Cooperative Mechanisms for pairings in Low Dimensional Organic Conductors

C. Bourbonnais
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Les gens. La découverte. L'innovation.

Outline

Part I

- Magnetism and Superconductivity in q-1D organics:
  - Linear resistivity and Nuclear relaxation rate
  - Quantum critical effects
  - One-loop RG of q-1D e-gas for purely repulsive Int.

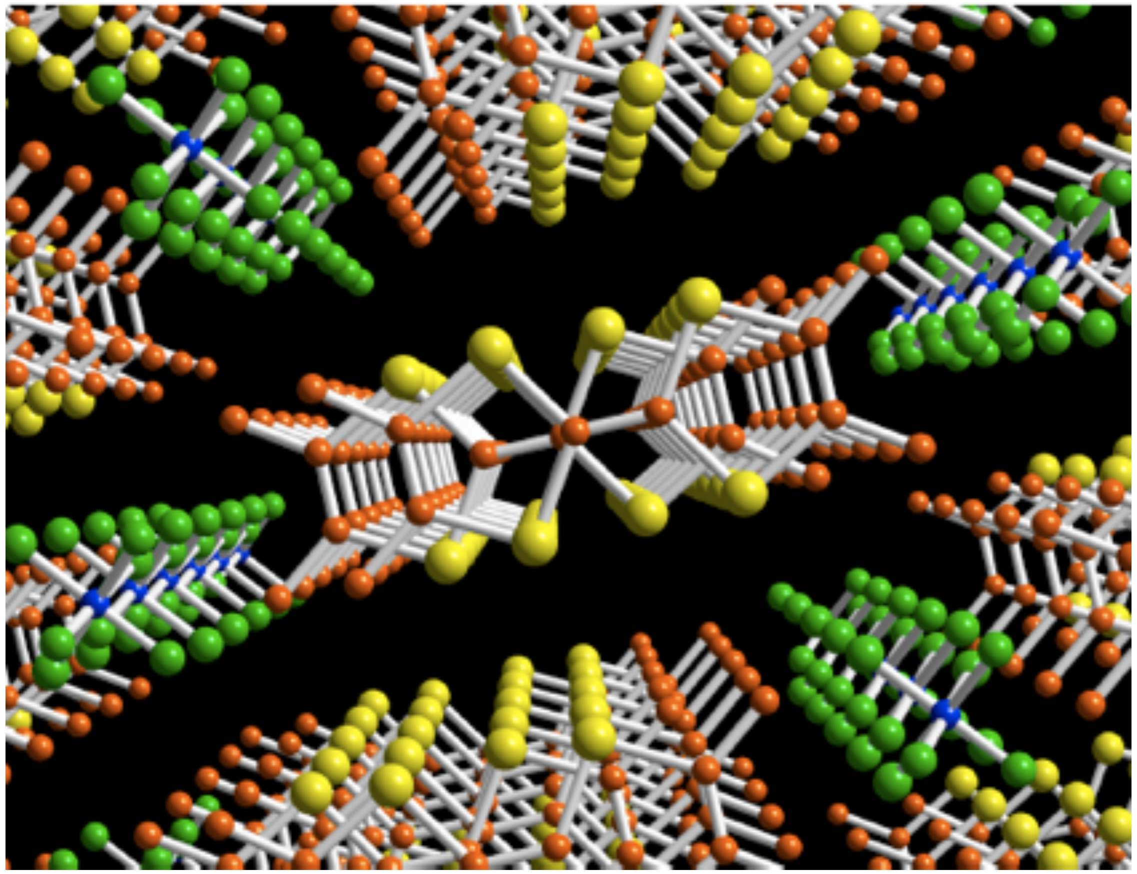
Part II

- Role of e-phonon int. for SDW magnetically driven SC-*d*

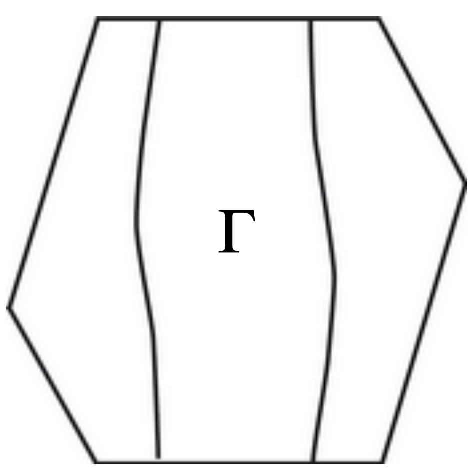
Summary & Conclusion

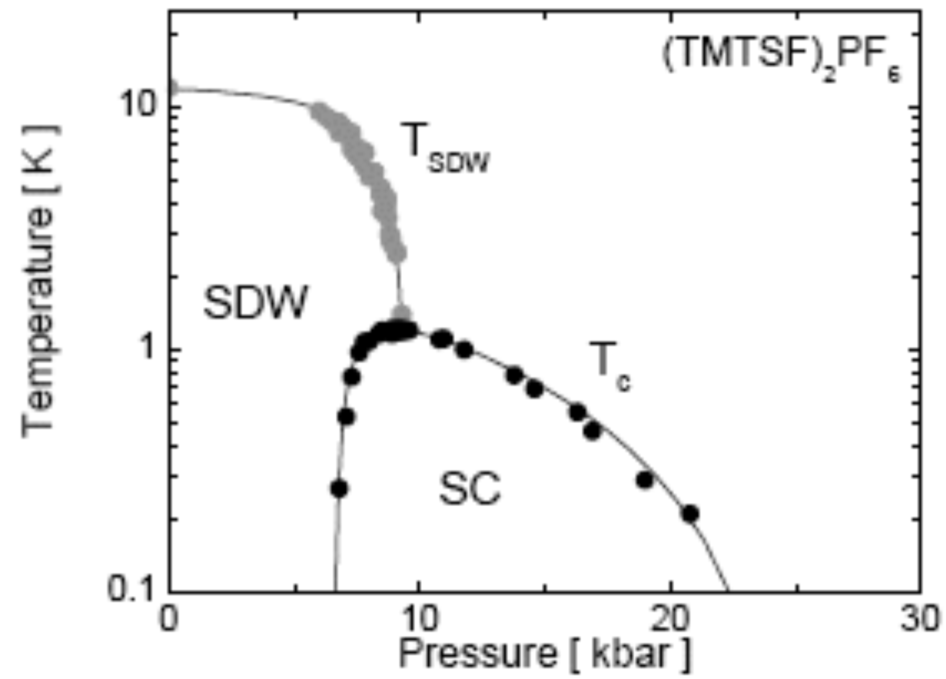
Motivation: The Bechgaard salts, paradigm of SDW- SC proximity

$(TMTSF)_2X$ X= PF_6, AsF_6, ...



Quasi-1D organic metal





N. Doiron-Leyraud *et al.*, PRB 80, 214531 (2009)

- SDW (~10K) $\xrightarrow{P}$ SC (~ 1K)
- Spin fluct.(Normal phase)

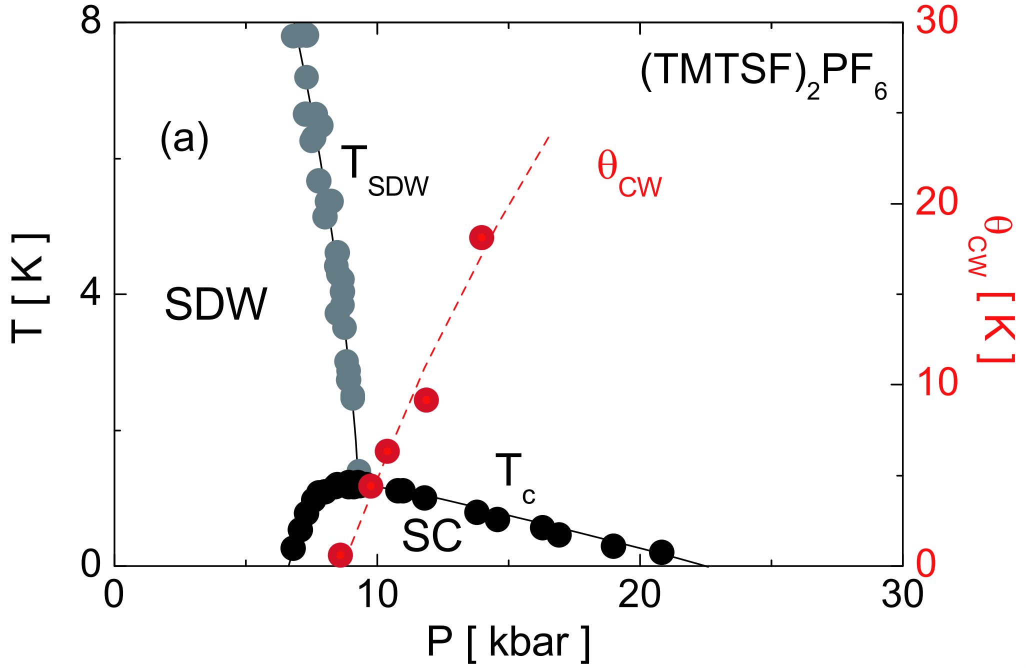
$\rho \sim AT$ (***linear-T*** resist.)

$(T_1 T)^{-1} \sim (T+\Theta)^{-1}$ (***CW***-NMR relax.)

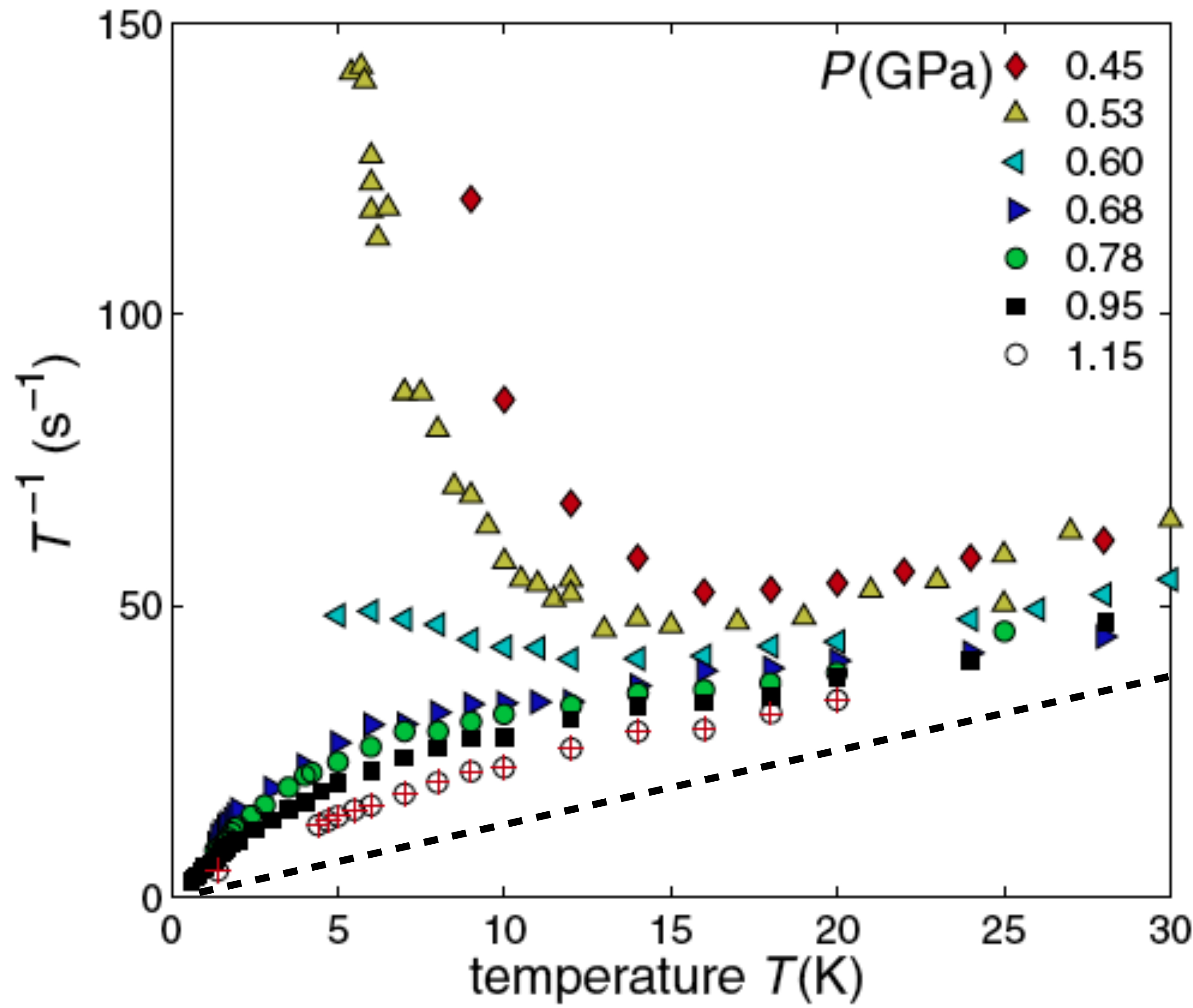
- Repulsive Int. dominate

SC magnetically driven

Spin fluctuations in the metallic state: NMR



N. Doiron-Leyrault *et al.,* PRB (2009)



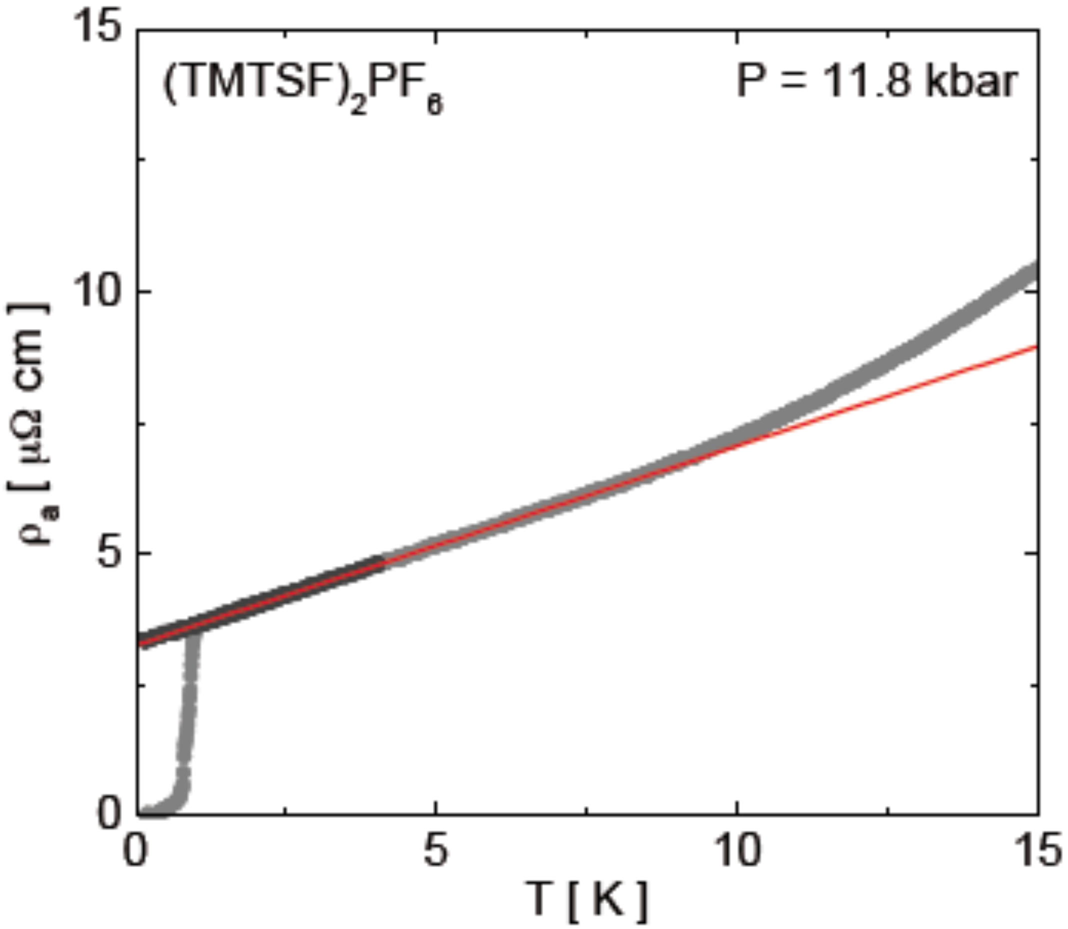
S. Brown *et al.,* The Physics of *Organic Superconductors and Conductors* (Springer, Heidelberg), 2008.

