SU(2) symmetry in underdoped cuprates

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Collège de France, Paris, March 26th, 2015

^{89}Y NMR Evidence for a Fermi-Liquid Behavior in $YBa_2Cu_3O_{6+x}$

H. Alloul, T. Ohno,[a] and P. Mendels
Physique des Solides, Université de Paris-Sud, 91405 Orsay, France

(Received 15 May 1989)

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PACS numbers: 74.70.Vy, 75.20.En, 76.60.Cq, 76.60.Es

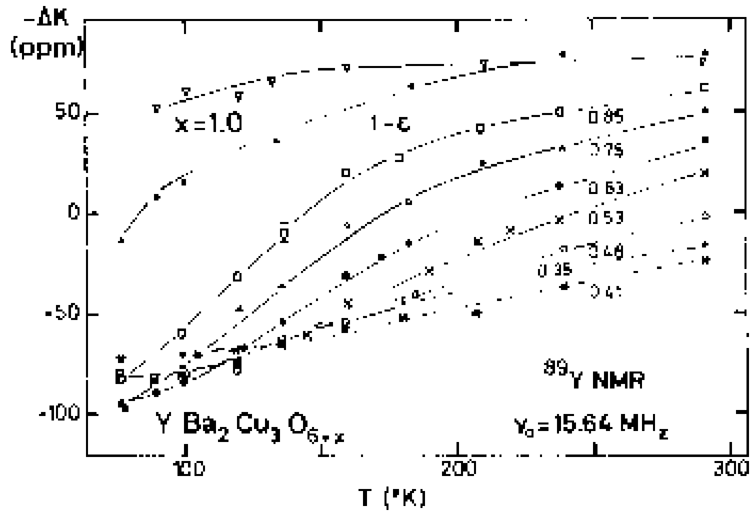

FIG. 1. The shift ΔK of the ^{89}Y line, referenced to YCl_3 plotted vs T, from 77 to 300 K. The lines are guides to the eye.

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VOLUME 63, NUMBER 16 PHYSICAL REVIEW LETTERS 16 OCTOBER 1989

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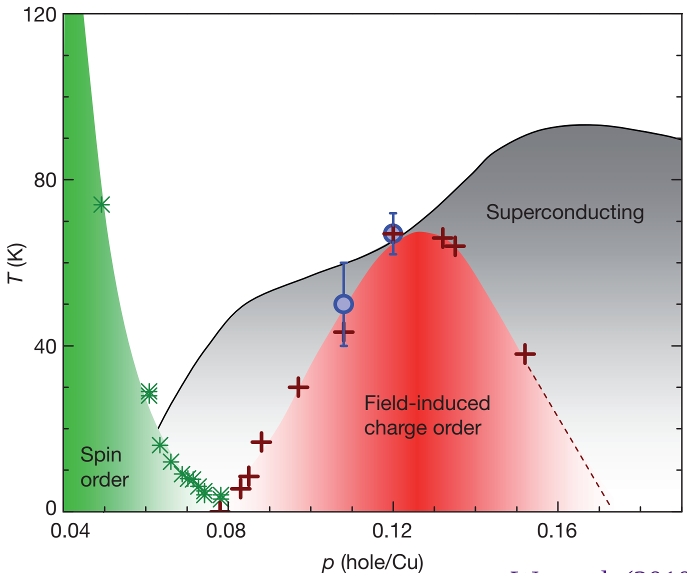
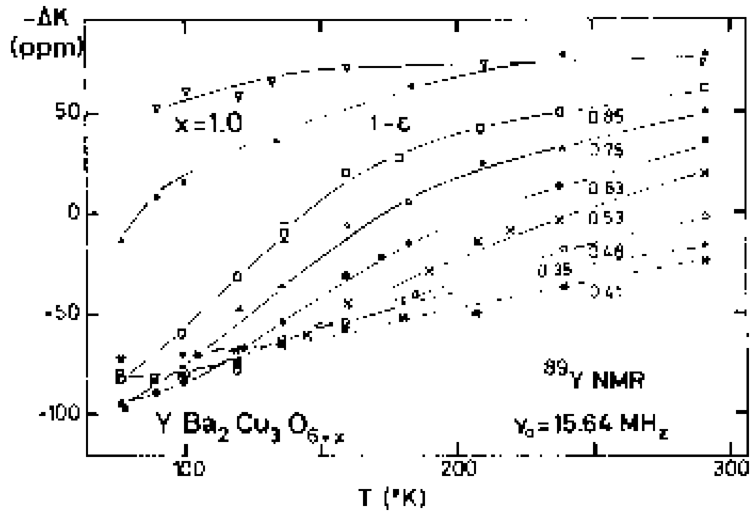


Wu et al, (2010)



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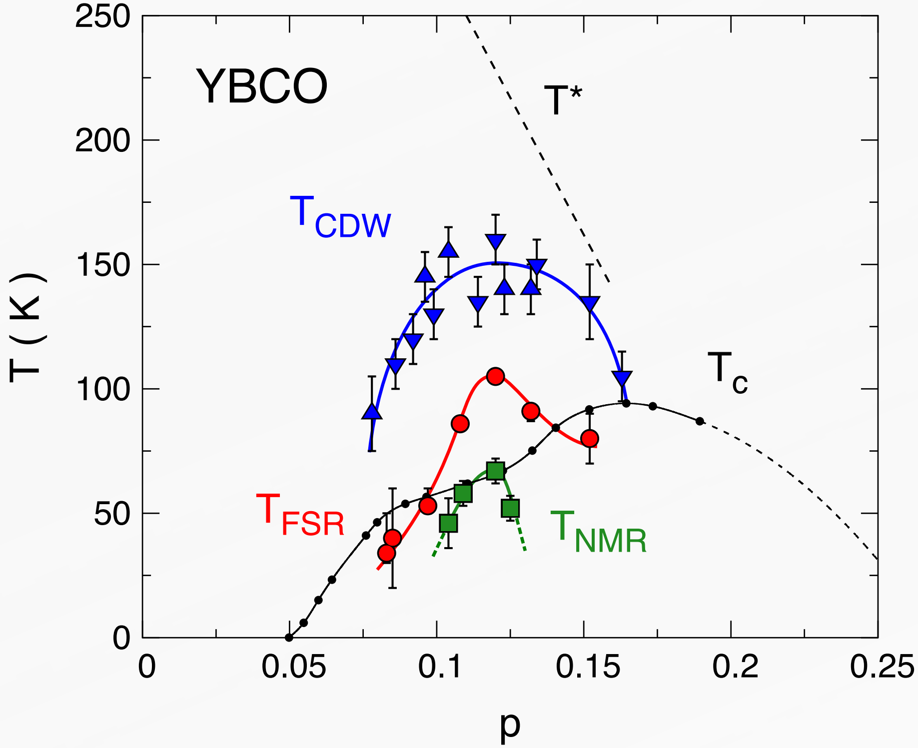
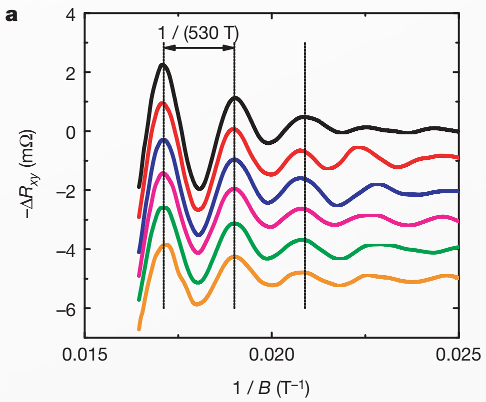
Cyr-Choignière, preprint 2015



Doiron-Leyraud et al. (2007)
Sebastian et al. (2011)



