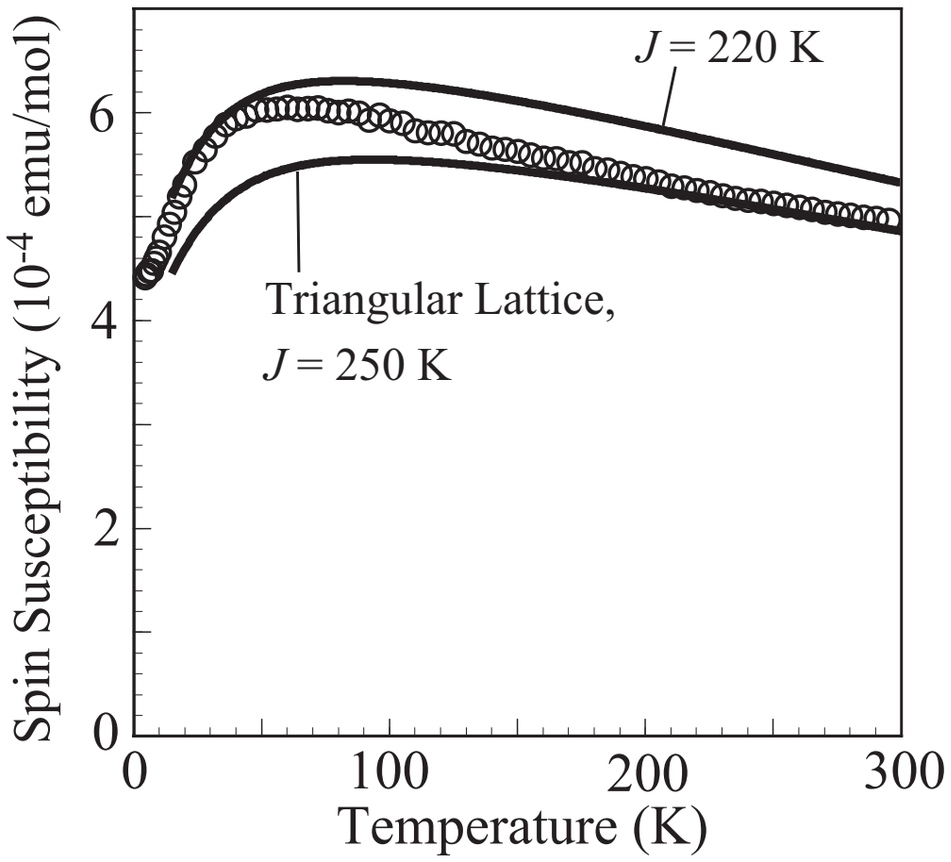
- Note that both of the DFT and the Huckel calculations predict that the Z^+ $[Pd(dmit)_2]_2$- salts are metals - as they have half filled bands
- Experimentally they are insulators
- This suggests that they are Mott insulators
- A Mott metal insulator transition can be driven in *some materials* by hydrostatic pressure [Shimizu et al. PRL 07; P-1, upper Fig.] or uniaxial stress [e.g. Kato et al. PRB '02; As-0; lower Fig.] (but not by chemical pressure)