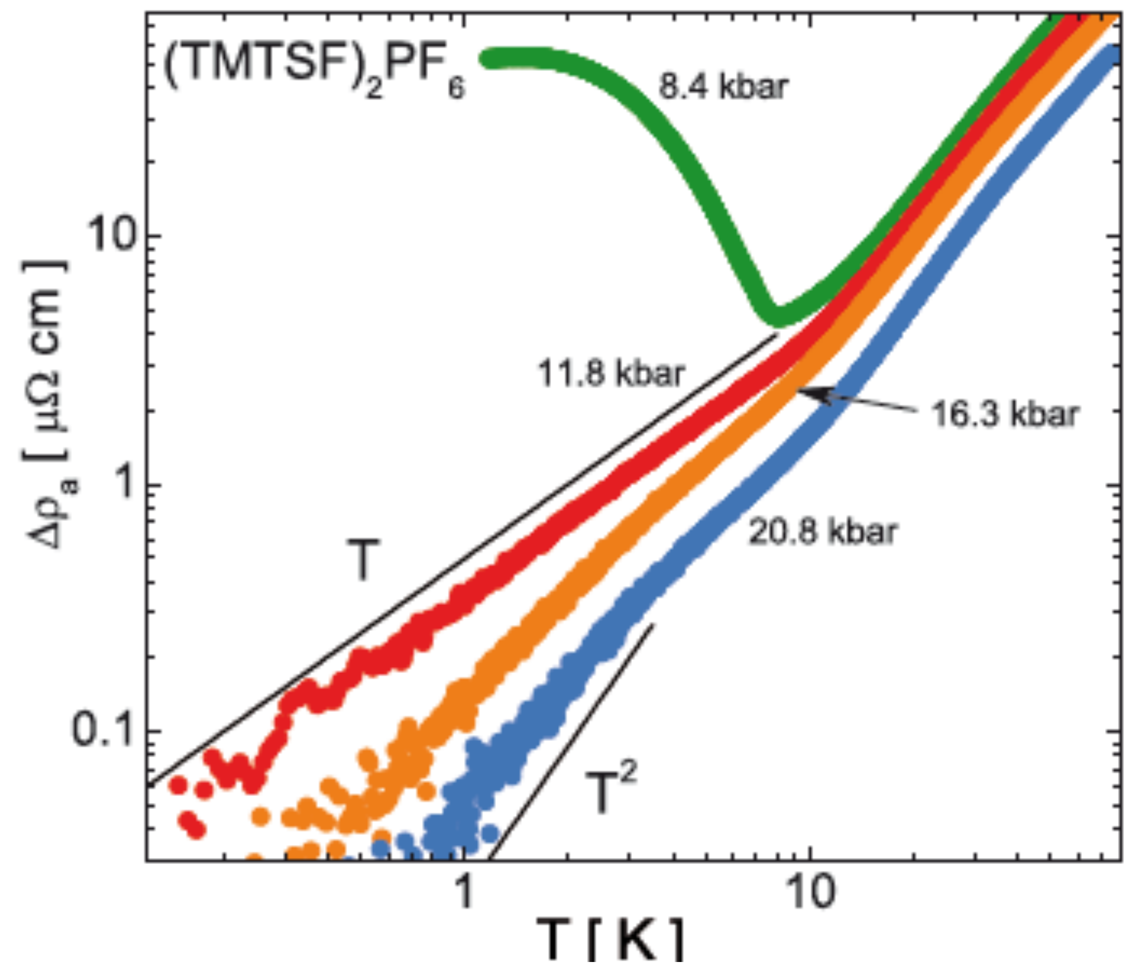
$$T_1^{-1} \sim \frac{T}{T + \Theta}$$

Curie-Weiss (NFL)

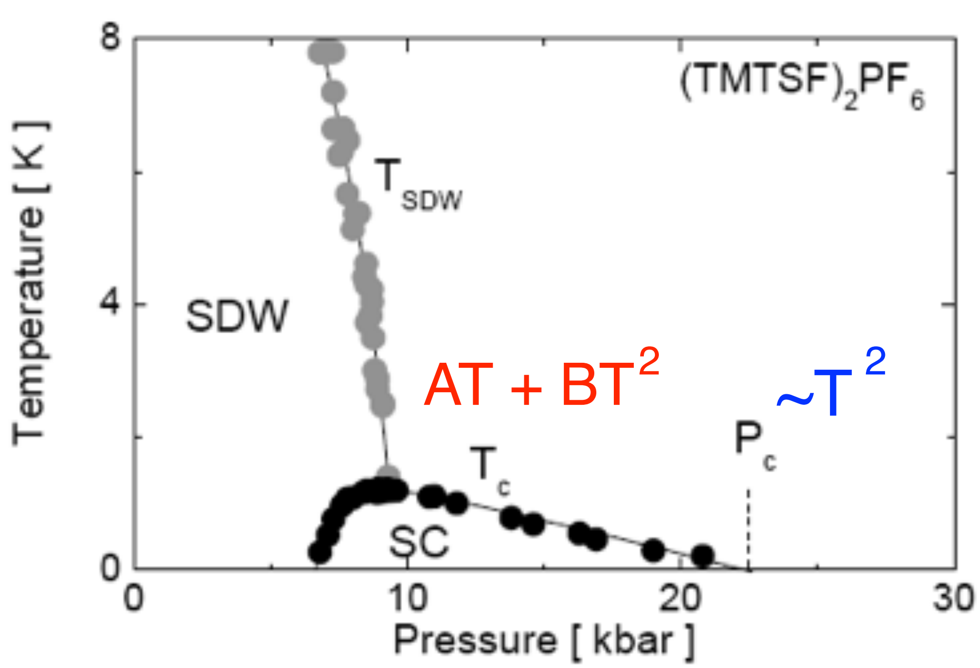
Also,
F. Creuzet *et al.,* Synthetic Metals (1987); J. Phys. Letters (1984)
Wu *et al.*, PRL (2005)
Y. Kimura, PRB (2011)

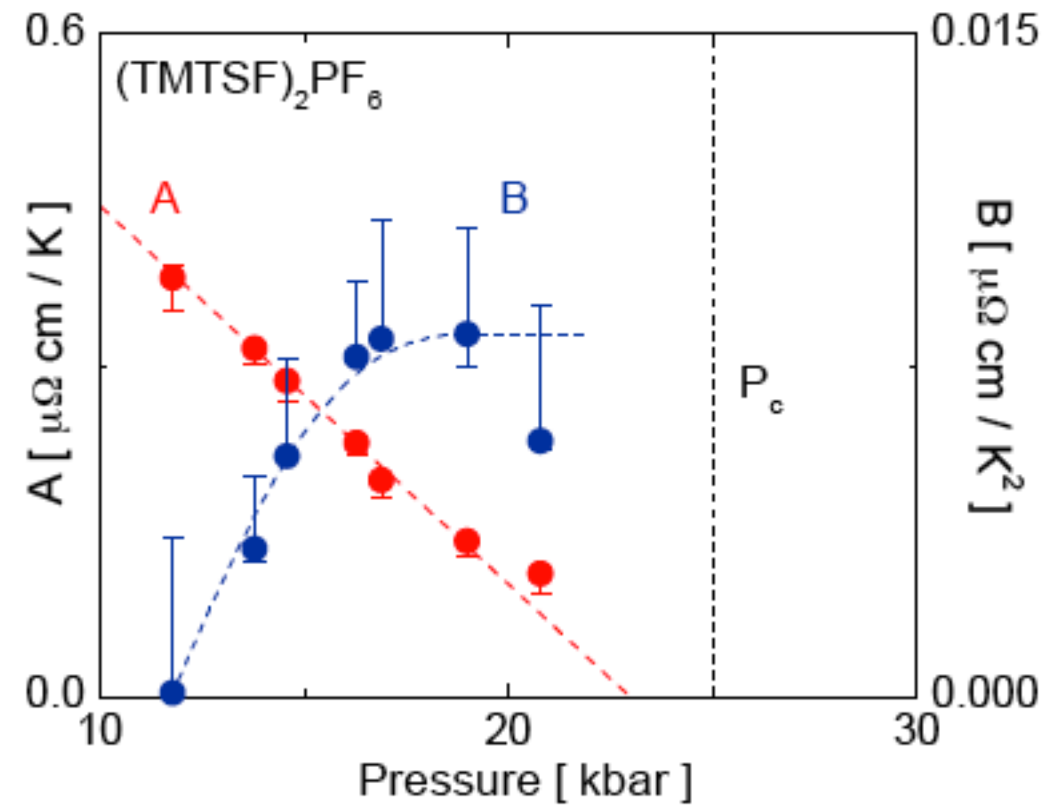
Spin fluctuations: Linear-T resistivity at QCP and beyond