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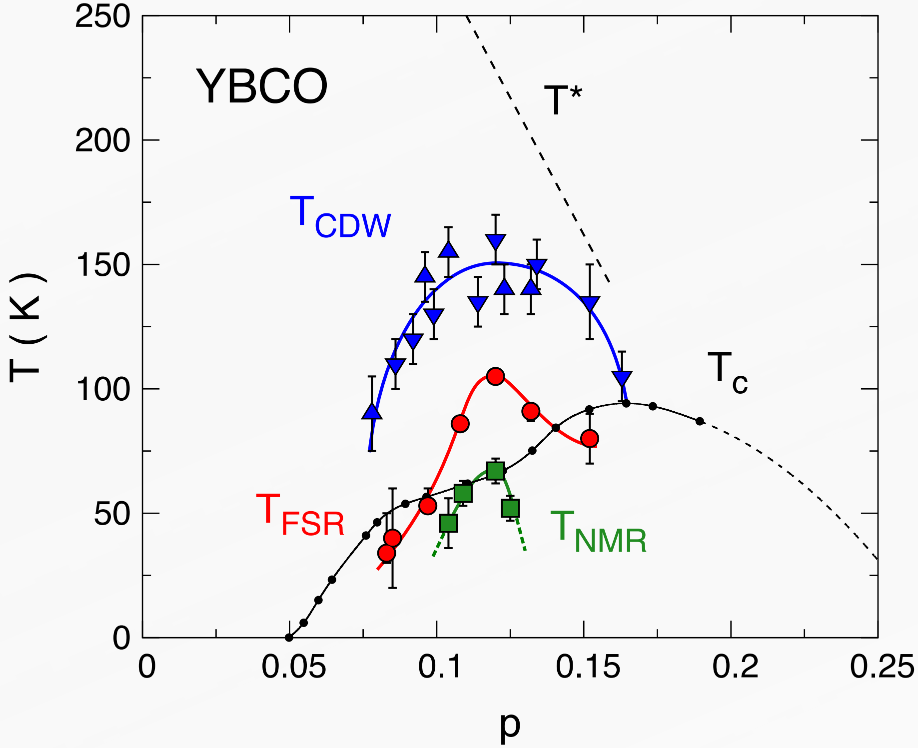

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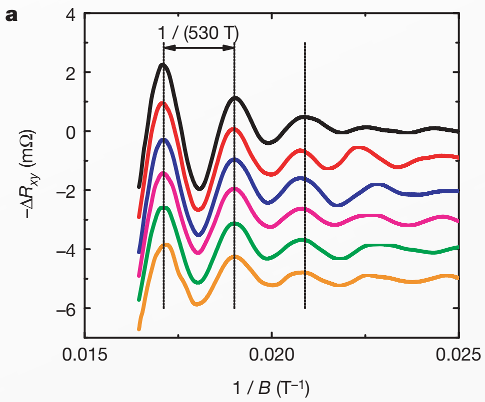
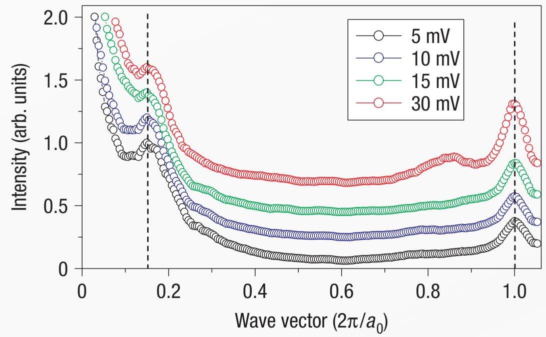
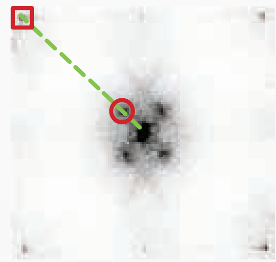


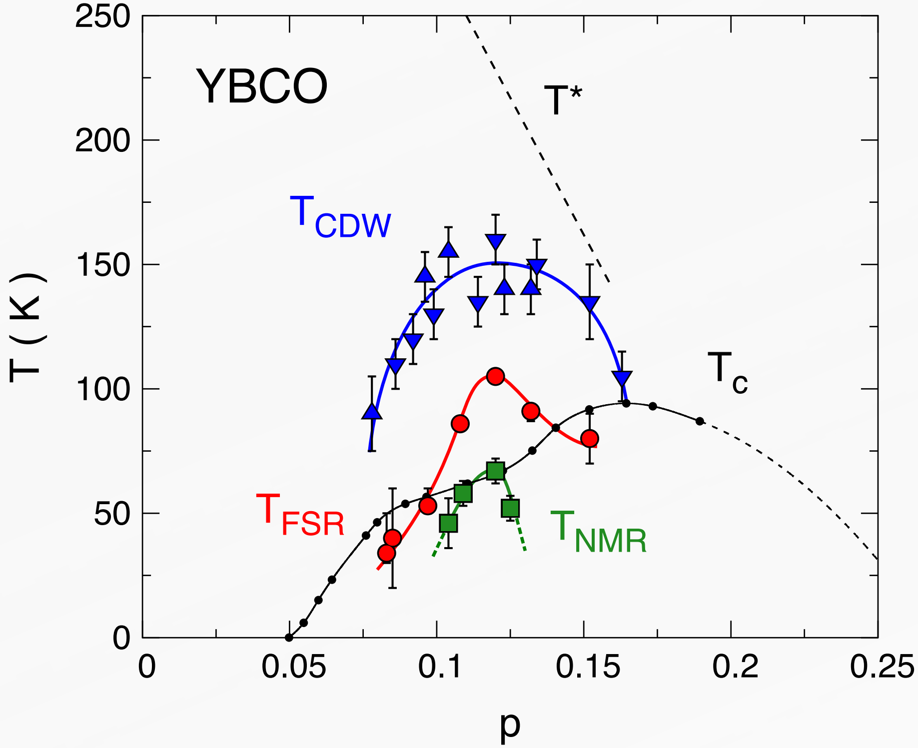
Wise et al, Nat. Phys. (2008)



BSCCO (opt. doped)



Cyr-Choignière, preprint 2015



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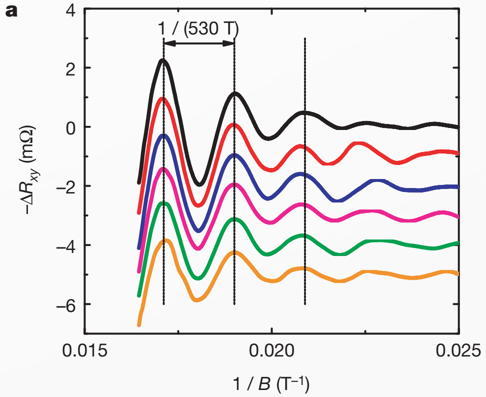

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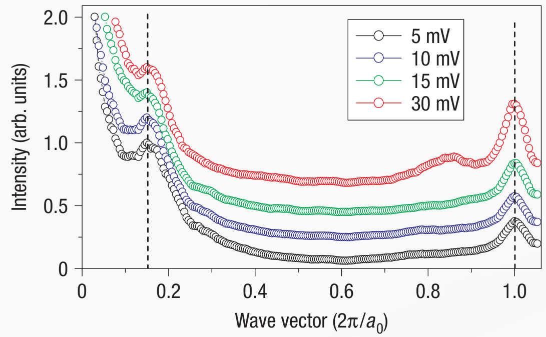

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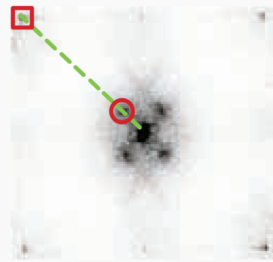
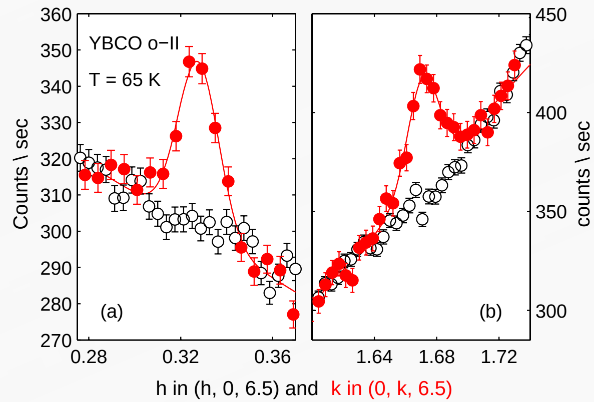
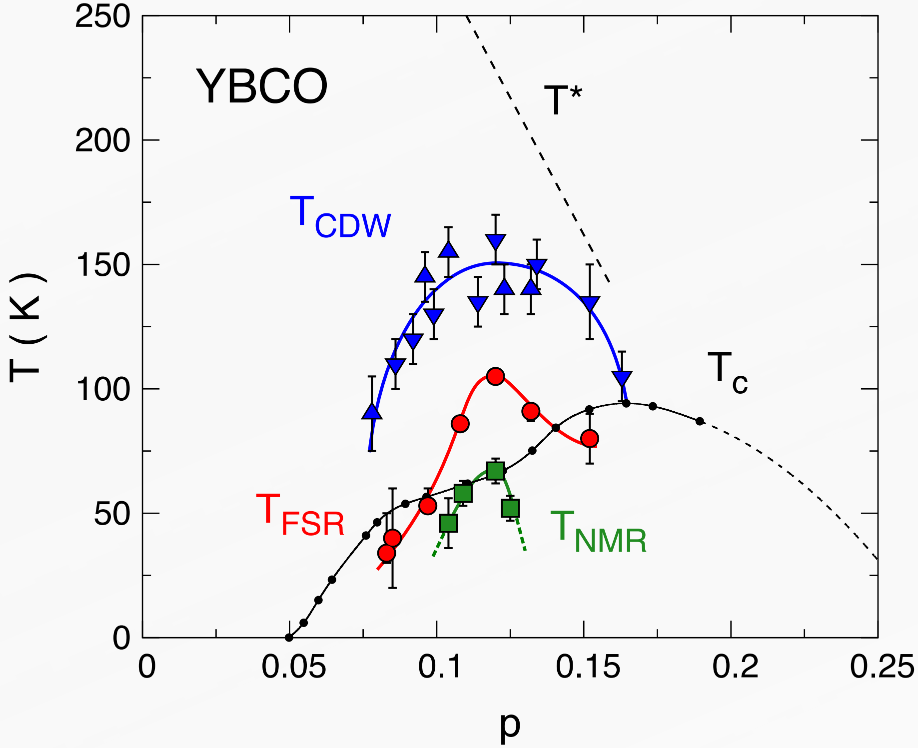