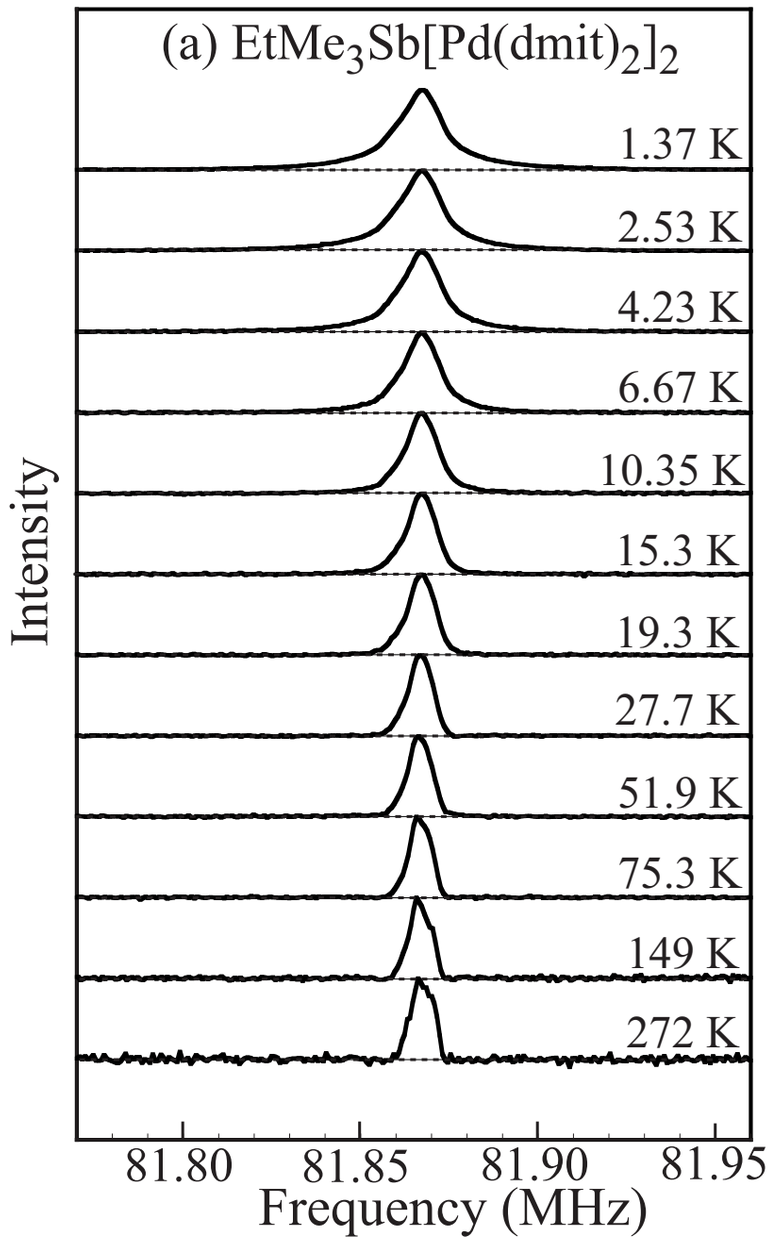


Spin liquid in Sb-1

Itou et al., PRB 77, 104413 (2008)

- No magnetic phase transition observed down to the lowest temperature studied
- J~240 K from fits to high temperature series expansions
- Very reminiscent of κ-CN_3

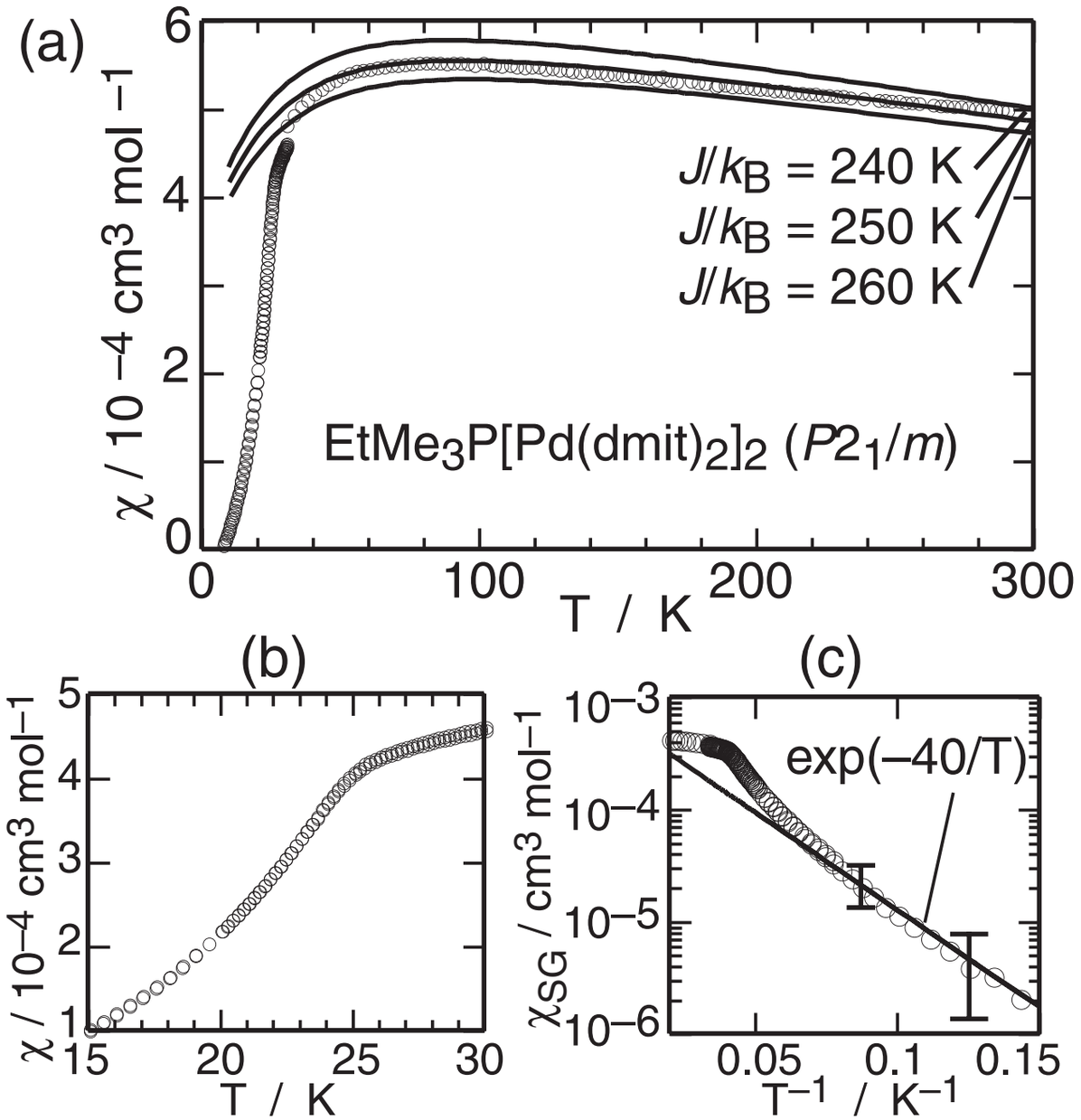




Valence bond solid in P-1?