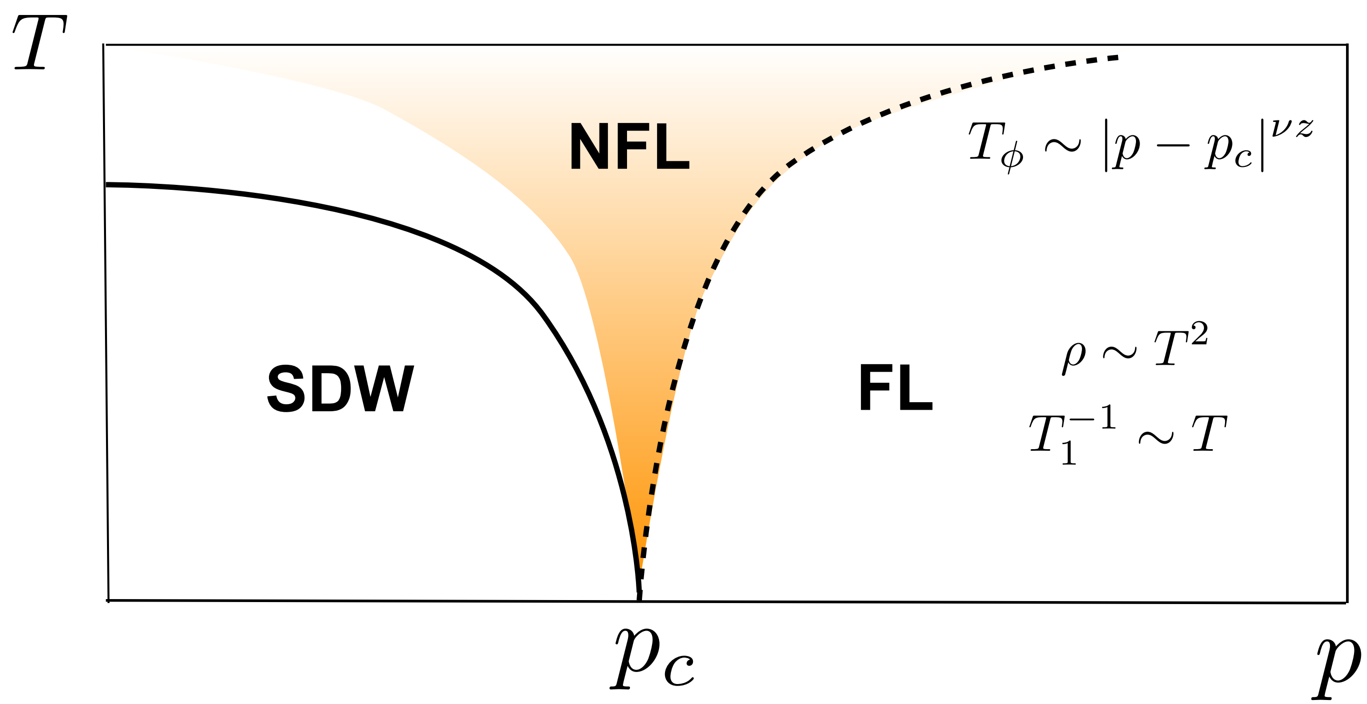


N. Doiron-Leyraud *et al.*, PRB **80**, 214531 (2009)

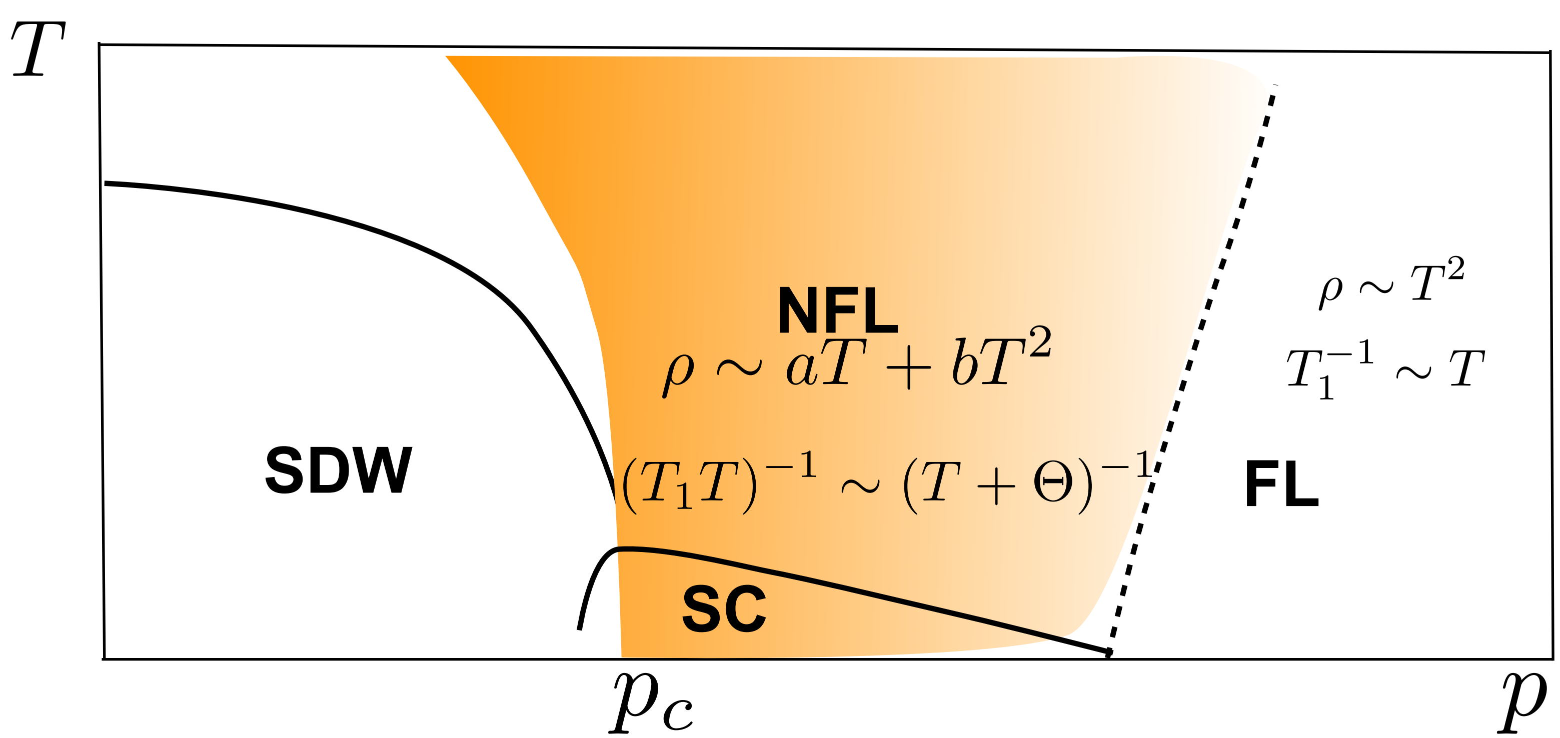




QCP



Standard scheme

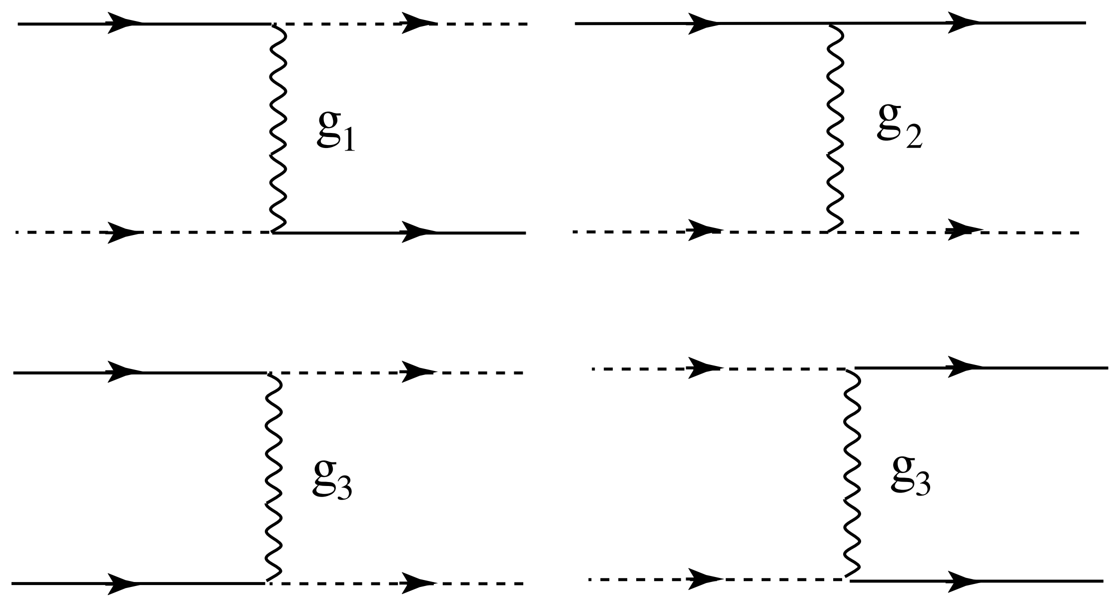


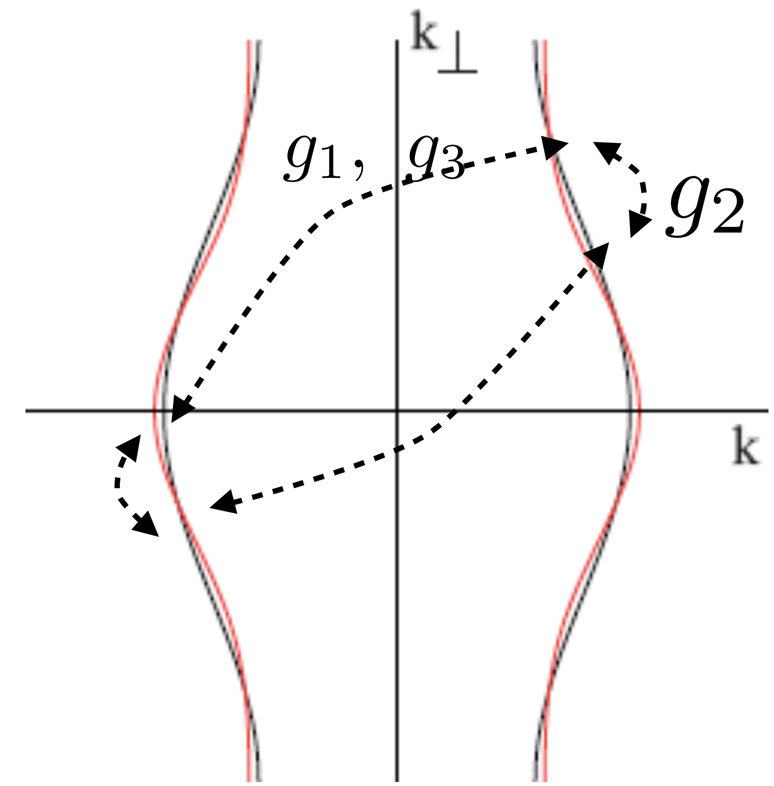
Extended quantum criticality

Role of SC ?

A. Sedeki, D. Bergeron and C. B., PRB **85**, 165129 (2012)

Q-1D electron gas model: Repulsive interactions





Quasi-1D Fermi surface

$$E(k) = -2t_a \cos k_a - 2t_\perp \cos k_\perp - 2t'_\perp \cos 2k_\perp$$

$$t_a \sim 1500K, \quad t_\perp \sim 200K,$$

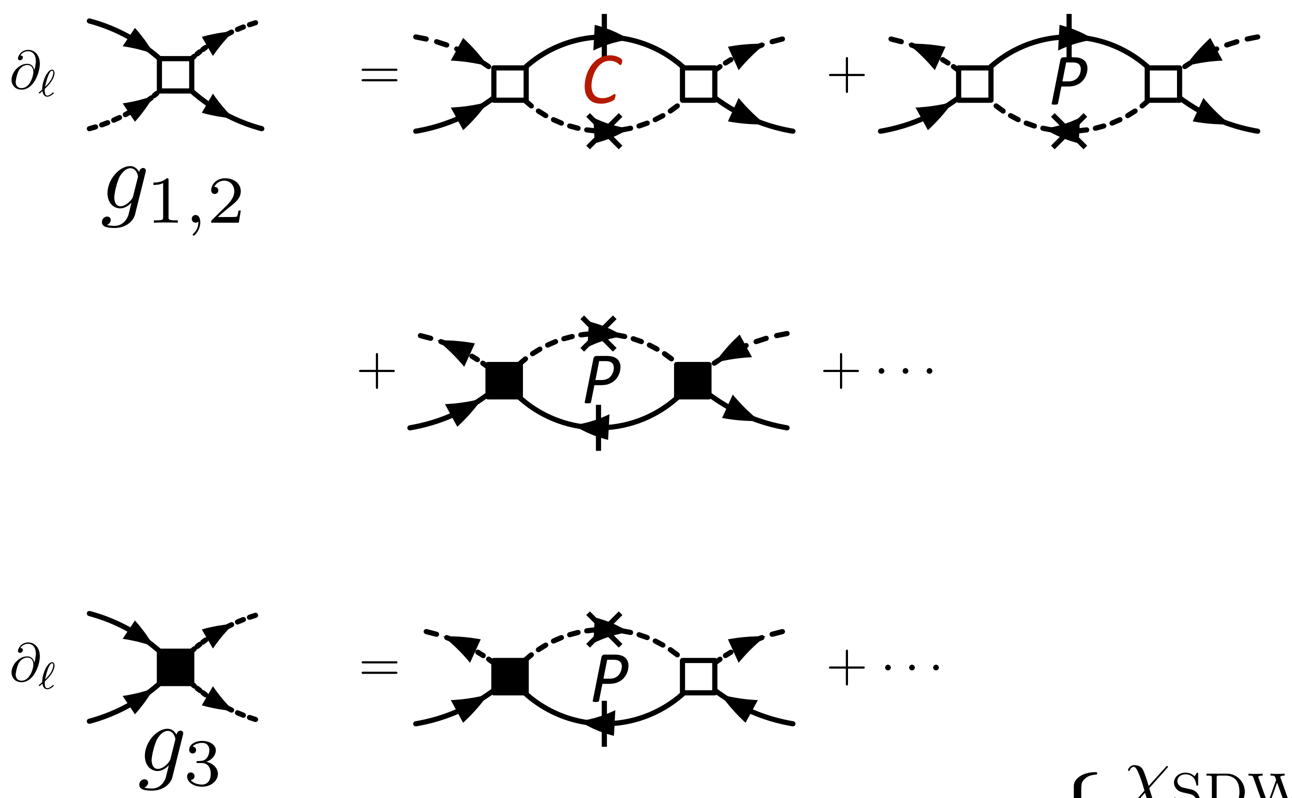
$$t_\perp \sim 10t'_\perp \quad E_0 \sim 5000K$$

$$g_1 > 0 \quad (\chi_\sigma)$$

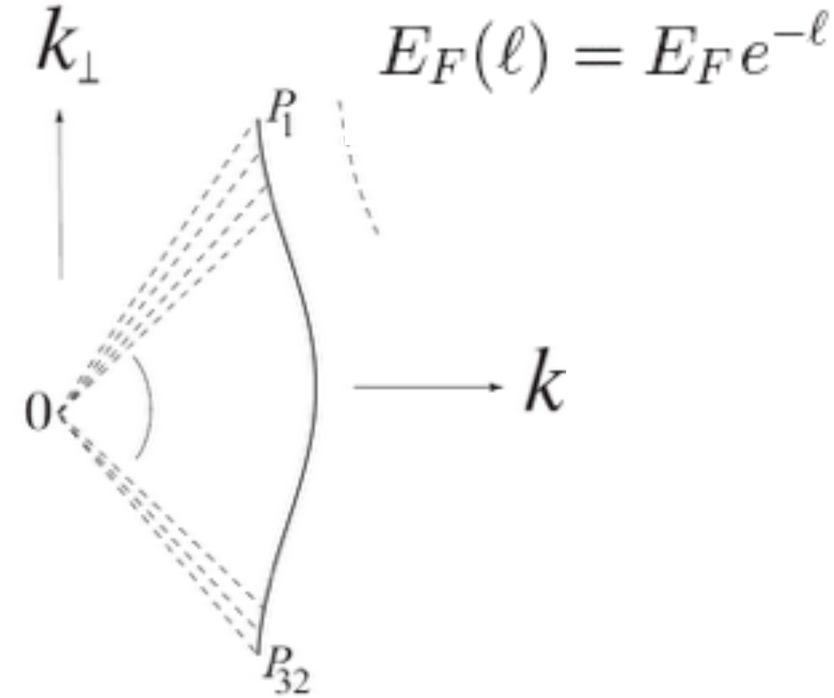
$g_3 = g_1 \Delta_D / E_F \ll 1$ Umklapp, weak dimerization

$$g_2 > 0$$

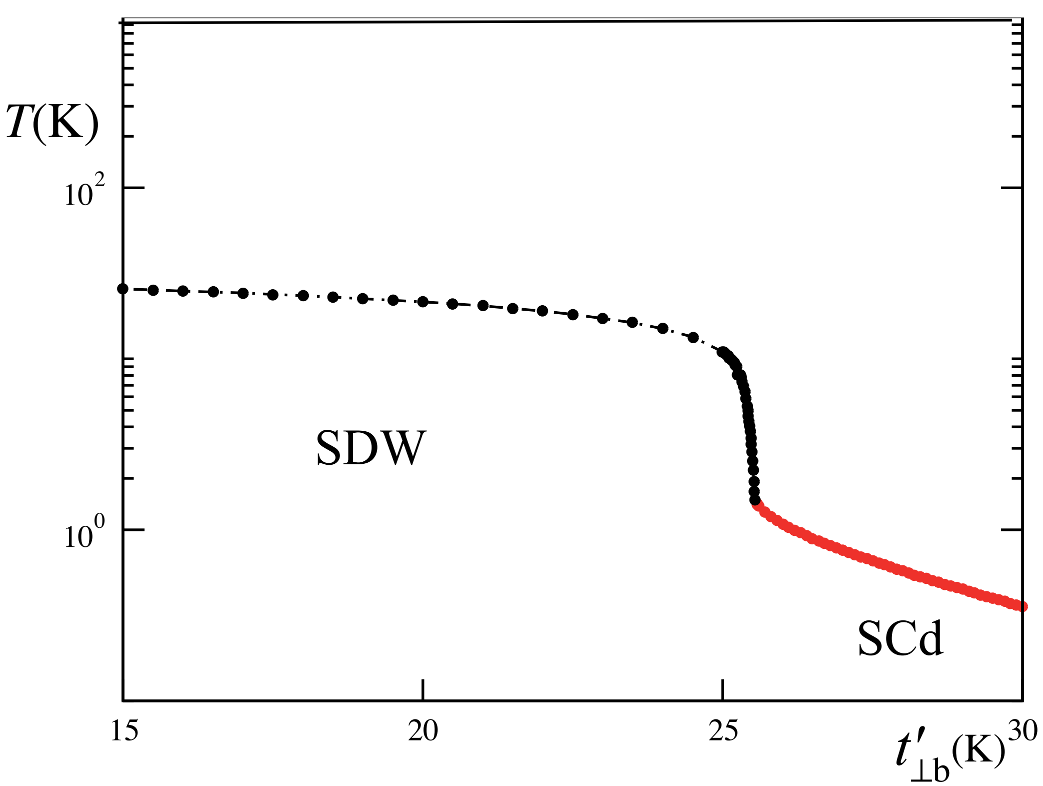
Scaling theory (RG) of both pairing channels



k-resolved flow of scattering amplitudes



Singularities ↔ *T* scales for instabilities *via* $\left\{ \begin{array}{l} \chi_{\mathrm{SDW}}(T; g_2, g_3) \\ \chi_{\mathrm{SCd}}(T; g_1, g_2) \end{array} \right.$