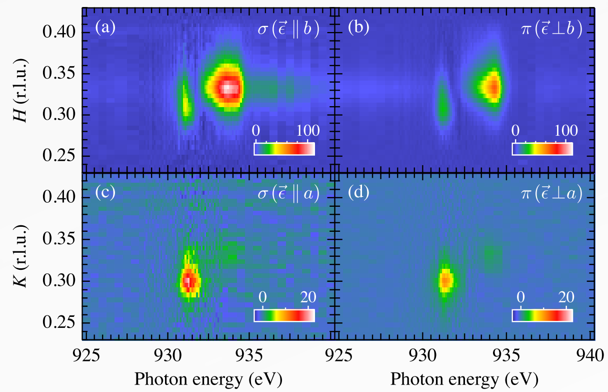
Blackburn et al, PRL (2013)



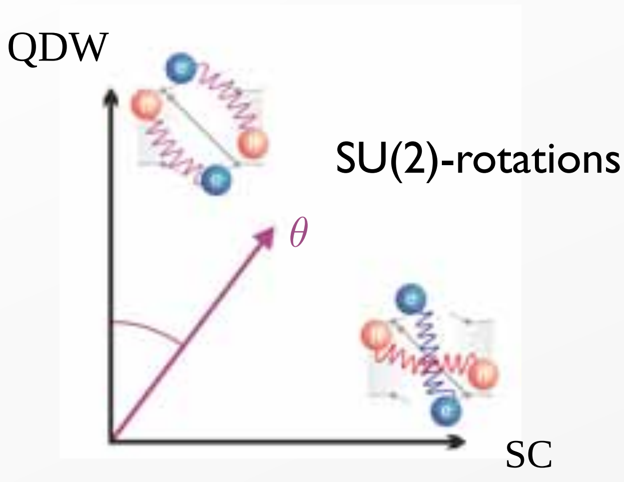
Cyr-Choignière, preprint 2015

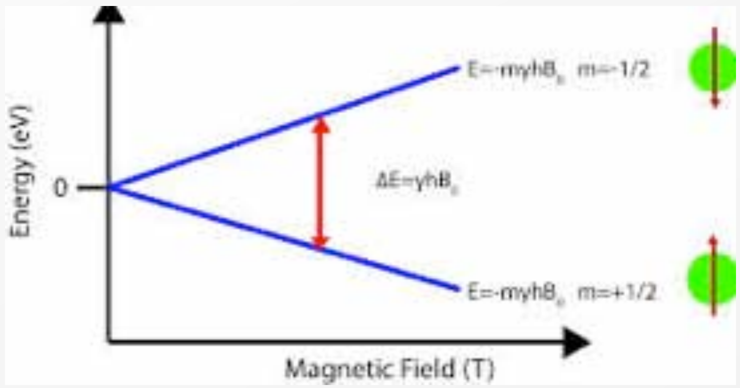


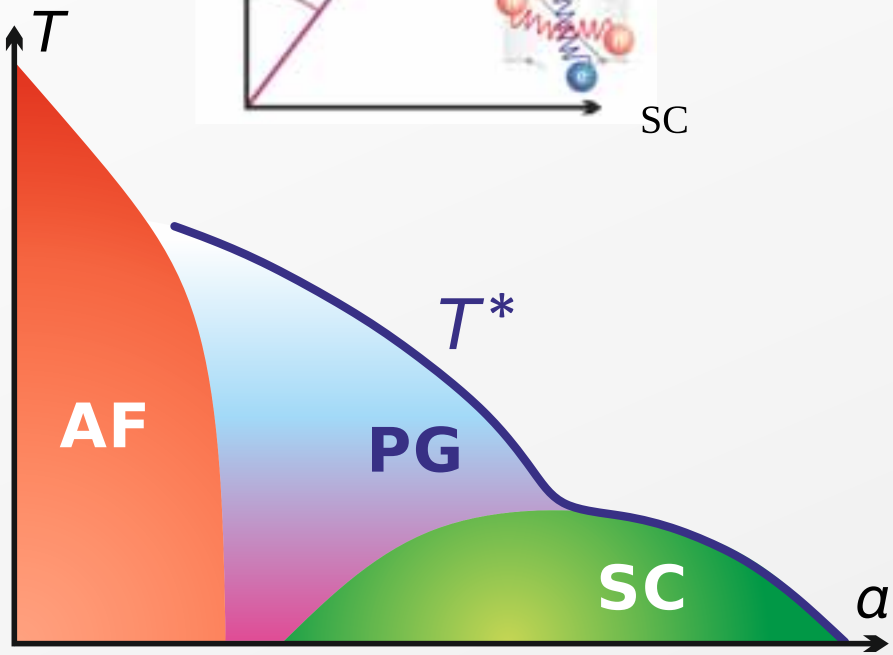
Achkar et al, PRL (2012)



Emergent symmetries for the pseudo-gap





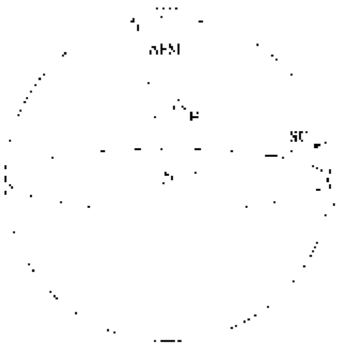


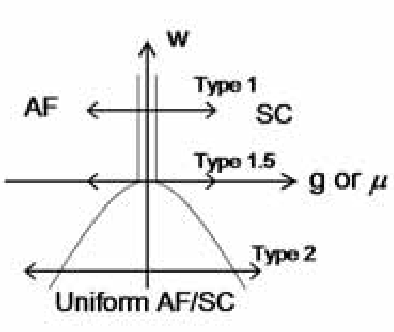
Degenerescence of levels:

accidental ?
symmetry related ?

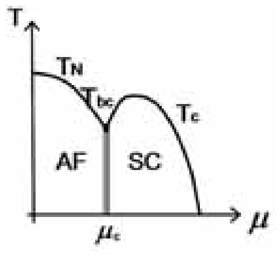
Sachdev et al (2013)
Efetov, Meier, CP (2013)

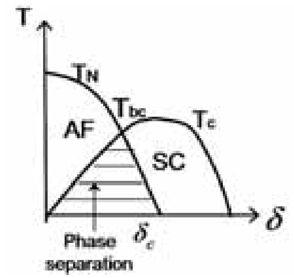
SO(5)-group

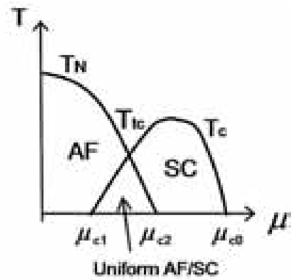




Fine-tuning condition ?