Tamura et al. JPSJ 75, 093701 (2006)

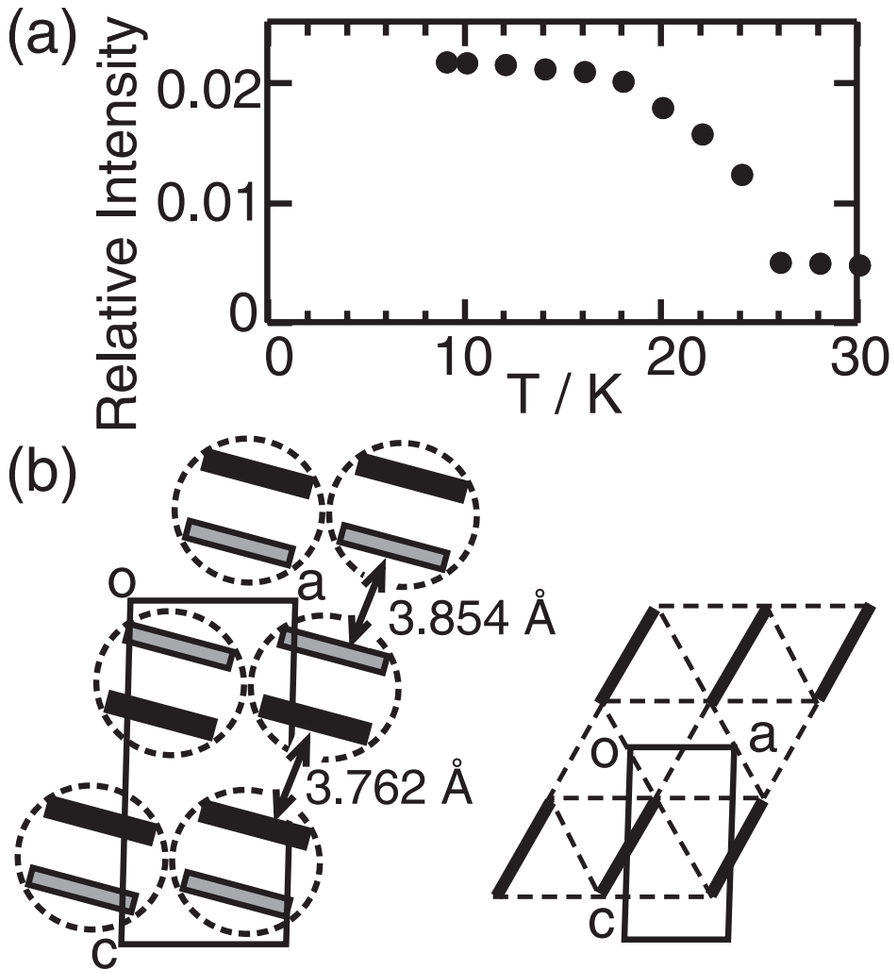
- Sudden drop in the magnetic susceptibility, χ, at 25 K.
- The transition is hysteric (first order)
- Below the transition there susceptibility displays an Arrhenius behaviour (i.e., a gap opens between the ground state and the lowest lying triplet excitation - there is no such gap in the high temperature phase)
- The VBS phase has a gap between the ground state and the lowest lying triplet excitation



Valence bond solid in P-1?

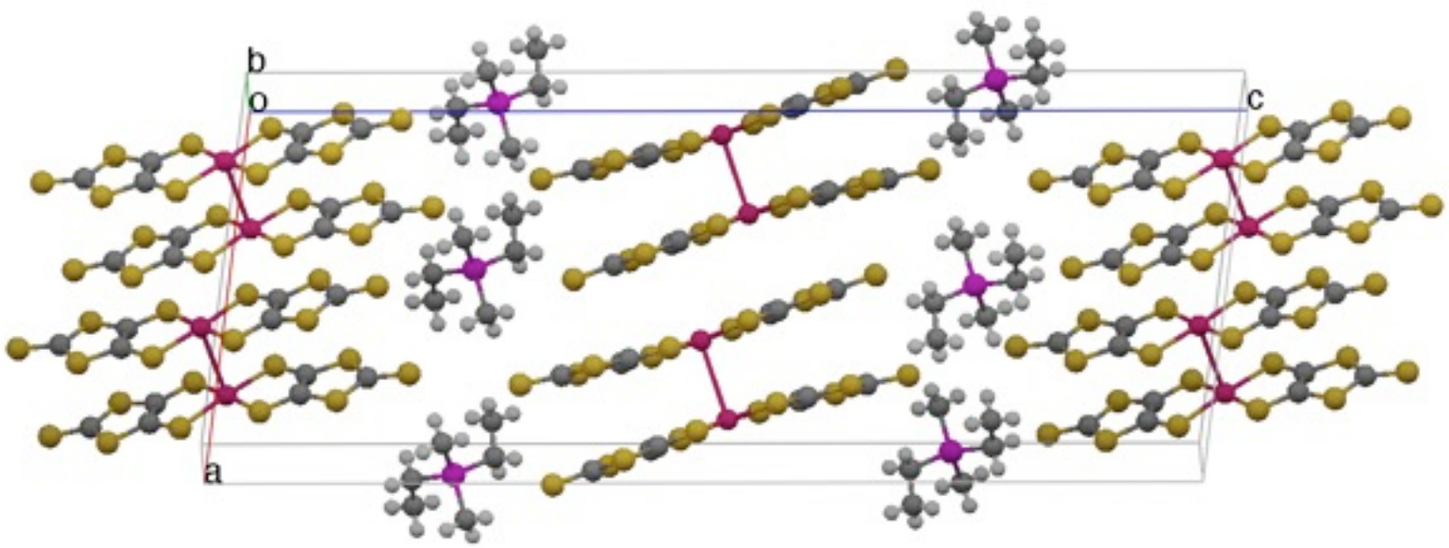
Tamura et al. JPSJ 75, 093701 (2006)