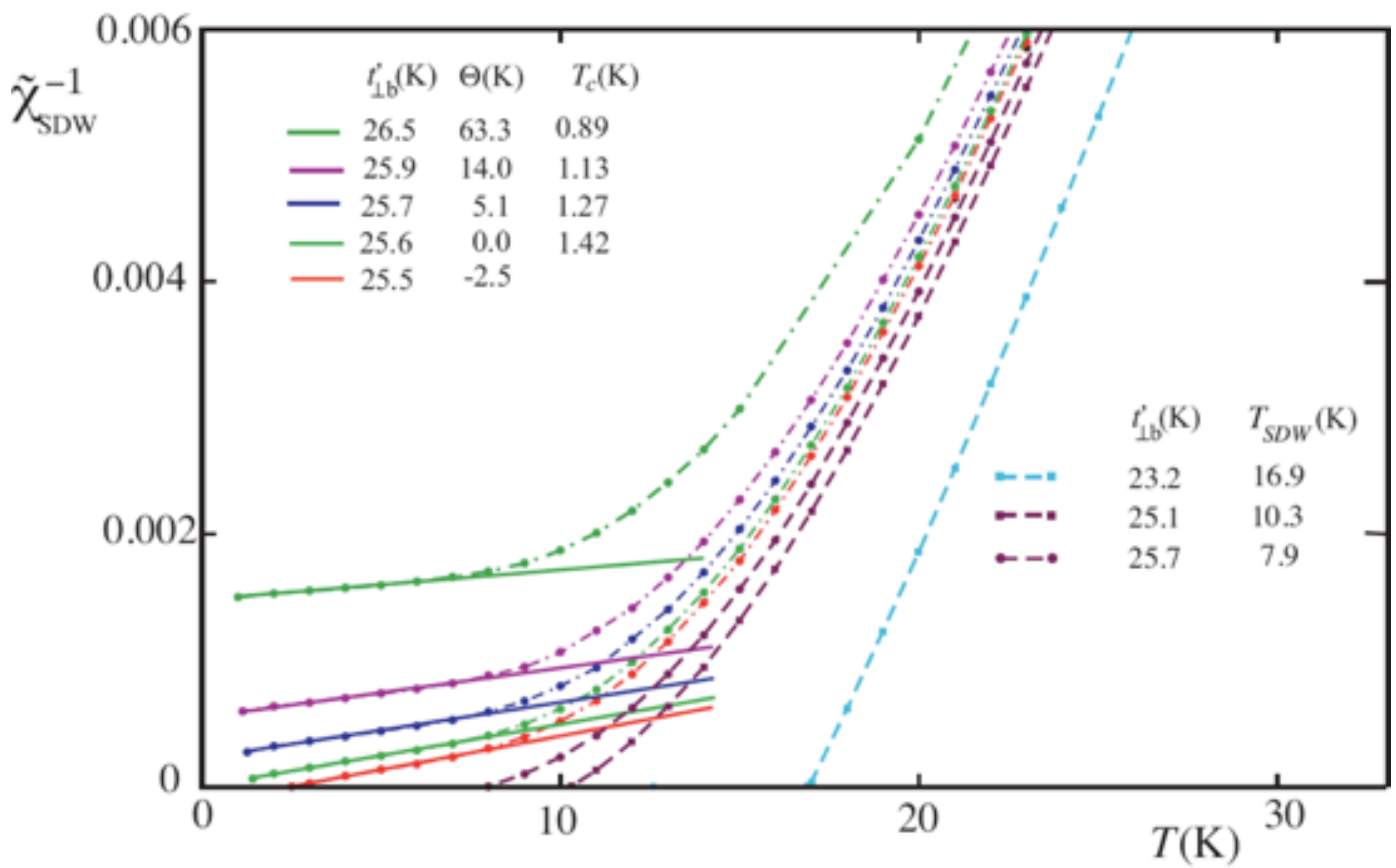


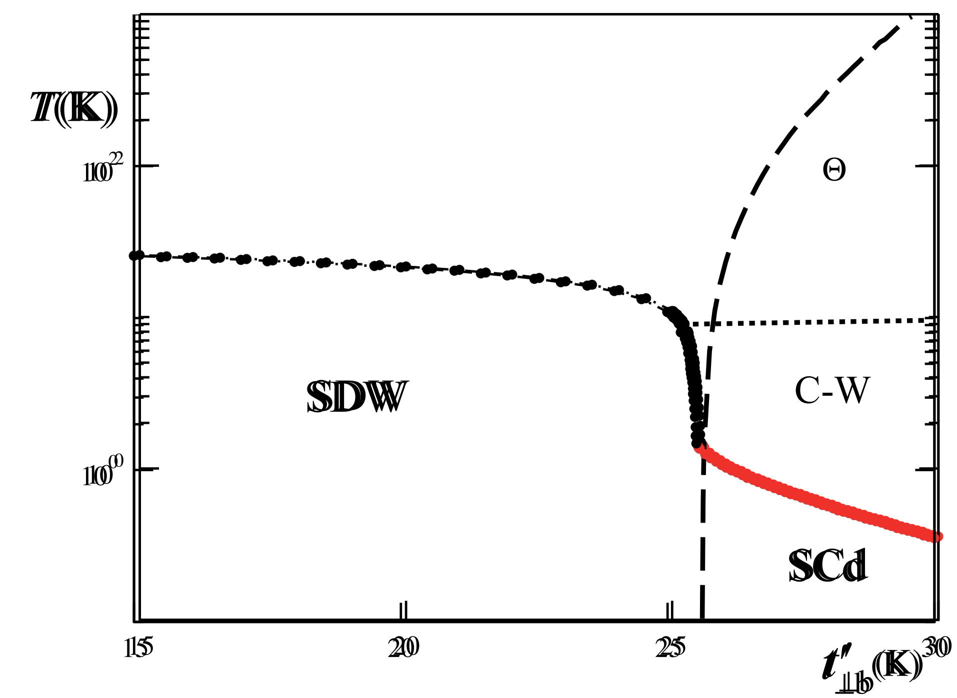
SDW fluct. induce d-wave pairing
(Interference)

Instability lines *vs* nesting alterations ('pressure')

A. Sedeki, D. Bergeron and C. B., Phys. Rev. B **85**, 165129 (2012)
C.B. & A. Sedeki, PRB **80**, 085105 (2009)
C.Nickel *et al.,* Phys. Rev. Lett. **95**, 247001 (2005)
R.Duprat & C.B., Eur. Phys. J. B, **21**, 219(2001)

Normal phase: extended Curie Weiss regime

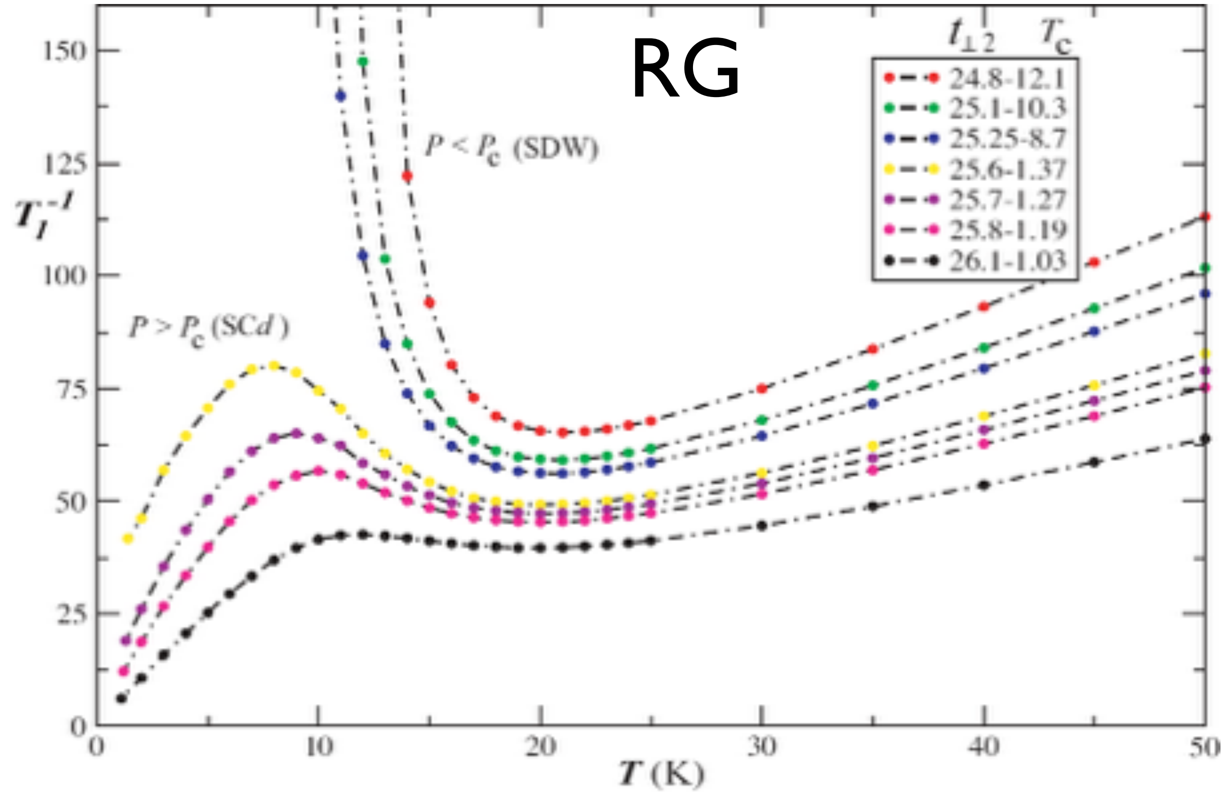




C. B. and A. Sedeki, PRB **80**, 085105 (2009)

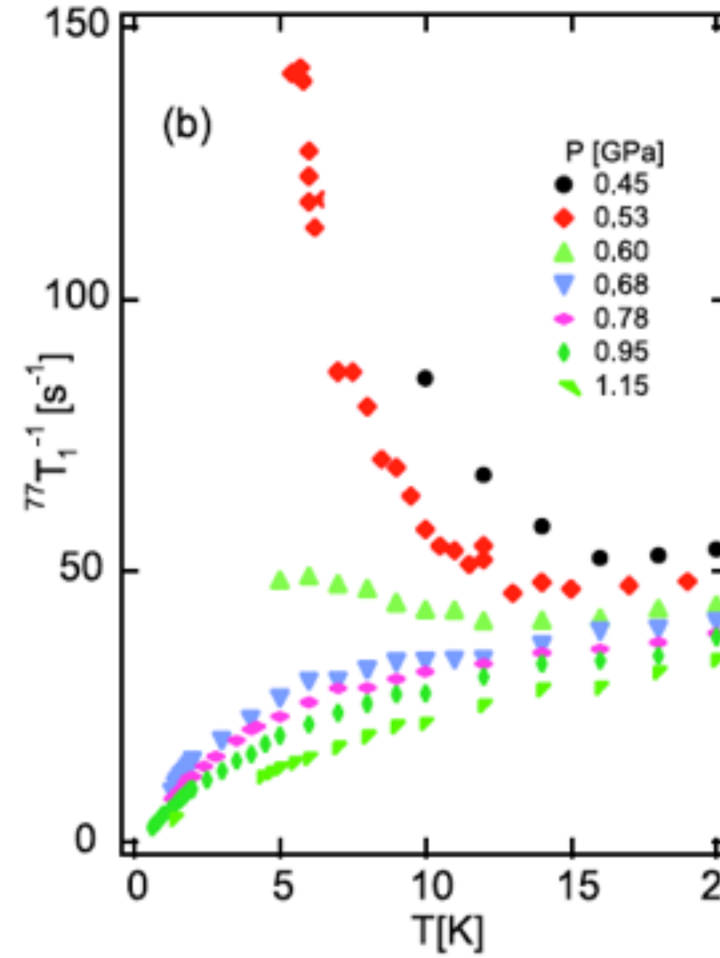
- d-Cooper pairing boosts (interferes constructively with) SDW
- Enhancement Fits a Curie-Weiss law $\chi_{\rm SDW}(\mathbf{q}_0) \sim (T+\Theta)^{-1}$

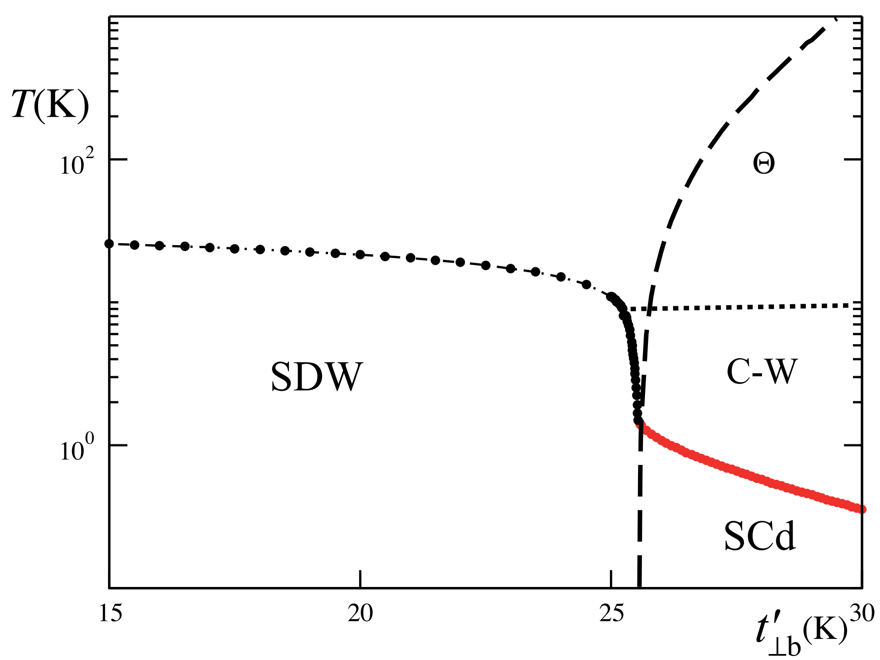
Impact on the normal phase : NMR



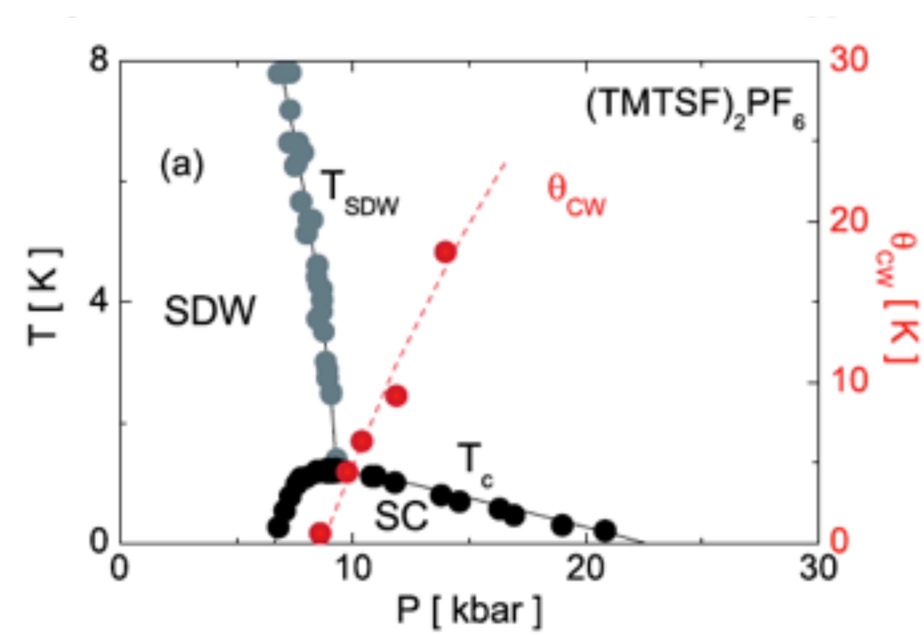
$$T_1^{-1} \approx C_0 T + C\frac{T}{T+\Theta} \quad P > P_c$$