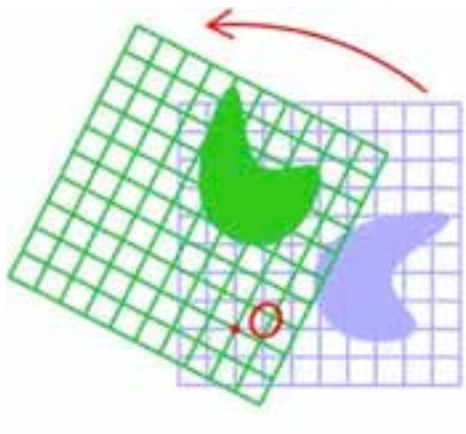
Demler, Zhang, Hanke (2005)

SU(2) symmetry related to the SU(2) symmetry of the superexchange hamiltonian and gauge SU(2) symmetry

$$U_{ij} = \begin{pmatrix} -\chi_{ij}^* & \Delta_{ij} \\ \Delta_{ij}^* & \chi_{ij} \end{pmatrix}$$

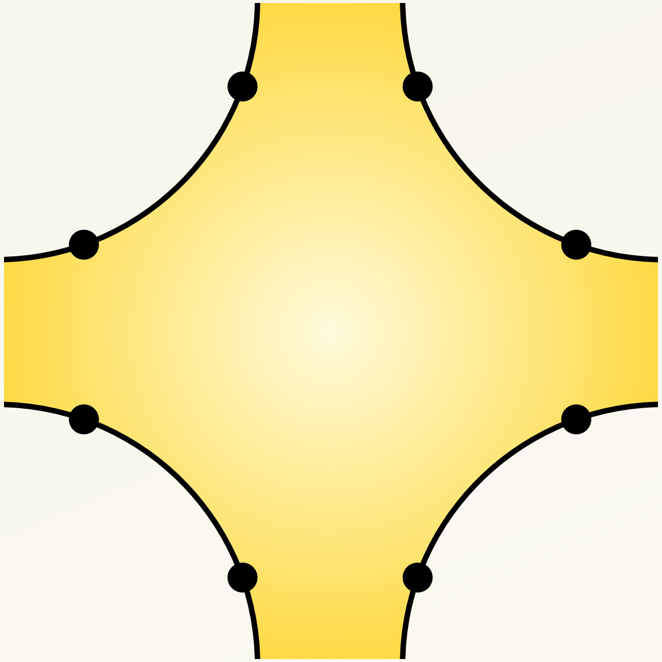
$$\chi_{ij}\delta_{\alpha\beta} = 2\langle f_{i\alpha}^\dagger f_{j\beta}\rangle, \quad \chi_{ij} = \chi_{ji}^*,$$

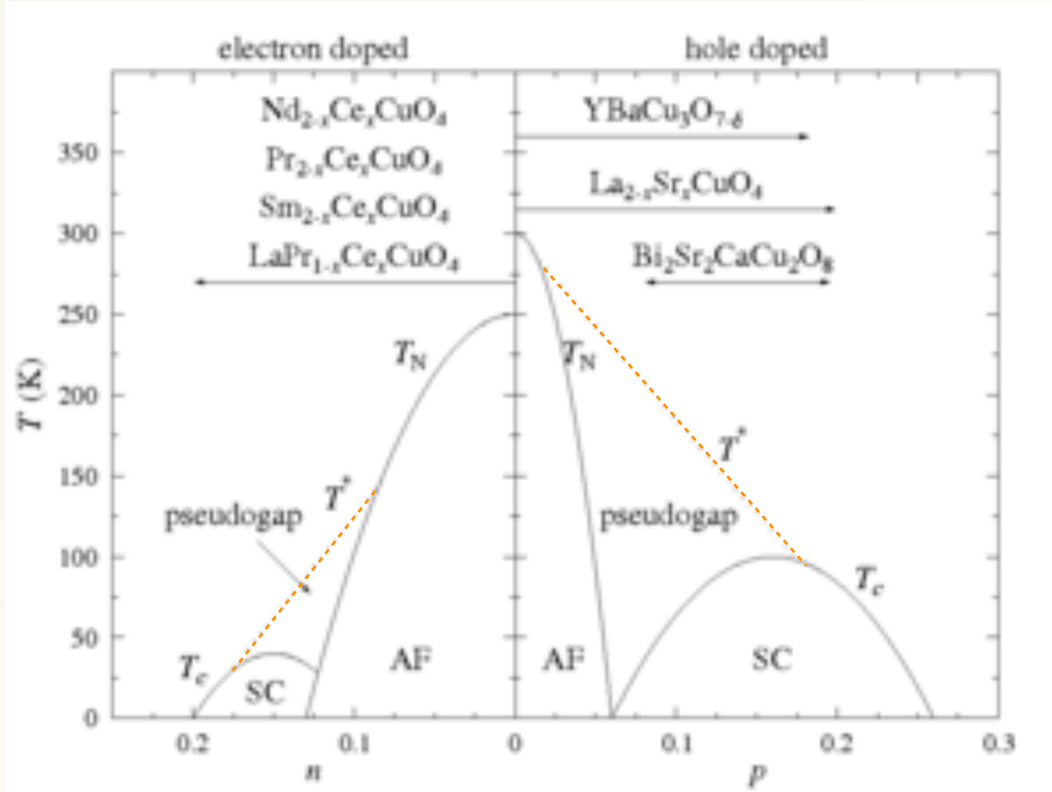
$$\Delta_{ij}\epsilon_{\alpha\beta} = 2\langle f_{i\alpha} f_{j\beta}\rangle, \quad \Delta_{ij} = \Delta_{ji}.$$



Sachdev et al (2013)
Kotliar and Liu (1988)
Lee, Wen, Nagaosa, RMP (2006)

Picture of the relation between the SC and Charge sector





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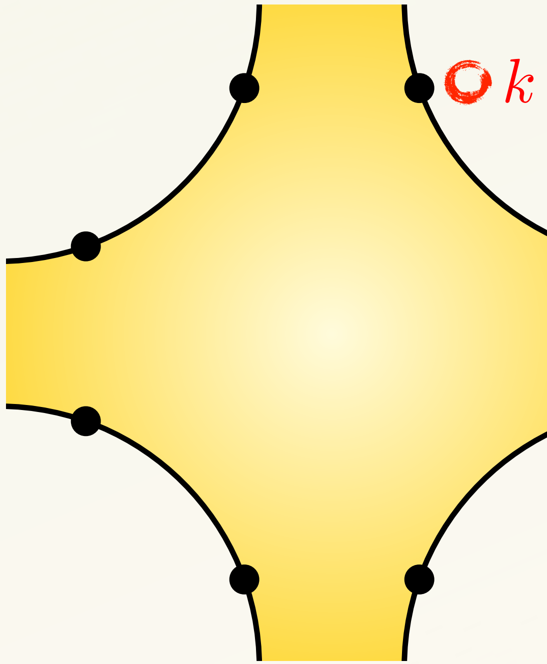