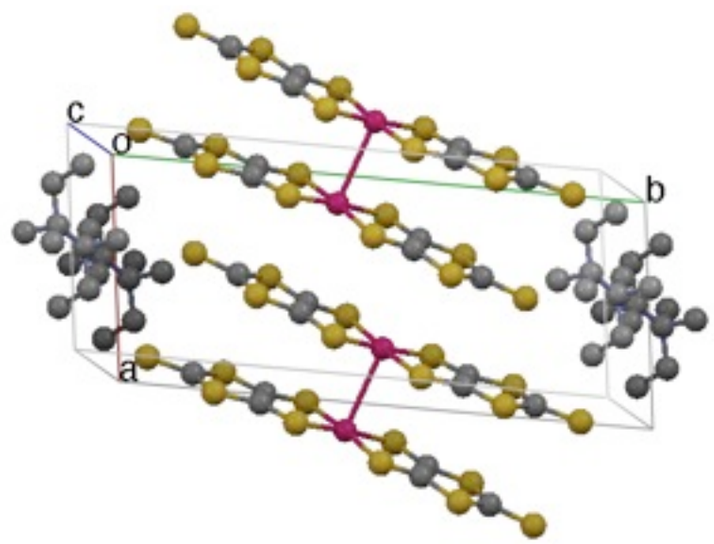
- Satellite reflections are also seen in the x-ray diffraction pattern below 25 K
- These correspond to a loss of periodicity in the crystal
- In the low temperature phase the distances between (the planes of S atoms neighbouring the Pd atom in) neighbouring dimers is either 3.85 or 3.76 Å, whereas in the high temperature phase the all dimers are separated by 3.82 Å
- This is what one would expect in the VBS phase as the spin-phonon coupling would favour exactly this type of disorder in the VBS phase



What is special about P-1?

- None of the other *V-n* salts show a VBS phase so we would like to understand what is special about P-1.
- P-1 has a $P2_1/m$ crystal whereas most of the others have a C2/c crystals
- The loss of the glide plane (.../m instead of .../c) in P-1 corresponds to absence of the “solid crossing” crystal packing (shown, right)
- In P-1 all the organic layers are equivalent
- Tamura *et al*. argued that the in the C2/c crystals the lattice distortion in different layers would be in different directions, and so would cause a large strain making the VBS phase unfavourable