S. Brown *et al.*, (2005-2008)





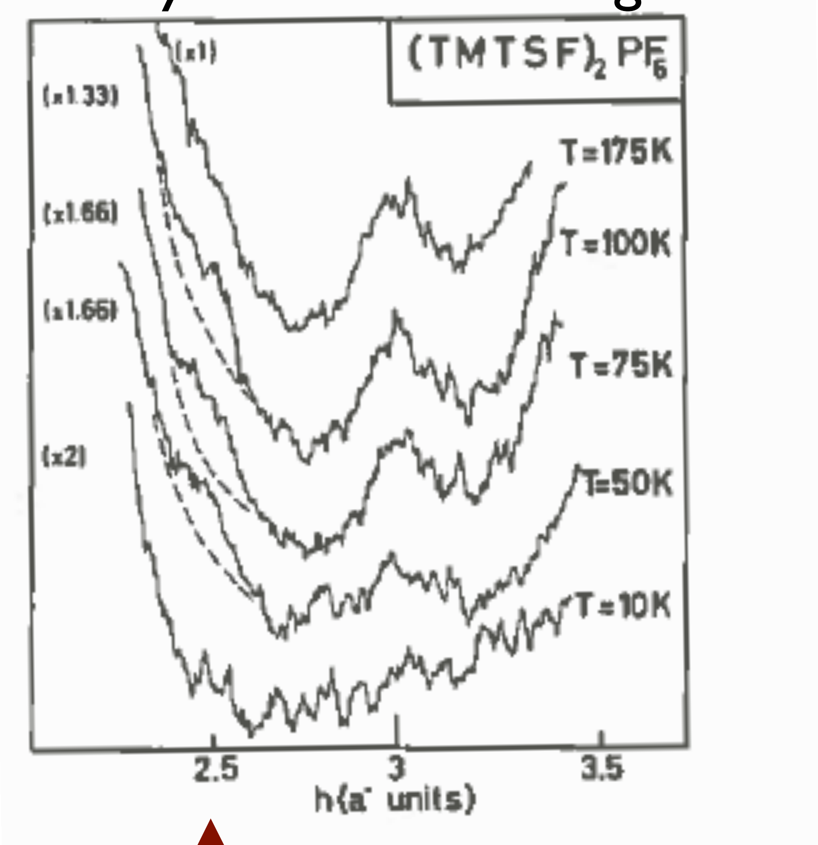
C. B. and A. Sedeki, PRB **80**, 085105 (2009)

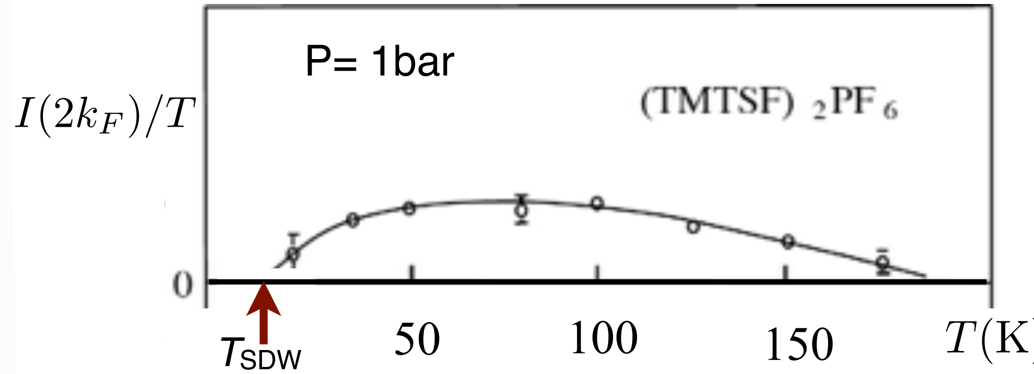


N. Doiron-Leyraud et al., Phys. Rev. B **80**, 214531 (2009); EPJB (2010)

II - Electron-Phonon Interaction

X-Ray diffuse scattering





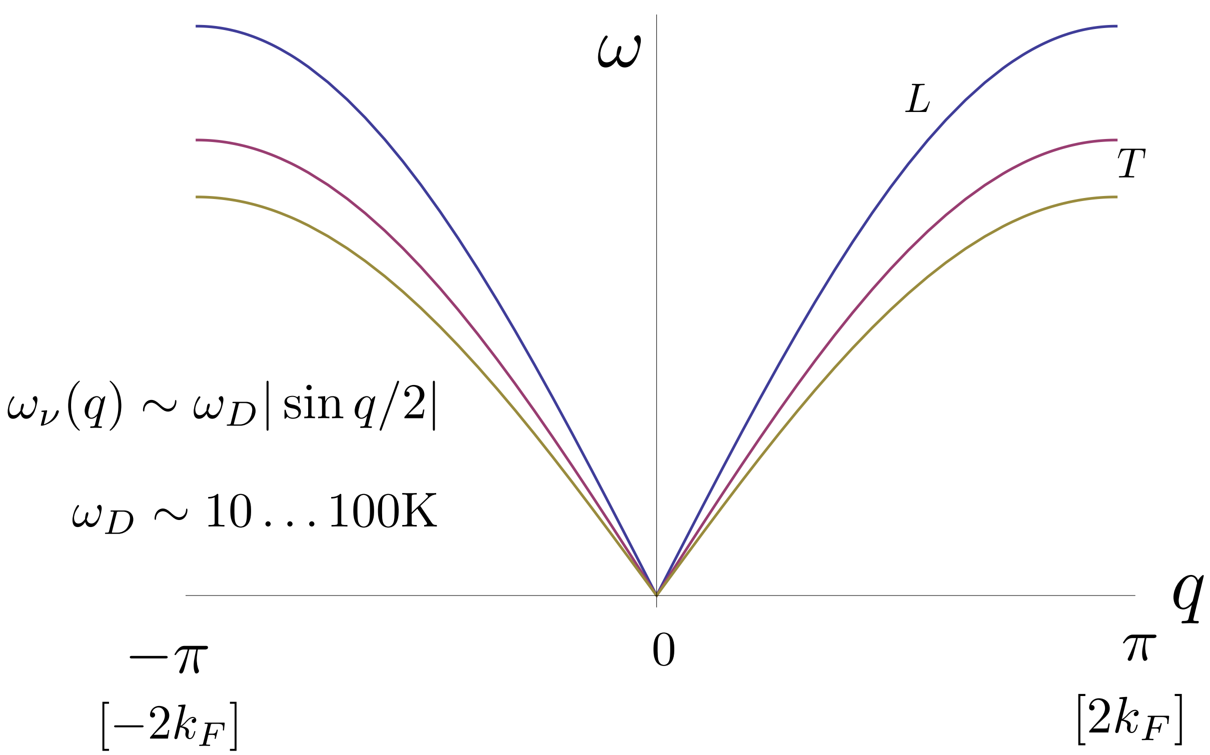
J. P. Pouget *et al.,* Mol. Cryst. Liq. Cryst. **79**, 129 (1982)

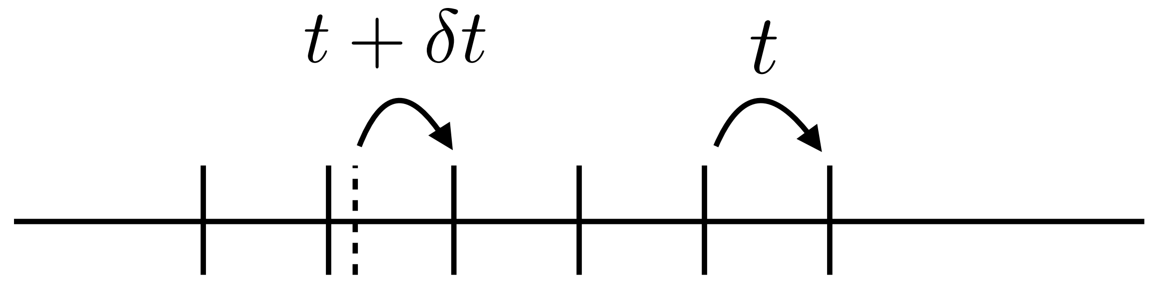
Crystals **2**, 466 (2012)

$2k_F$ lattice fluctuations

- Phonons (acoustic) do couple to electrons *via* modulation of chain transfer integral
- Impact on a magnetically driven mechanism for SC ?

Electron-Phonon Interaction in tight binding





Modulation of hopping by lattice vibrations
Su, Schrieffer & Heeger PRL (79)

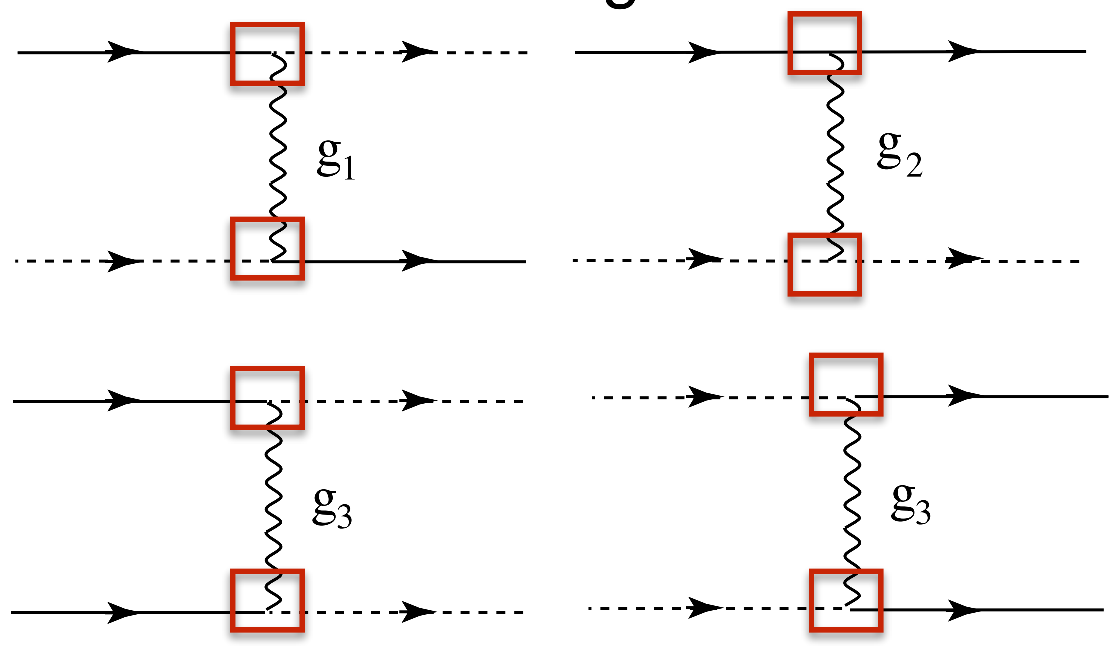
$$H_{\mathrm{ep}} = \quad (LN_\perp)^{-\frac{1}{2}} \sum_{p,\sigma,\nu} \sum_{\mathbf{k},\mathbf{q}} g_\nu(k,q) c^\dagger_{p,\mathbf{k}+\mathbf{q},\sigma} c_{-p,\mathbf{k},\sigma} (b^\dagger_{\mathbf{q},\nu} + b_{-\mathbf{q},\nu})$$

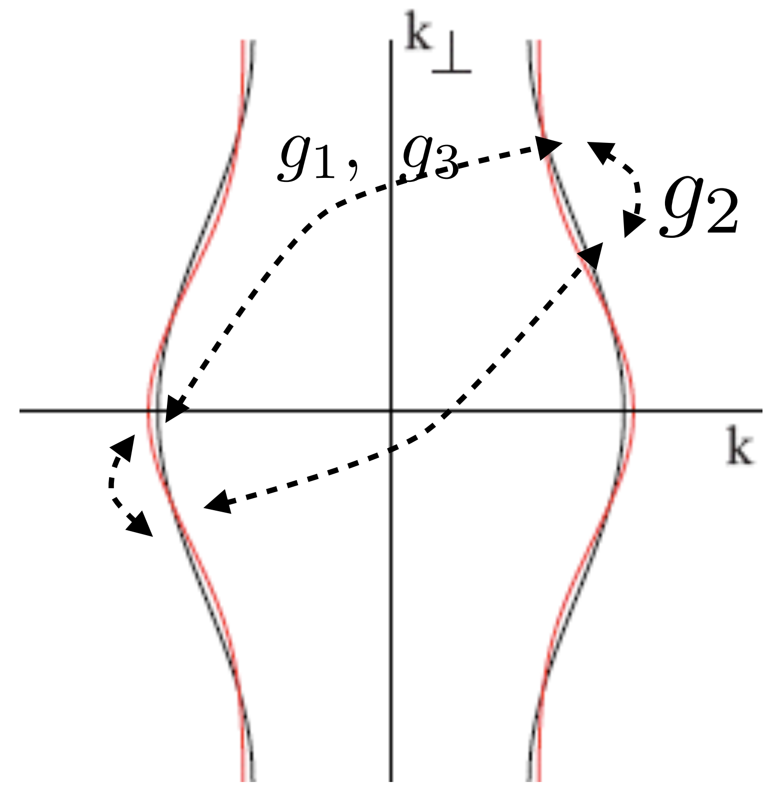
$$g_\nu(k,q) = i4 \frac{\lambda_\nu}{\sqrt{2M\omega_\nu}} \sin \frac{q}{2} \cos\left(k + \frac{q}{2}\right)$$