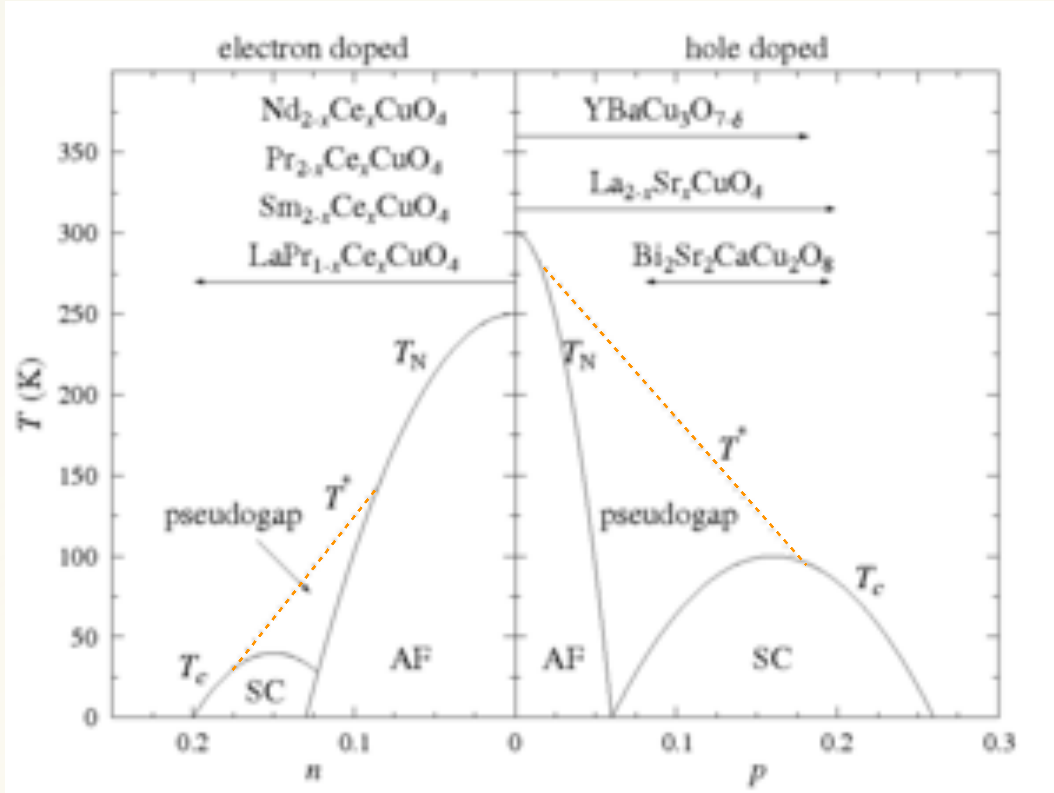

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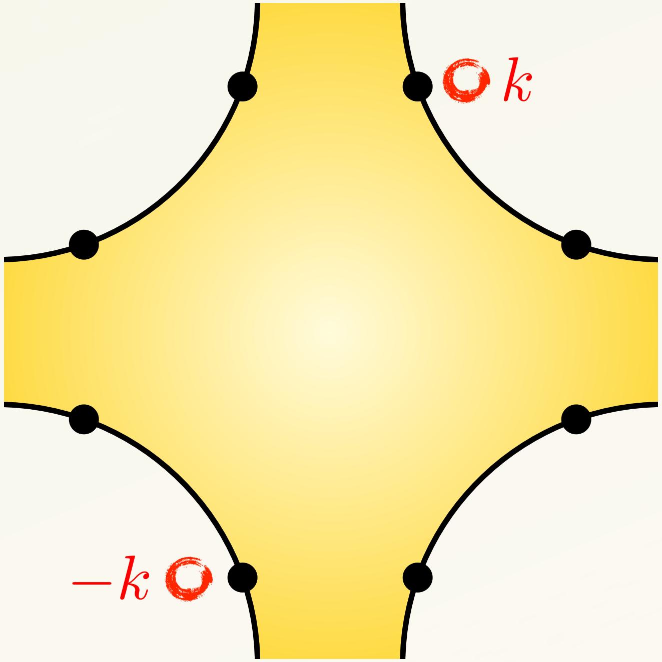

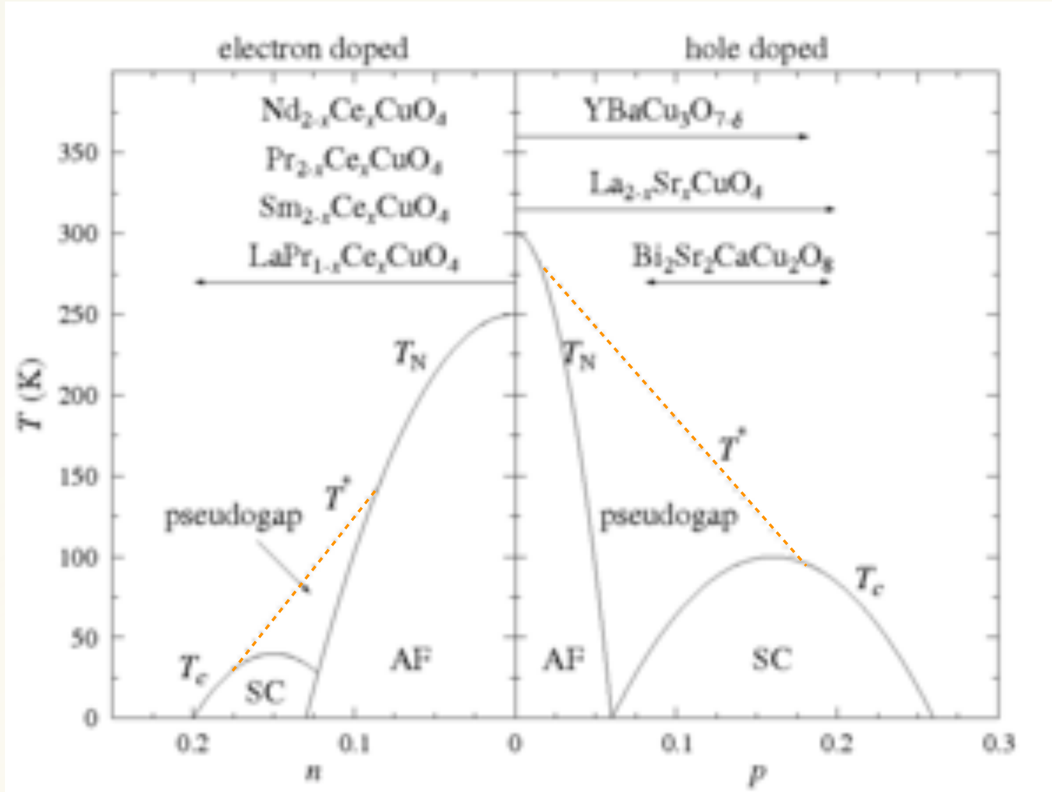

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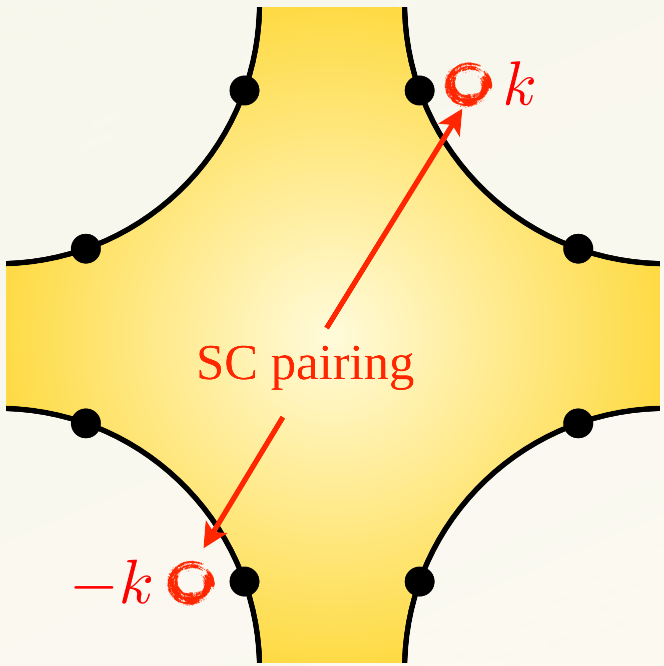
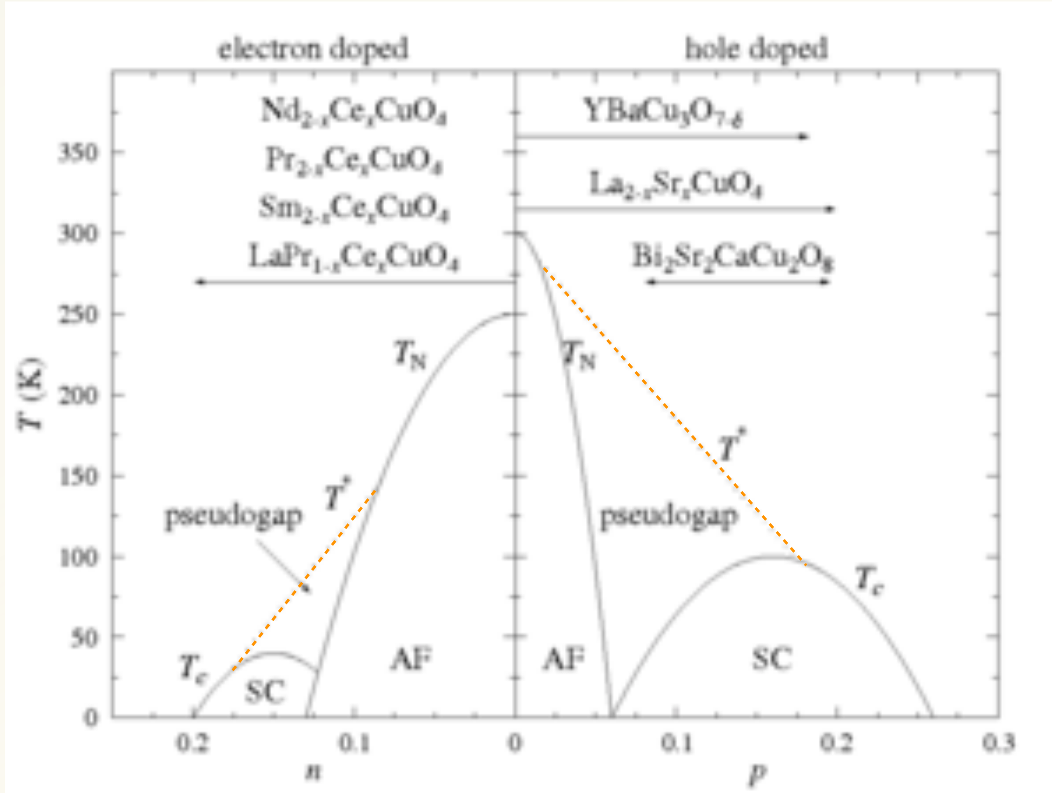
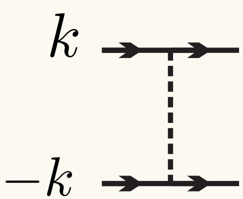
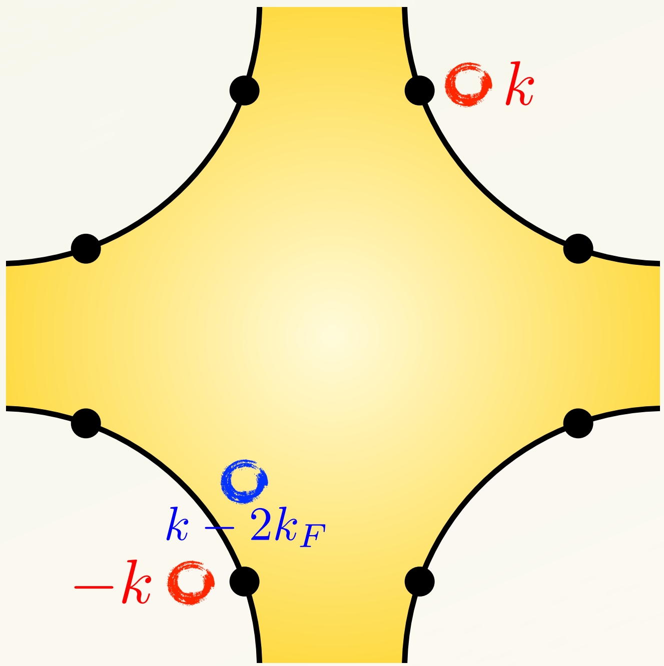