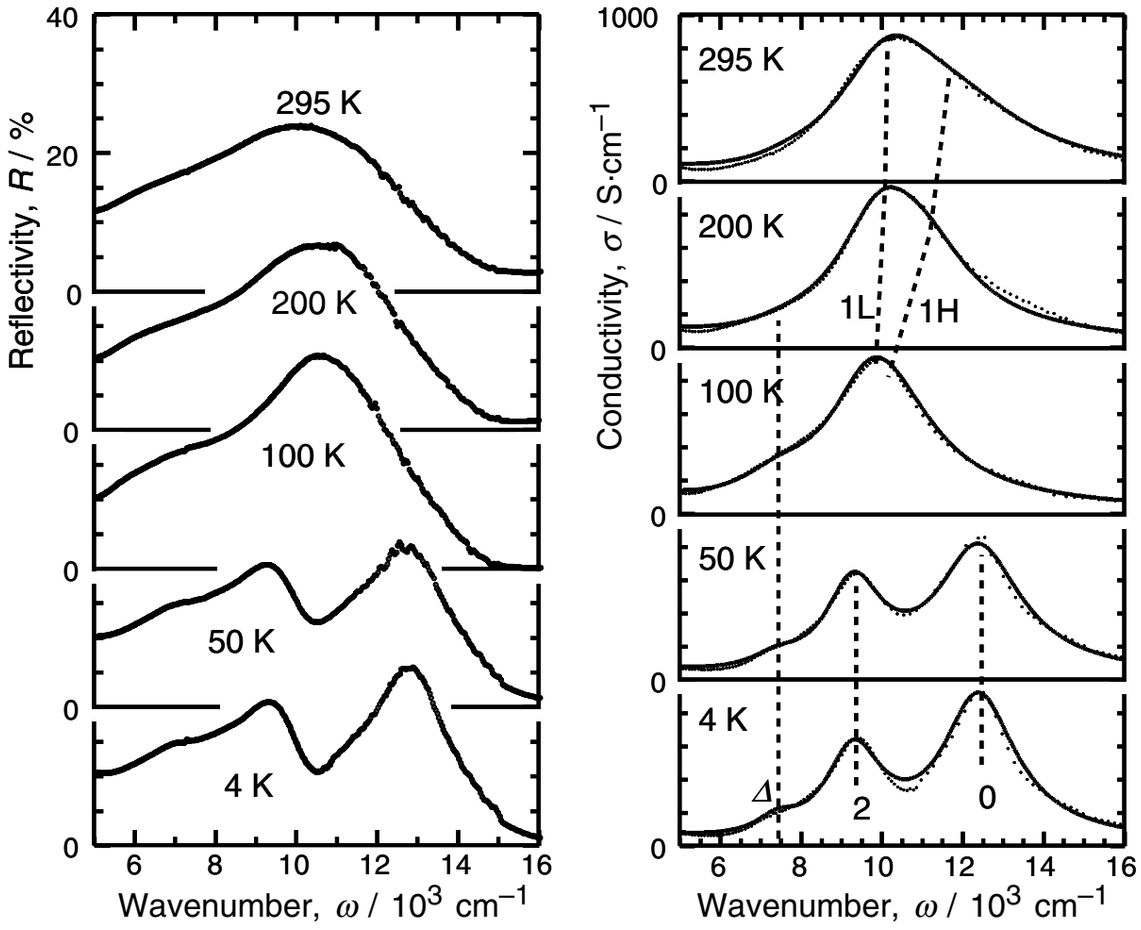


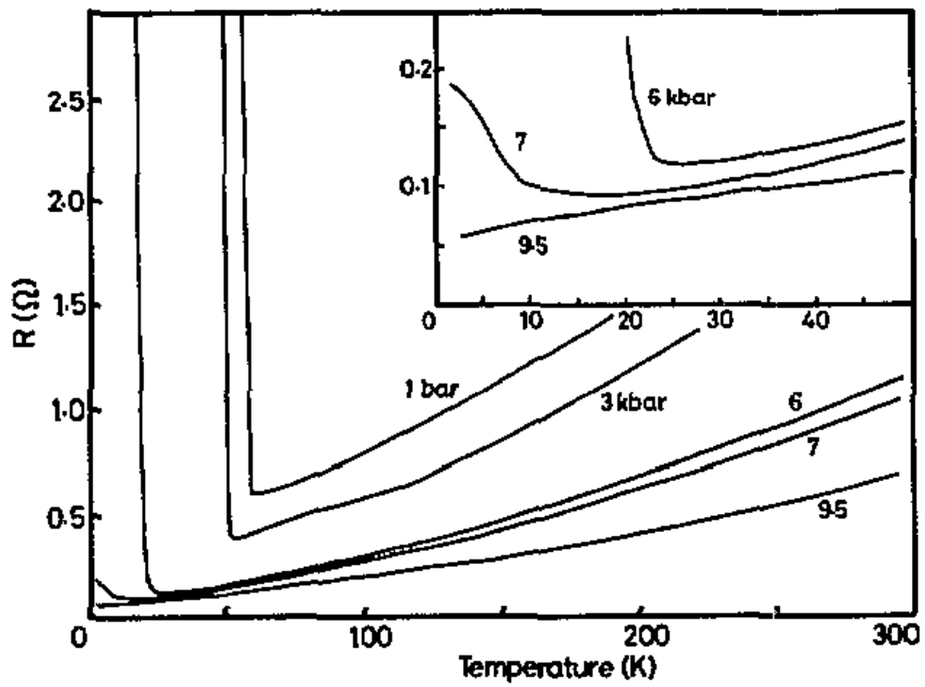


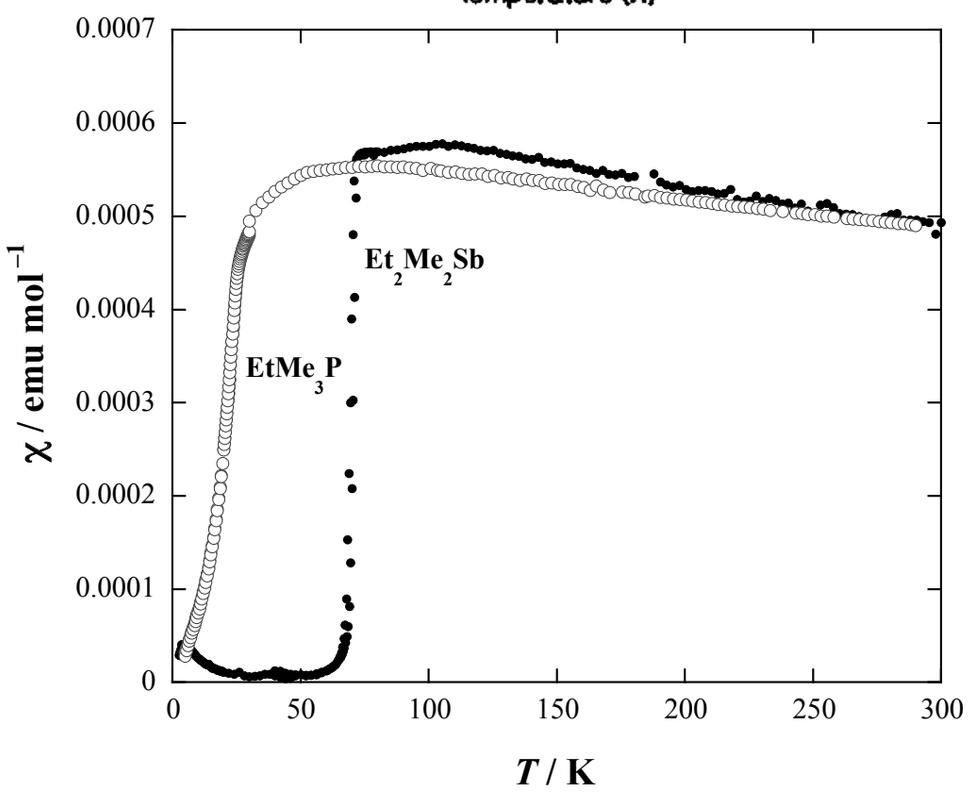
Charge ordered insulator in Sb-2 and Cs-00?

Tamura et al. CPL **411**, 133 (2005)

- P-2 and Cs-00 show very similar phase transitions are 70 & 65 K respectively
- The susceptibility vanishes rapidly in both materials, suggest all the spins pair up
- Cs-00 undergoes a metal-insulator transition at the same temperature (I am not aware of equivalent data for Sb-2)