<u>Momentum dep.</u>

Repulsive & Phonon-Mediated Interactions

Q-1D electron gas model





+ Phonon-mediated interactions

Quasi-1D Fermi surface

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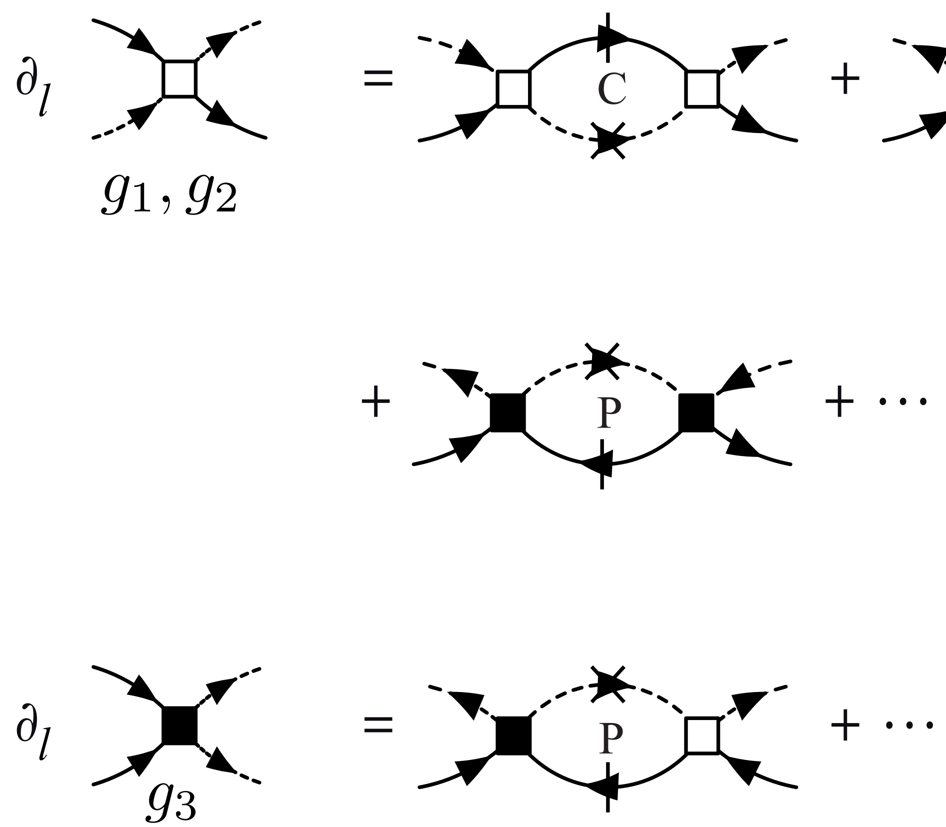
$$t_a \sim 1500K, \quad t_\perp \sim 200K,$$
$$t_\perp \sim 10t'_\perp \quad E_0 \sim 5000K$$

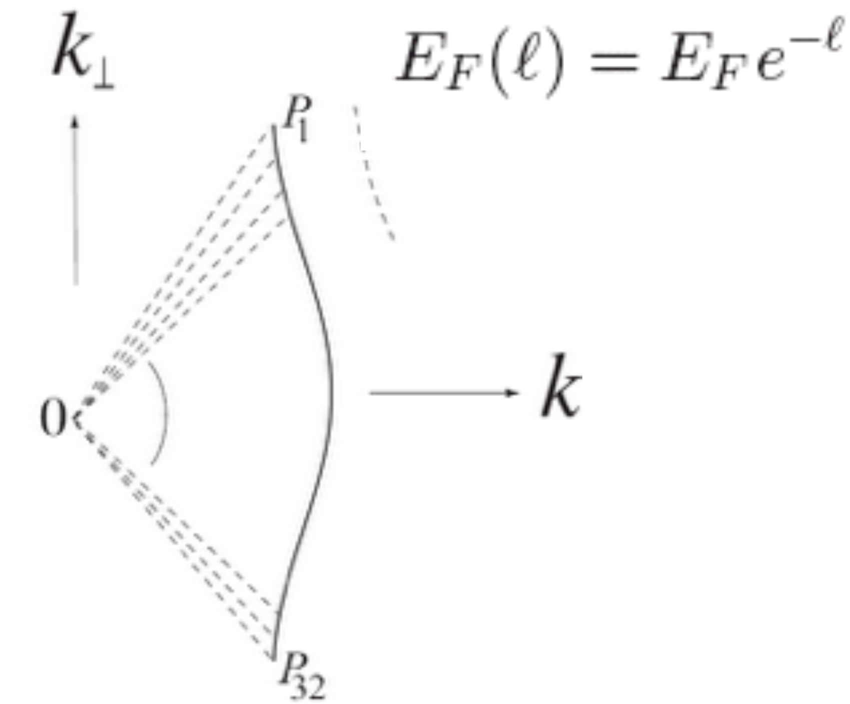
$$g_{i=1,2,3}(\omega_1, \omega_2, \omega_3, \omega_4) = g_i + \frac{g_{\mathrm{ph,i}}}{1 + \frac{(\omega_1 - \omega_3)^2}{\omega_D^2}}$$

$$g_{\mathrm{ph},1} = g_{\mathrm{ph}} < 0$$
$$g_{\mathrm{ph},2} \approx 0$$
$$g_{\mathrm{ph},3} = \eta |g_{\mathrm{ph}}| > 0, \quad \eta \ll 1$$

Repulsive quasi-1D el. gas model & phonon-mediated interaction

Finite T - RG: 3 + 3 variables





32 patches- *k* space

1 patch 14 ω_n

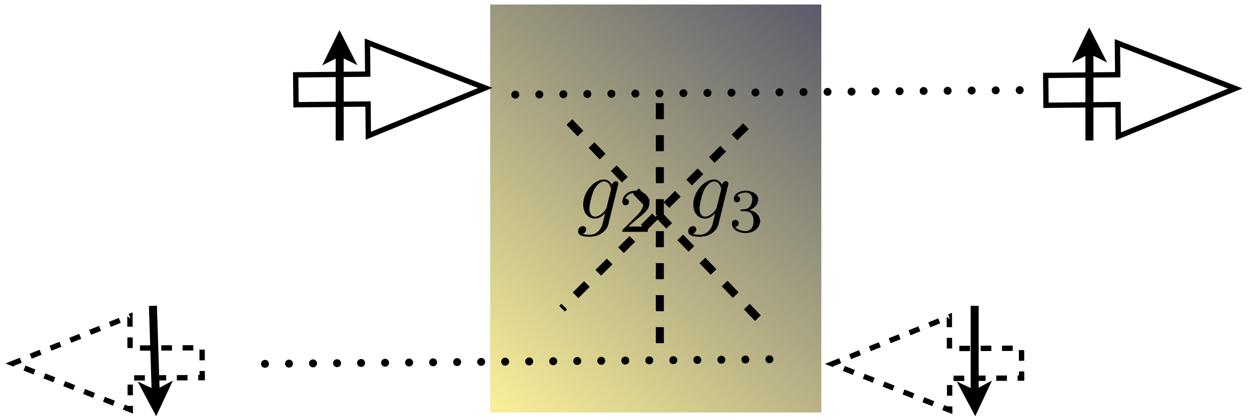
$$\partial_\ell g_{i=1,2}(\bar{k}'_{\perp 1}, \bar{k}_{\perp 2}, \bar{k}_{\perp 1}) = \sum_{\mathcal{P}_{n,n'}} \left[\epsilon^{n,n'}_{C,i} \left\langle \langle g_n \odot g_{n'} \rangle_\omega \odot \partial_\ell \mathcal{L}_C \right\rangle_{k_\perp} + \epsilon^{n,n'}_{P,i} \left\langle \langle g_n \odot g_{n'} \rangle \odot \partial_\ell \mathcal{L}'_P \right\rangle_{k_\perp} \right]$$

$$\partial_\ell g_3(\bar{k}'_{\perp 1}, \bar{k}_{\perp 2}, \bar{k}_{\perp 1}) = \sum_{n=1}^{2} \epsilon^{3,n}_{P,3} \left\langle \langle g_3 \odot g_n \rangle_\omega \odot \partial_\ell \mathcal{L}_P \right\rangle_{k_\perp},$$

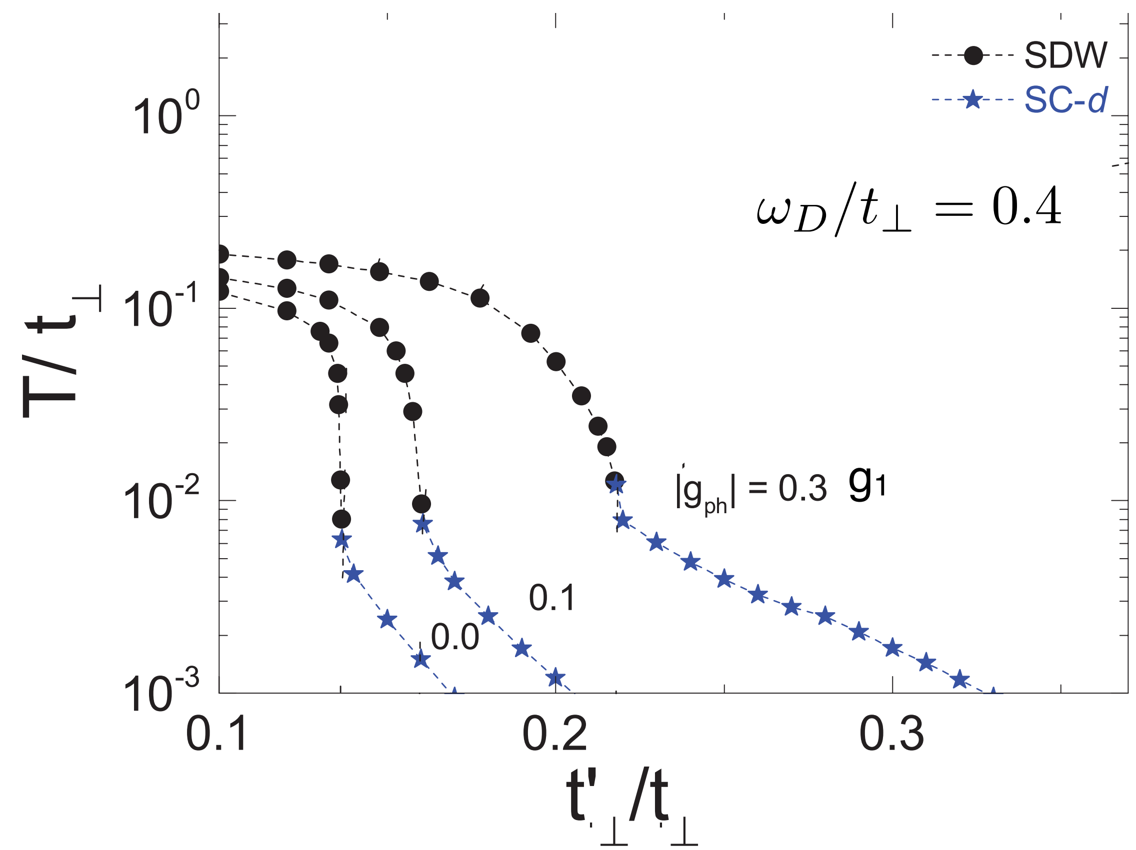
H. Bakrim and C. Bourbonnais, PRB **90**, 125119(2014)

EPL **90,** 2701 (2010)

Phonon-mediated int. *vs* Magnetism & Superconductivity

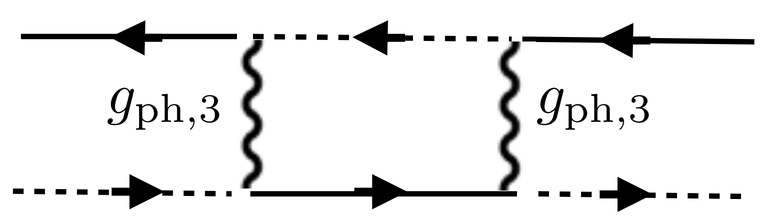


AF exchange for itinerant electrons



Weak e-phonon interaction reinforces SDW & D-wave SC

$$S_I^{\rm ex} \sim \sum_{\{\bar{\mathbf{k}}\},\bar{\mathbf{q}}_P} \frac{1}{2}(g_2+g_3)\circ \vec{S}_{\bar{\mathbf{k}}_1,\bar{\mathbf{q}}_P}\cdot\vec{S}_{\bar{\mathbf{k}}_2,-\bar{\mathbf{q}}_P}$$

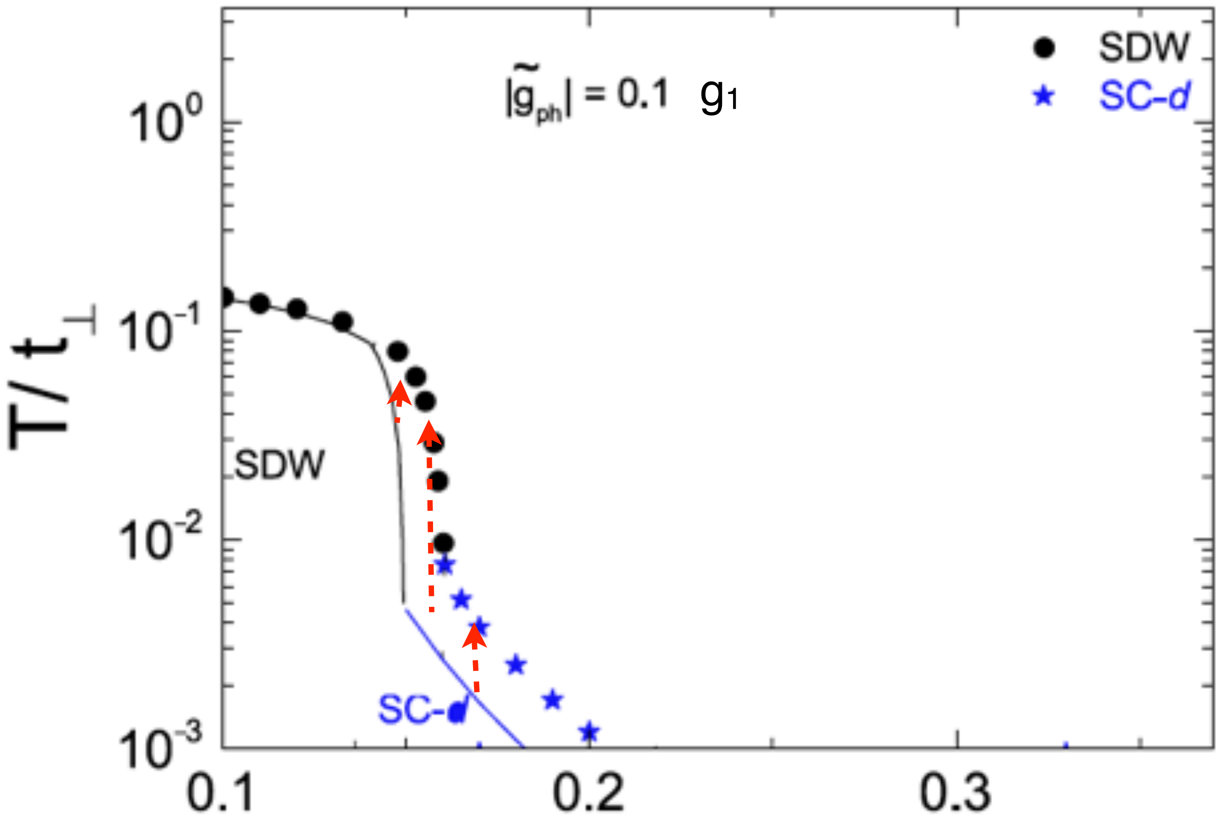


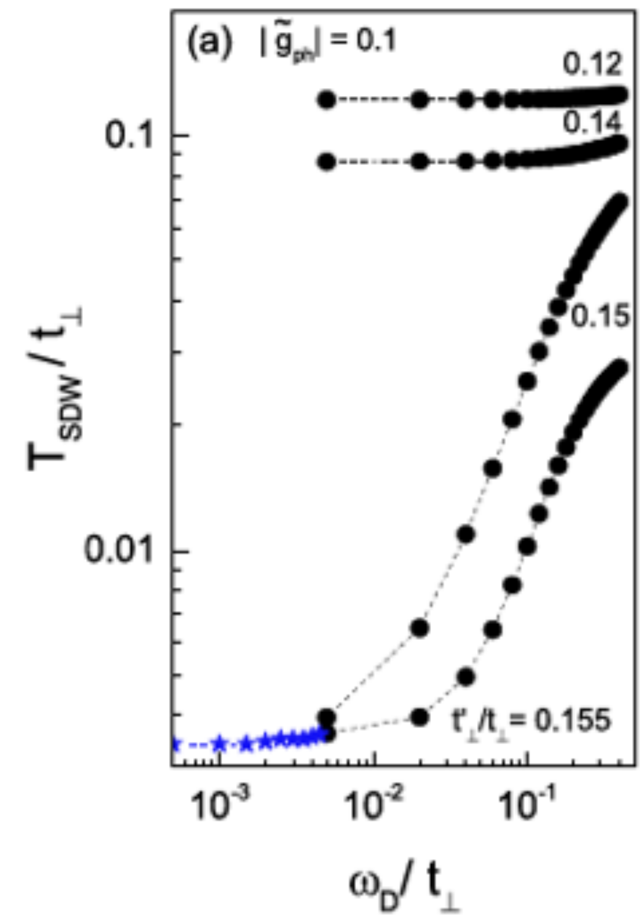
+ ...