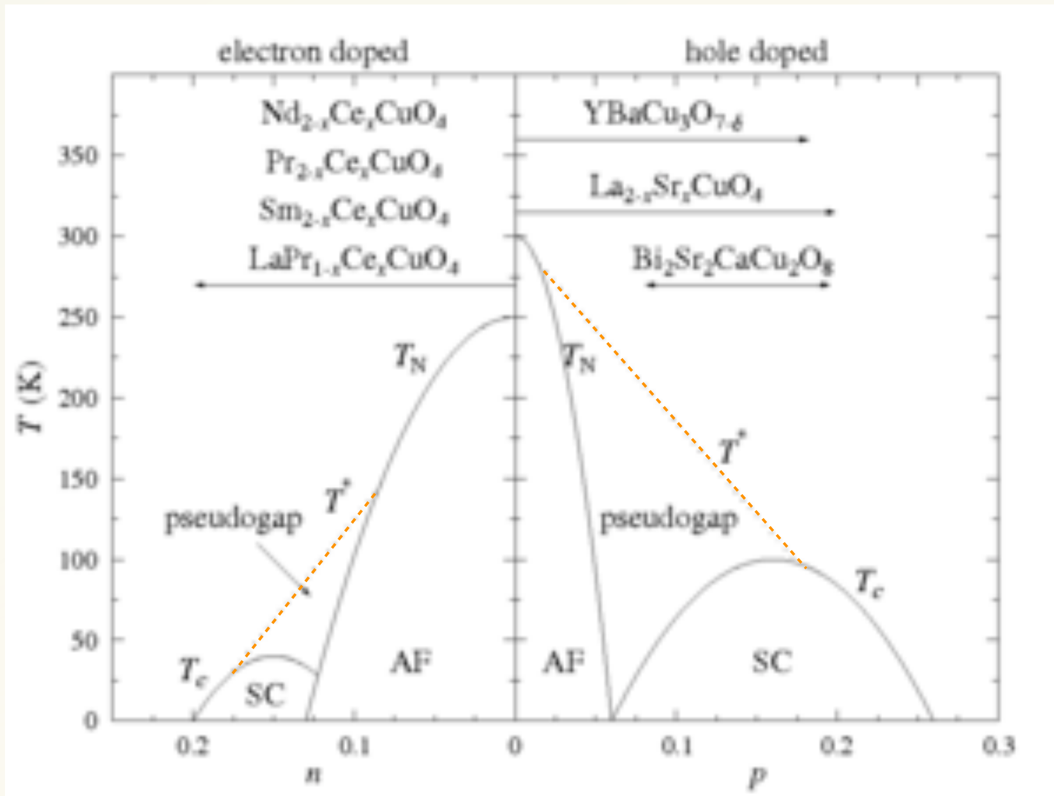


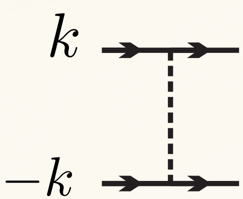


$$\Delta_{SC}$$

Picture of the relation between the SC and Charge sector

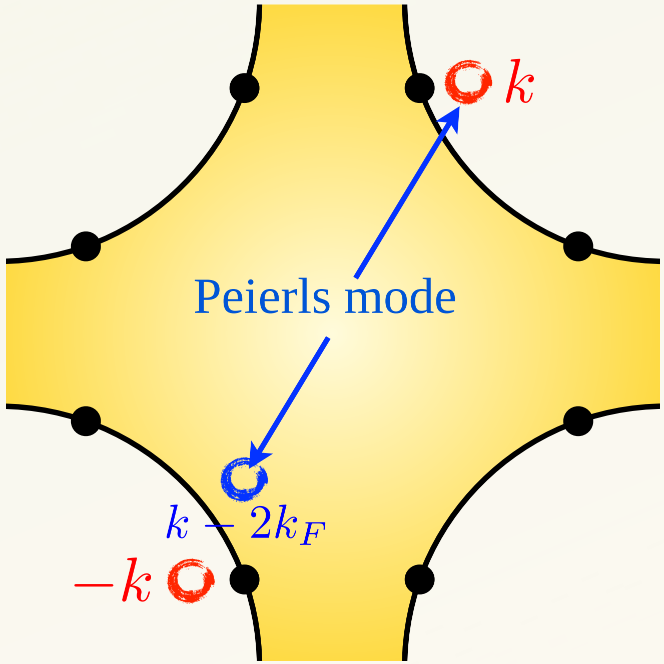


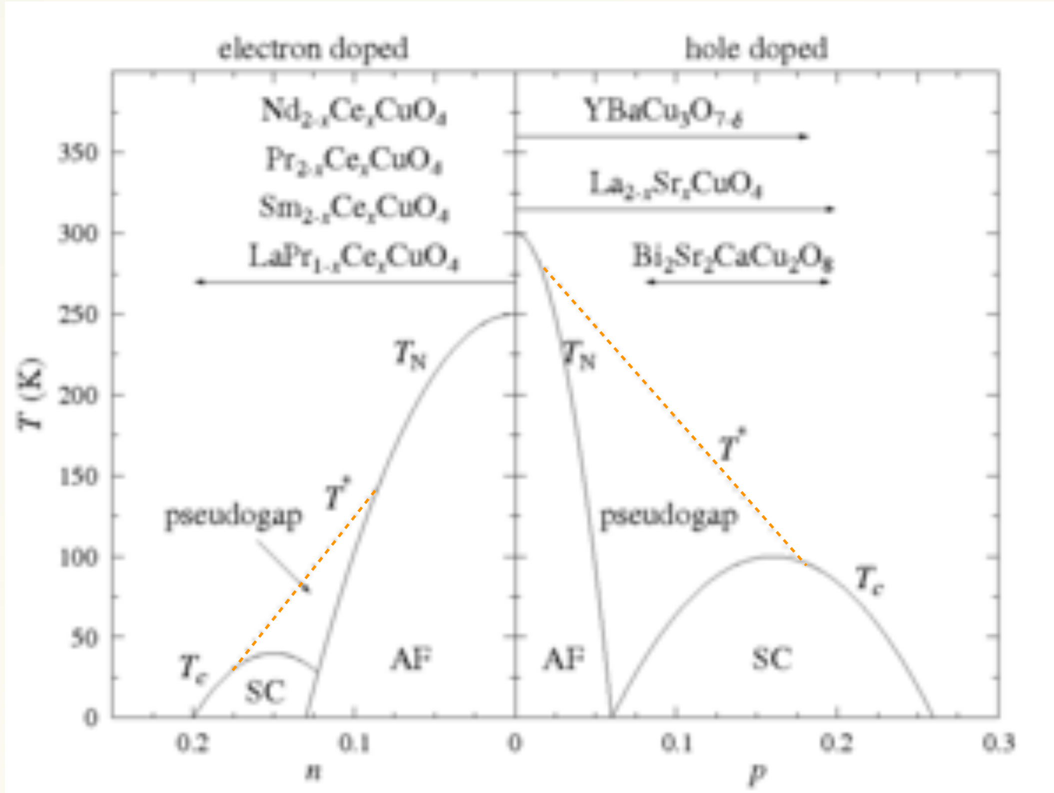


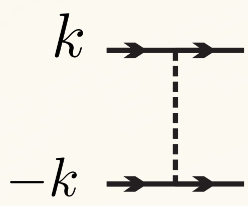


Δ_{SC}

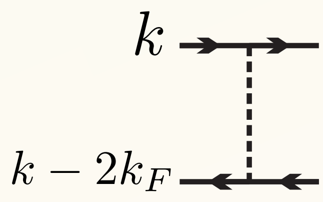
Picture of the relation between the SC and Charge sector