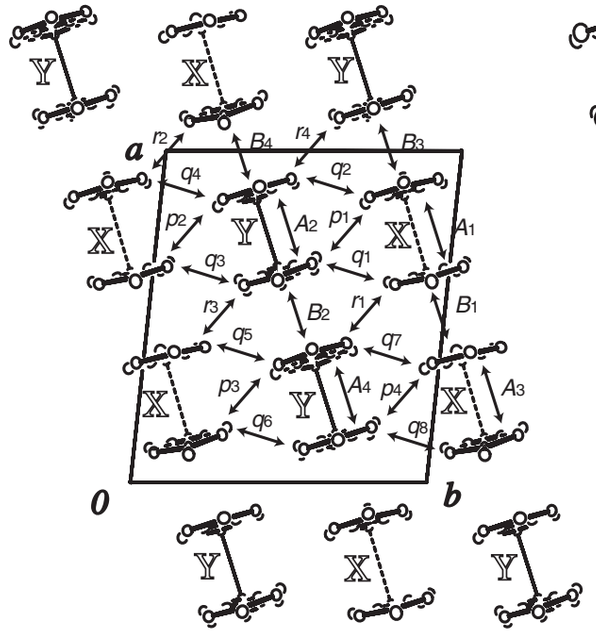


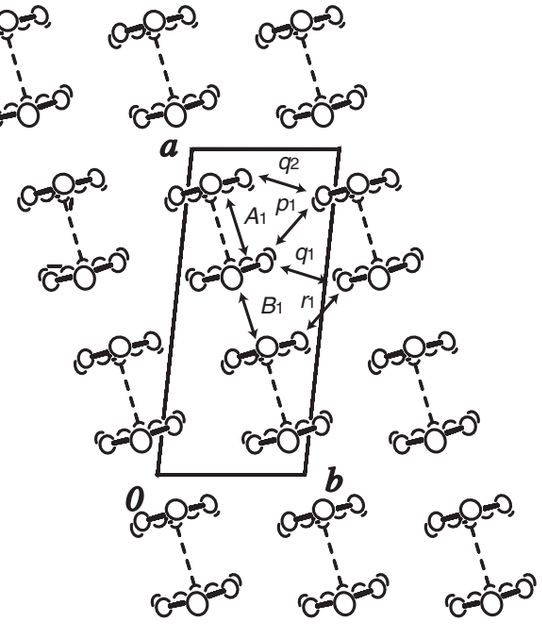


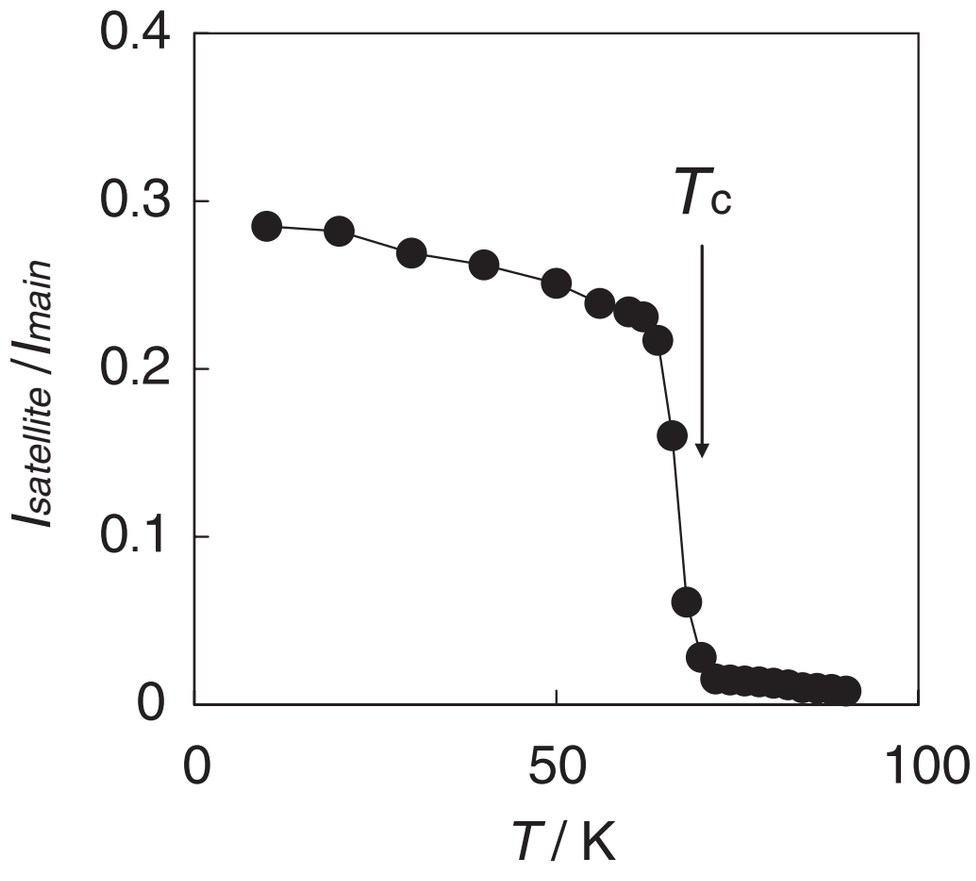
Structural phase transition in Sb-2 and Cs-00?

Nakao & Kato, JPSJ **74**, 2754 (2005)

- Nakao *et al*. [JPSJ **74**, 2754 (2005)] found that this phase transition is associated with a crystallographic phase transition C2/c →$P2_1/m$
- This basically corresponds to a doubling of the unit cell
- The phase transition appears to be first order