Enhancement of AF exchange for itinerant spins & Cooper (d-wave) pairing (T_c)

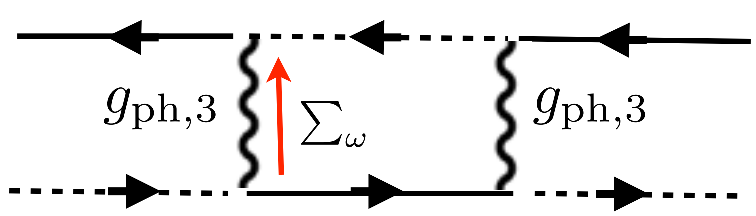
H. Bakrim and C. Bourbonnais, PRB **90**, 125119(2014)

Retardation: Isotope effect on SDW & SC-d





$$S_I^{\rm ex} \sim \sum_{\{\bar{\mathbf{k}}\},\bar{\mathbf{q}}_P} \frac{1}{2}(g_2+g_3)\circ \vec{S}_{\bar{\mathbf{k}}_1,\bar{\mathbf{q}}_P}\cdot \vec{S}_{\bar{\mathbf{k}}_2,-\bar{\mathbf{q}}_P}$$



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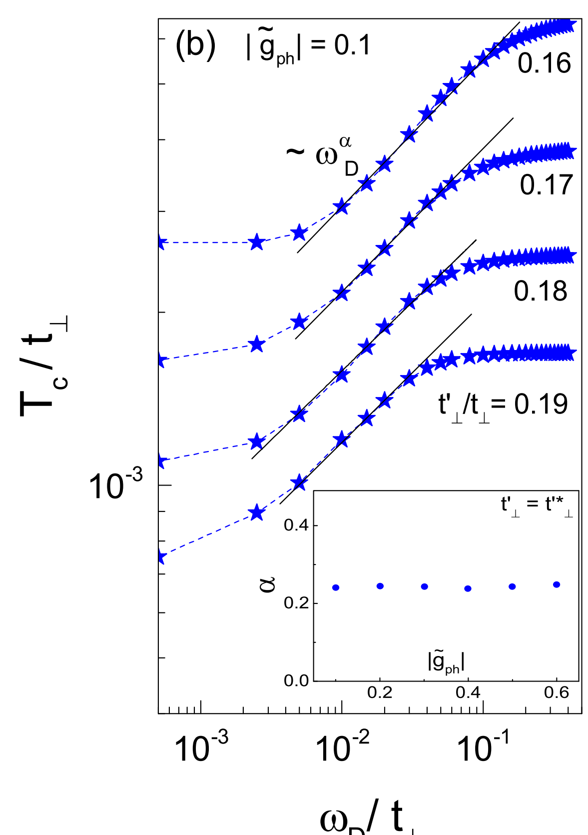
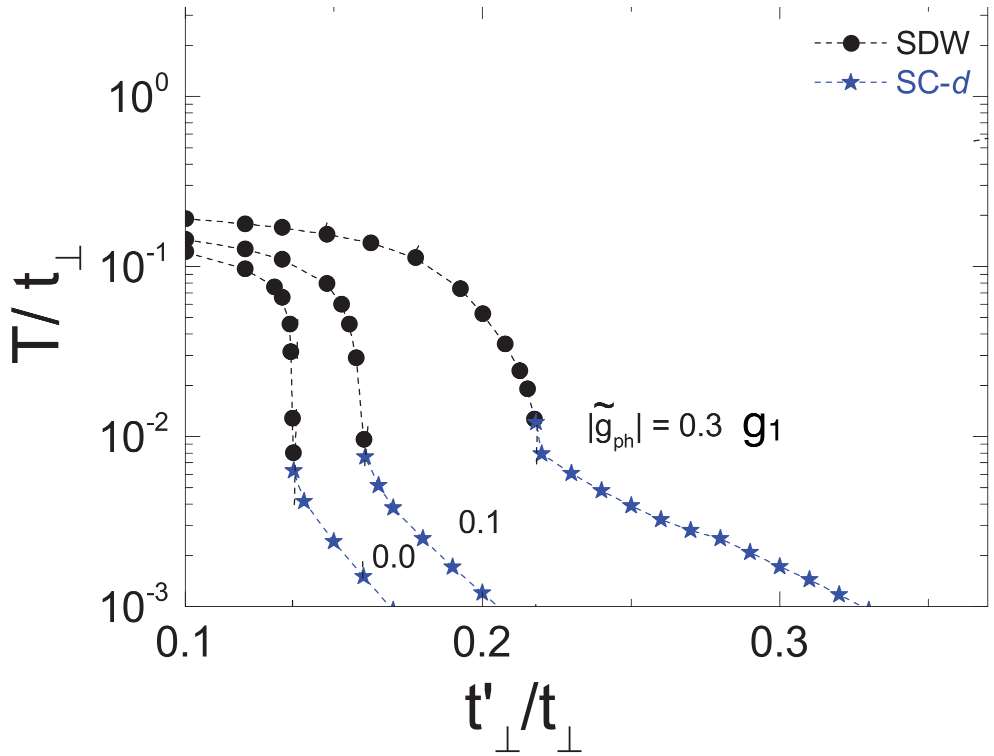
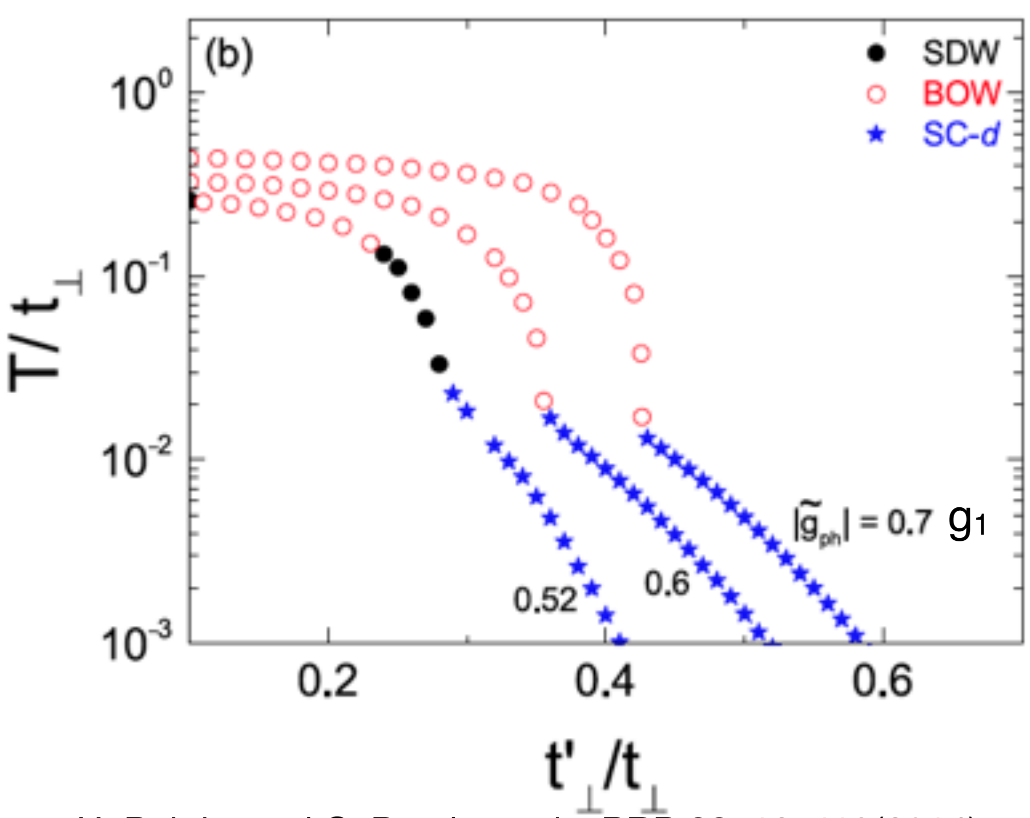


$T_c \sim \omega_D^\alpha \quad \alpha \simeq 0.25 = 1/4$ BCS

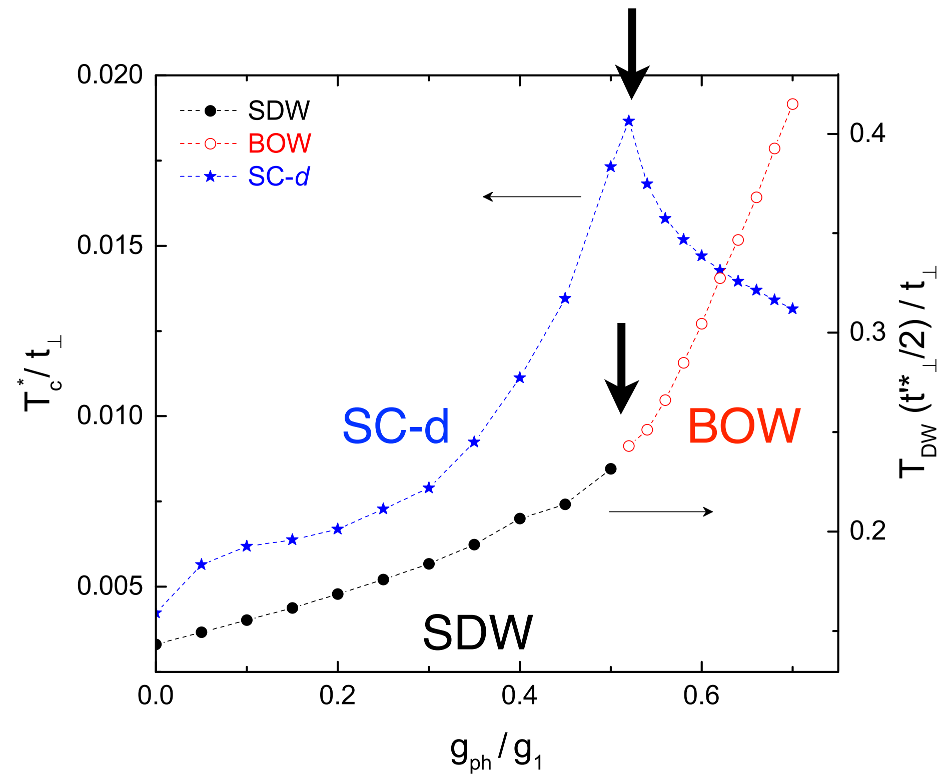
H. Bakrim and C. Bourbonnais, PRB **90**, 125119(2014)

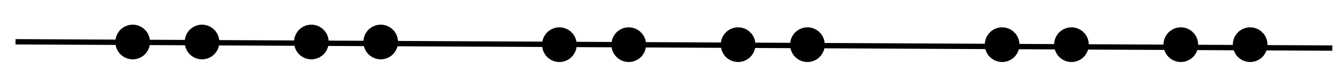
Crossover to the Peierls lattice distorted state