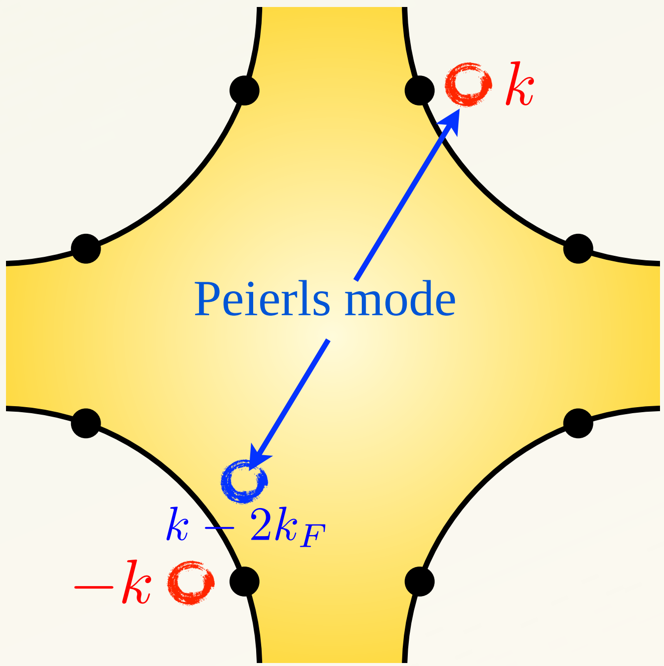


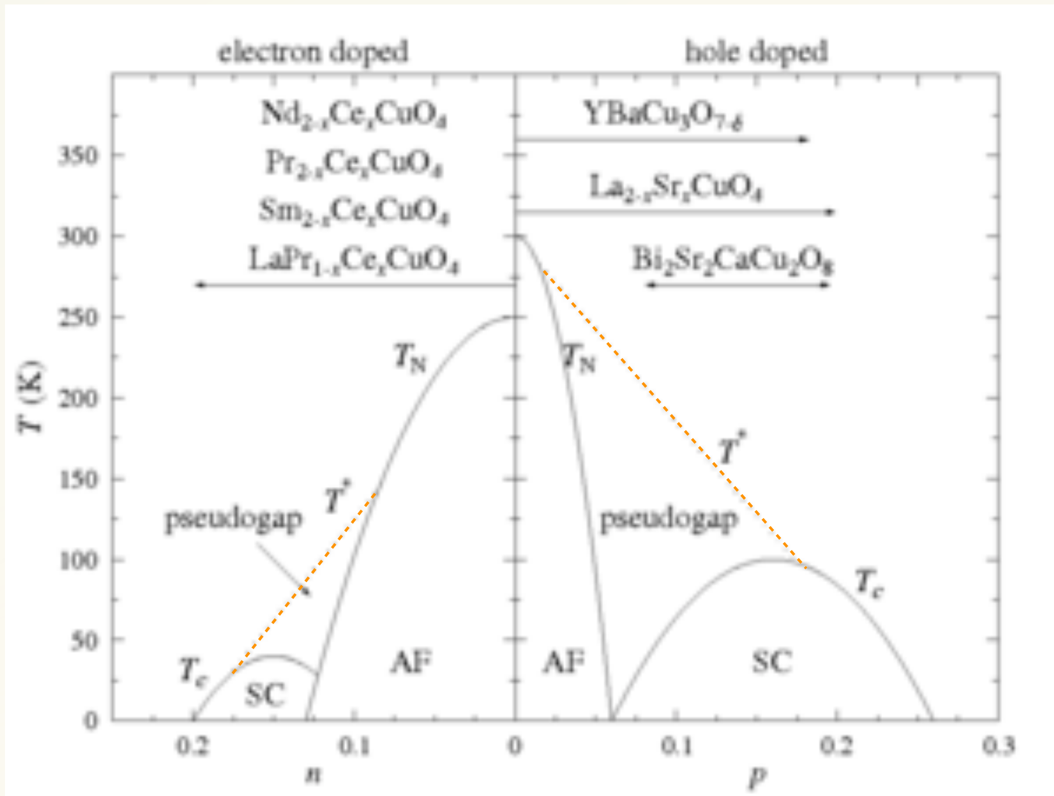
Δ_{SC}

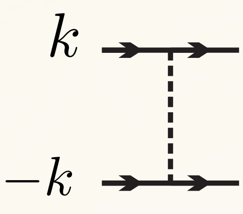


Δ_{QDW}

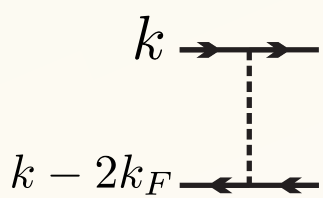
Picture of the relation between the SC and Charge sector





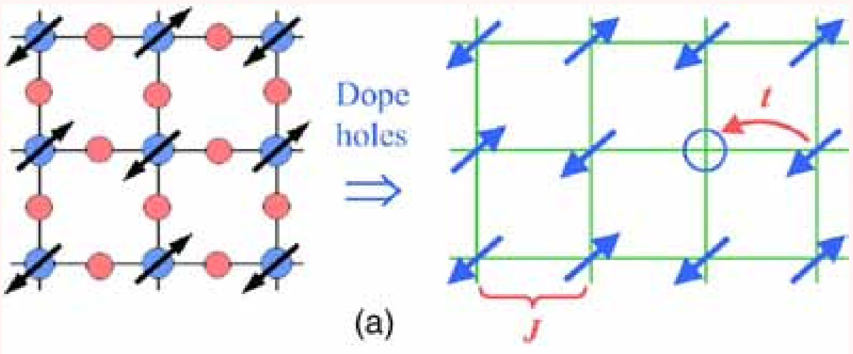


Δ_{SC} ⟵ **d-wave** ⟶

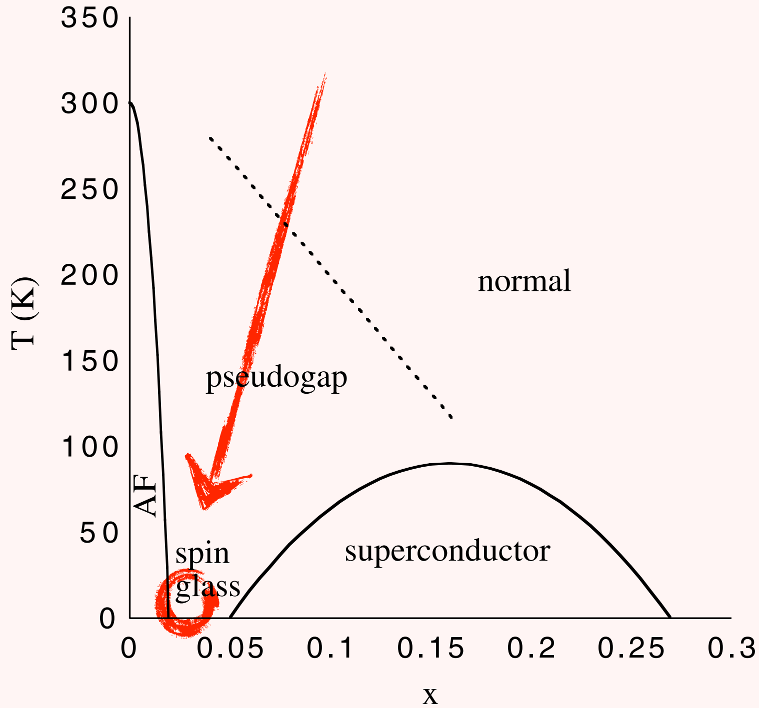


Δ_{QDW}

Exact realization : neglecting Coulomb interactions



Pines, Monthoux, Scalapino



$$H = \cancel{P}\left[-\sum_{\langle ij\rangle,\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{i\sigma} + J \sum_{\langle ij\rangle} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{1}{4} n_i n_j \right) \right] \cancel{P}$$