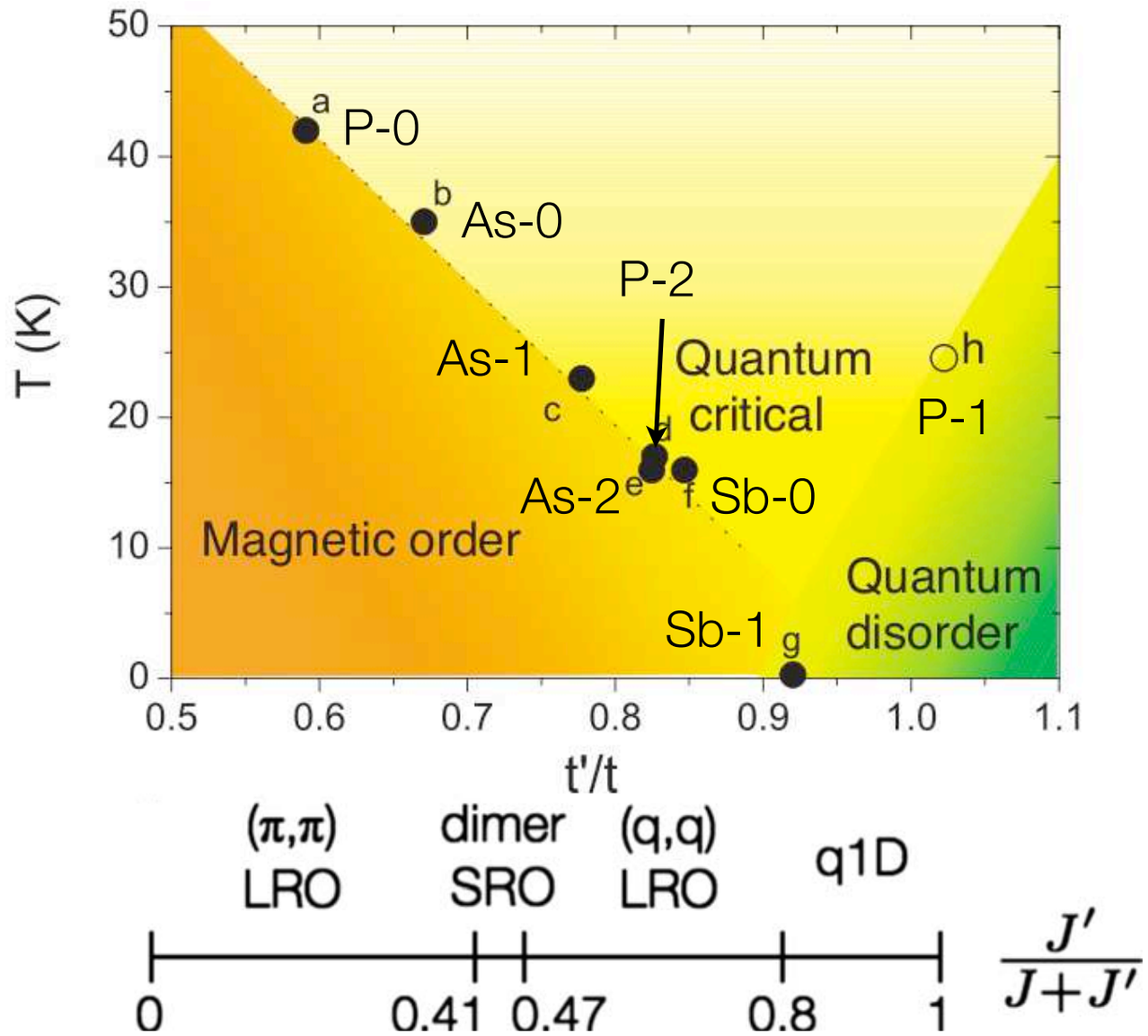




Phase diagram

Shimizu et al. JPCM **19** 145240 (2007)

- Shimizu *et al*. [JPCM '07] have argued that controlling the frustration drives the system into the spin liquid state
- However their phase diagram does not match what is known theoretically about the model
- Their *t* values come from Huckel - is this the problem?
- It is known the Huckel overestimates t'/t in the BEDT-TTF salts
- Another trend in the data is that systems near the Mott transition have lower T_Ns (i.e., become antiferromagnetic at lower temperatures)
- A simple trend is that salts with larger cations have lower T_Ns



Weihong *et al*., PRB **59**, 14367 (1999).

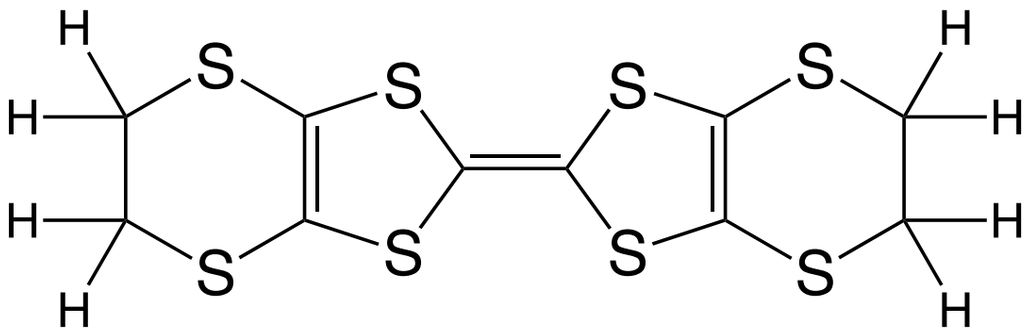
Superconductivity

- Very little is known about the superconducting state.
- Zero resistance has been observed under pressure or uniaxial stress in several $Pd(dmit)_2$ salts - this tells us that they superconduct, but not much more (T_c is typically a few K)
- The Meisner state has been observed in P-1 [Ishii *et al*., JPSJ '07], which confirms that it's bulk superconductivity
- As far as I'm aware we don't know any more about the superconducting state

Overview

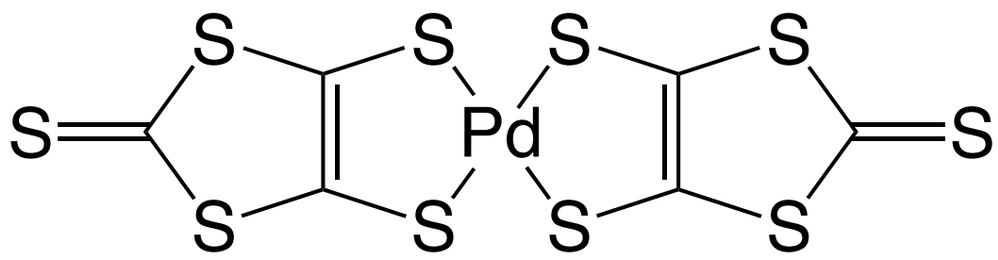
For a review see BJP and McKenzie, JPCM **18**, R827 (2006)

κ-(BEDT-TTF)$_2X$



- Structure and phase diagram
- Model Hamiltonian
- Metal-insulator transition
- Spin liquid
- Strongly correlated metal
- Nernst effect
- Superconductivity
- Parameters for the model Hamiltonian

β'-Z[Pd(dmit)$_2$]



- Structure and phase diagram
- Model Hamiltonian
- Metal-insulator transition
- Spin liquid
- Valence bond solid
- Charge ordered insulator
- Superconductivity
- White space for theorists!