H. Bakrim and C. Bourbonnais, PRB **90**, 125119(2014)



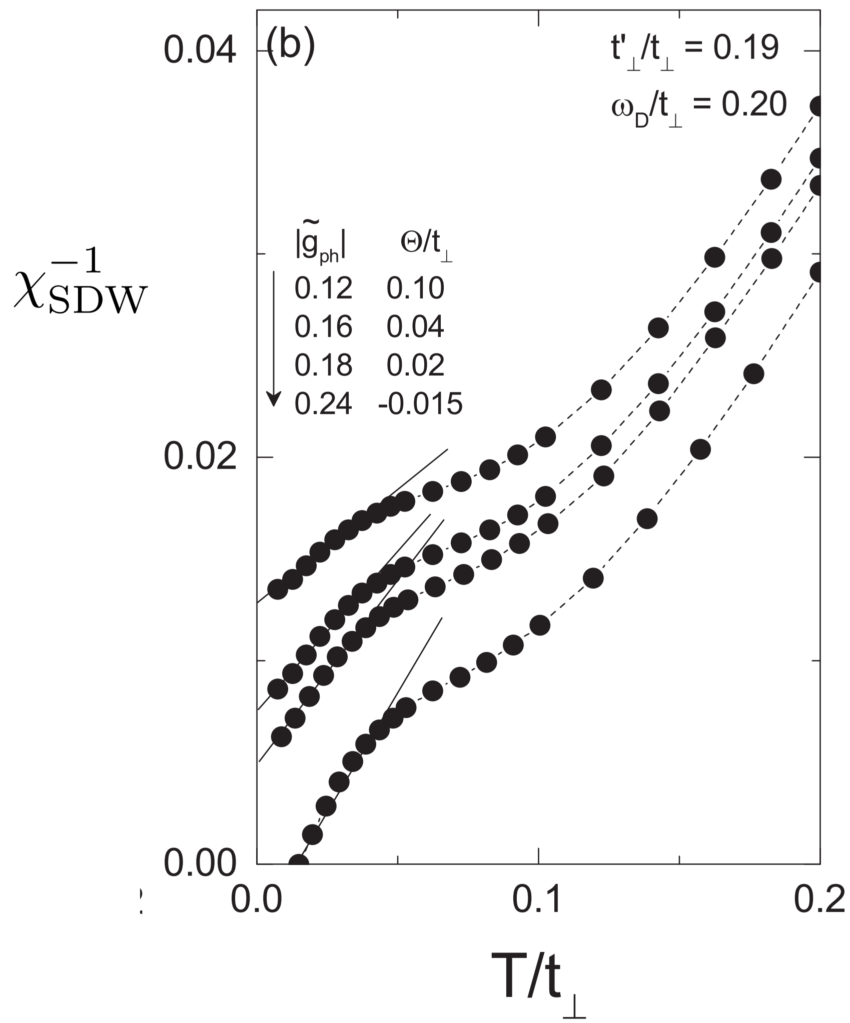


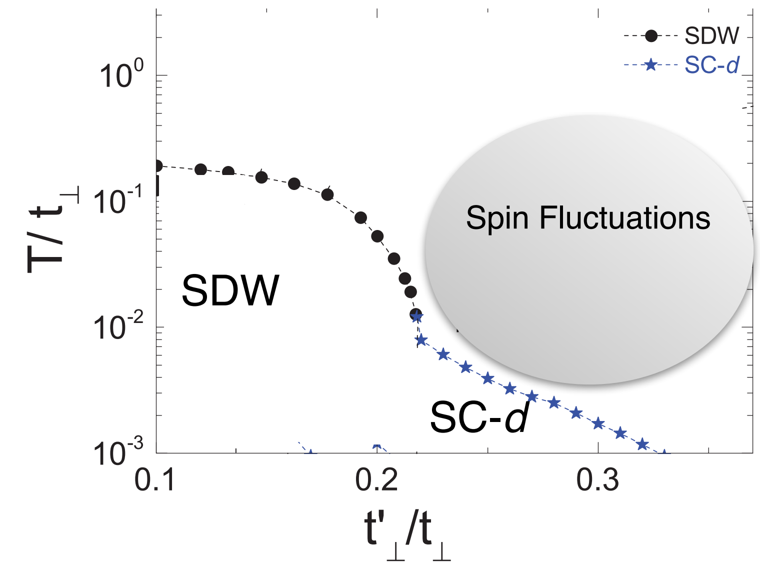
BOW-Peierls distortion

Normal state: spin fluctuations above T_c

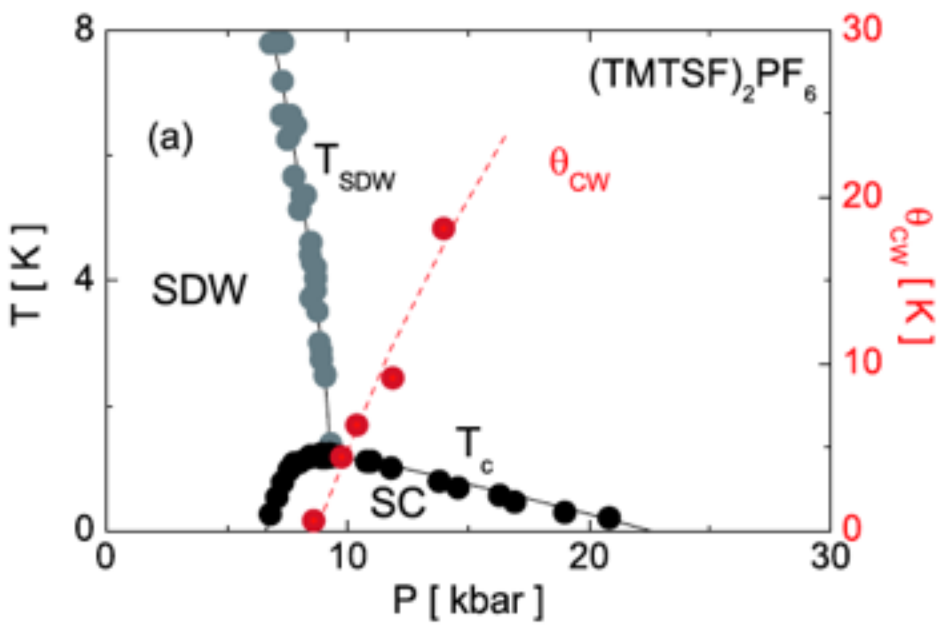
Curie-Weiss behaviour of SDW susceptibility

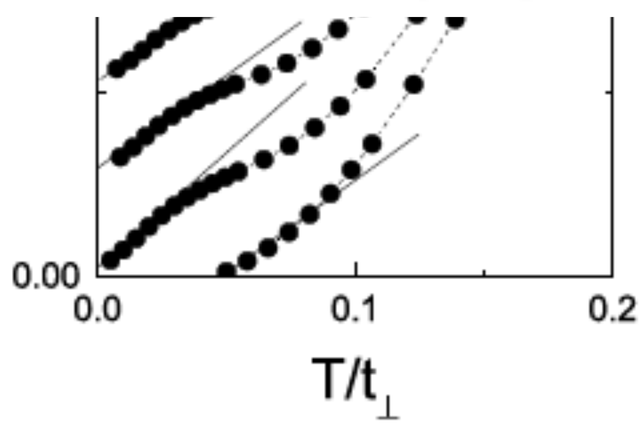
$$\chi_{\mathrm{SDW}} \sim \frac{1}{T+\Theta}$$

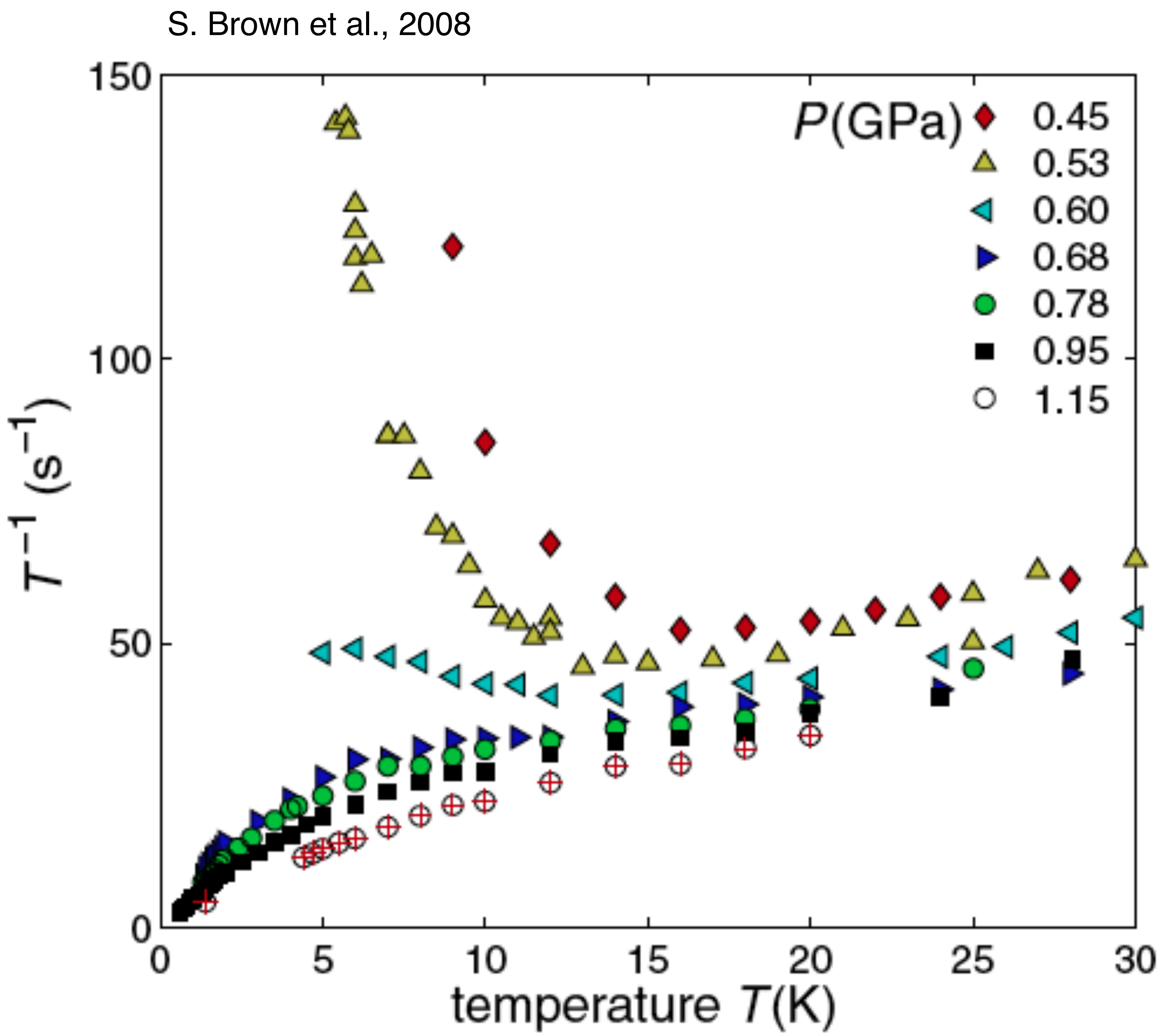




Normal state: spin fluctuations above T_c







$$\chi_{\rm SDW} \sim \frac{C}{T+\Theta} \propto \xi^2_{SDW}\uparrow$$

$$\Theta(|\tilde{g}_{\rm ph}|, \omega_D, t'_\perp) \sim A(t_\perp - t'^*_\perp)^{\underbrace{\nu z}_{1}}$$

Near QCP

Seen in NMR

$$(T_1 T)^{-1} \sim (T+\Theta)^{-1}$$

H. Bakrim and C. Bourbonnais, PRB **90**, 125119(2014)

Summary & Conclusion

Part I (TMTSF)$_2$X as an archetype of proximity between SDW & SC

RG & repulsive q-1D electron gas model

Phase diagram SDW to SC-d

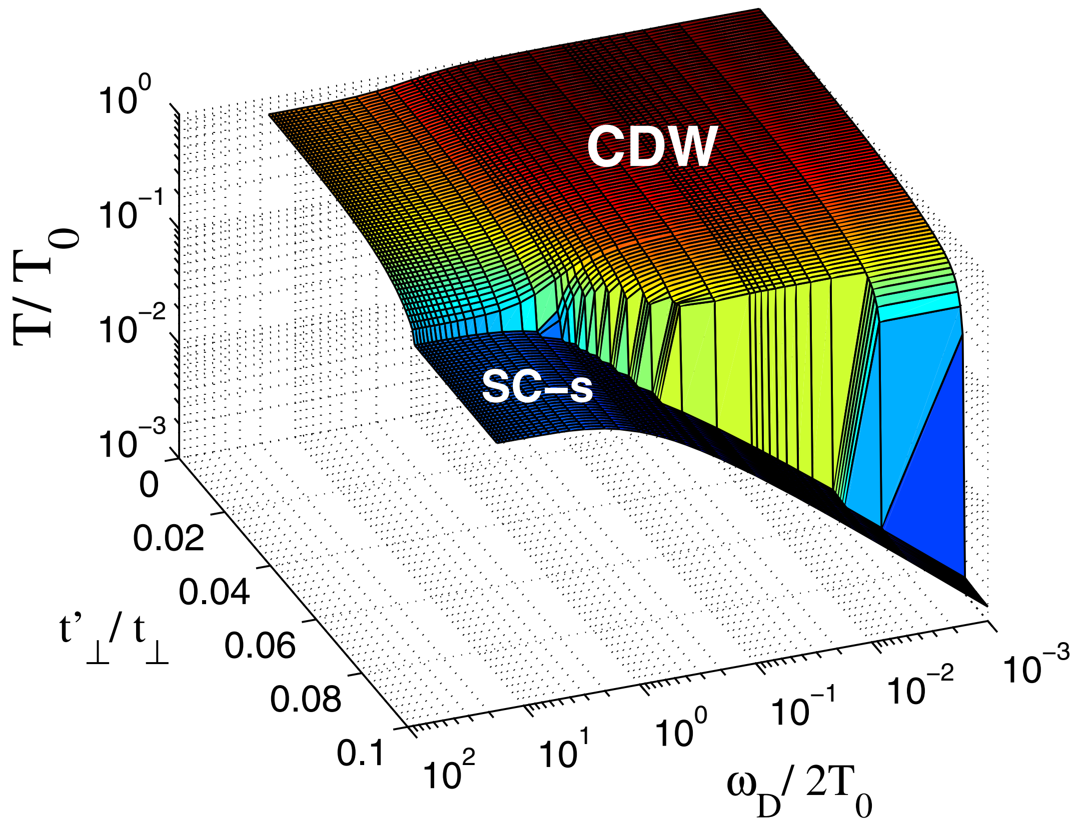
Spin fluctuations: Curie-Weiss vs T_c (NMR)

Part II Weak el.-phonon interaction enhances both SDW, SC-d & quantum critical effects (spin fluct),

Isotope effect

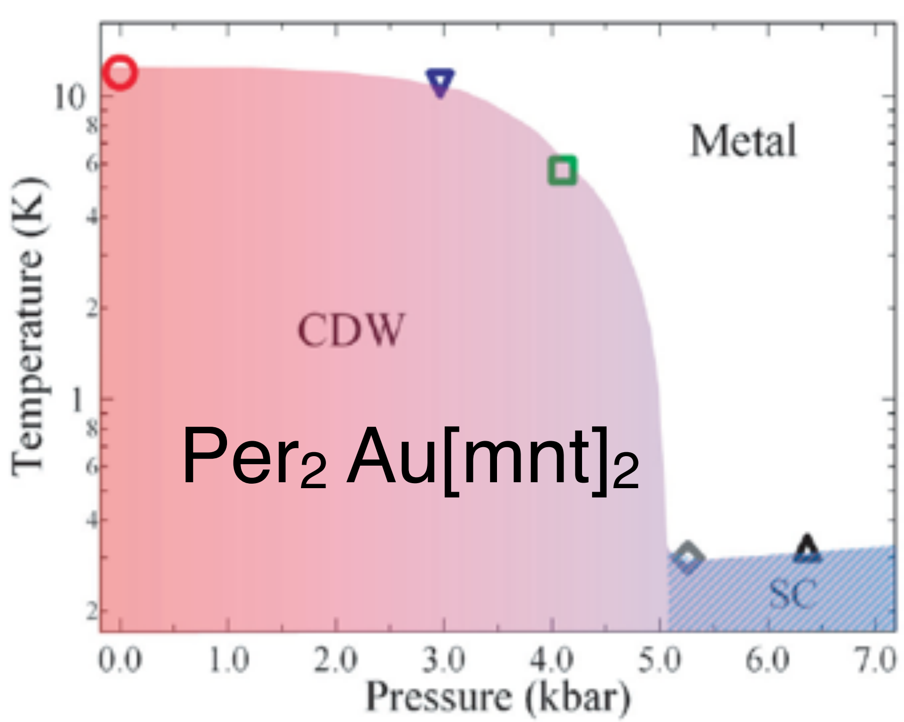
El.-phonon interaction can play active role in the existence of unconventional *d-wave* SC

Supplement: Pure electron-phonon limit



H. Bakrim and C. Bourbonnais EPL **90**, 27001 (2010)

Graf *et al.,* EPL (2009)



-> CDW -> s-wave SC [quasi-1D]

Trichalcogenides : $NbSe_3$ ...

Supplement: Correlation of spin fluctuations with T_c

T_1^{-1} CW enhancement *vs* T_c

$$(T_1 T)^{-1} = C_0 + \frac{C}{T + \Theta}$$

$C \;\; vs \;\; T_c :$

SDW fluct. correlated to pairing (T_c)

Y. Kimura *et al.,* PRB **84**,045123 (2011).

^{13}C NMR (TMTSF)$_2$PF$_6$