P: projection on no double occupancy

Exact realization of SU(2) symmetry

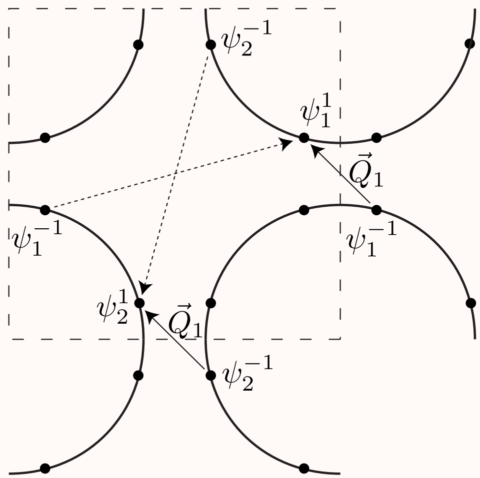
AFM QCP in d=2

K.B.Efetov, H.Meier, C.P. Nat. Phys. **9**, (2013)

$$\mathcal{L} = \chi^\dagger \left(\partial_\tau + \varepsilon(-i\hbar\nabla) + \lambda\vec{\phi}\vec{\sigma}\right)\chi \qquad \langle \phi^i_{\omega,\mathbf{k}}\phi^j_{-\omega,-\mathbf{k}}\rangle \propto \frac{\delta_{ij}}{(\omega/v_s)^2 + (\mathbf{k}-\mathbf{Q})^2 + a}$$

A Abanov, A. Chubukov, Schmalian RMP 2003
Belitz, Kirkpatrick, Vojta, RMP 2005
J Rech, CP, A Chubukov, PRB 2006

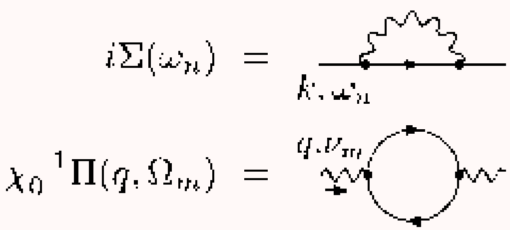
M. Metlitsky and S. Sachdev (2010)

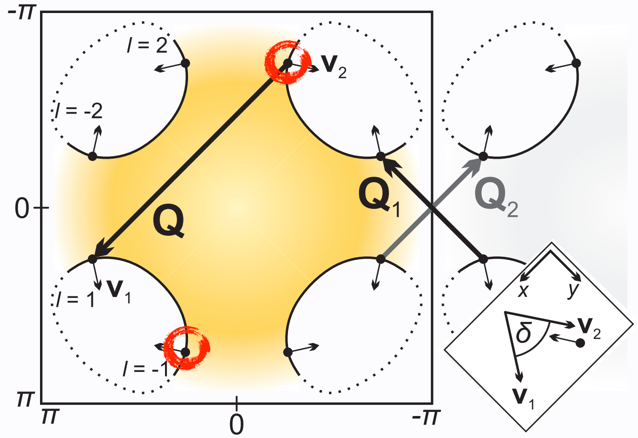


SU(2)-symmetry

Eliashberg theory : neglect vertices

Chubukov, Morr (2003 ...)





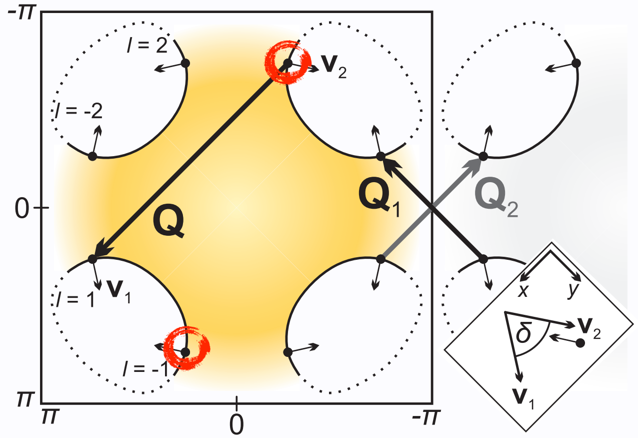
$$\delta \ll 1$$

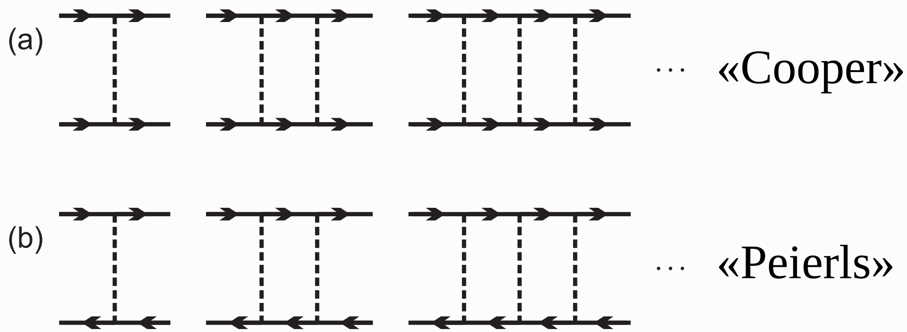
Composite order parameter

$$c_{\mathbf{p}}^{\mathrm{pp}} \left\langle (i\sigma_2)_{\alpha\beta}\, \psi_{\alpha,\mathbf{p}} \psi_{\beta,-\mathbf{p}} \right\rangle + c_{\mathbf{p}}^{\mathrm{ph}} \left\langle \delta_{\alpha\beta} \psi_{\alpha,\mathbf{p}} \psi^*_{\beta,-\mathbf{p}} \right\rangle ,$$

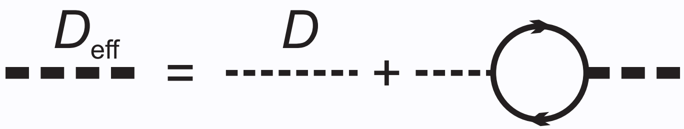
SU(2) symmetry and fluctuations

$$u = \begin{pmatrix} \Delta_- & \Delta_+ \\ -\Delta_+^* & \Delta_-^* \end{pmatrix} \quad \text{with} \quad |\Delta_+|^2 + |\Delta_-|^2 = 1$$





$$\delta \ll 1$$



Composite order parameter

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SU(2) symmetry and fluctuations

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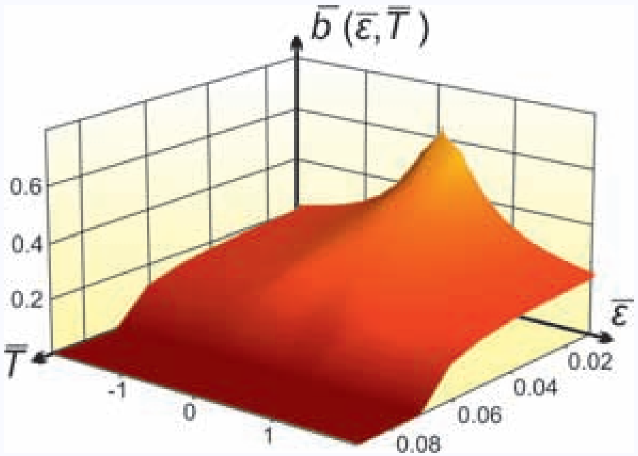
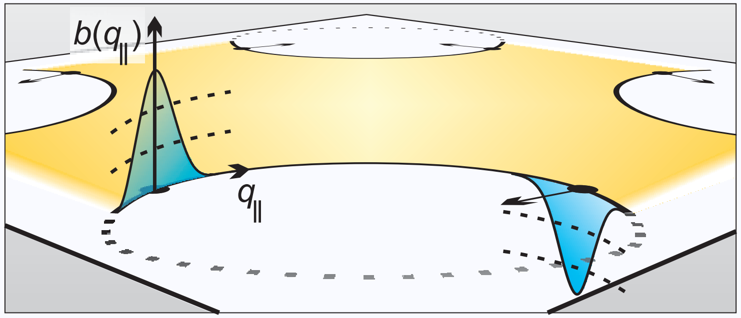
Gap equations around the QCP are universal

$$b(\varepsilon) \;=\; \frac{3\lambda^2}{4Nv} T \sum_{\varepsilon'} \frac{\bar{D}(\varepsilon-\varepsilon')\, b(\varepsilon')}{\sqrt{f^2(\varepsilon') + b^2(\varepsilon')}} \;,$$

$$\bar{D}(\omega) = \frac{1}{\sqrt{\gamma\Omega(\omega) + a}}$$

linear dispersion at the hot-spots



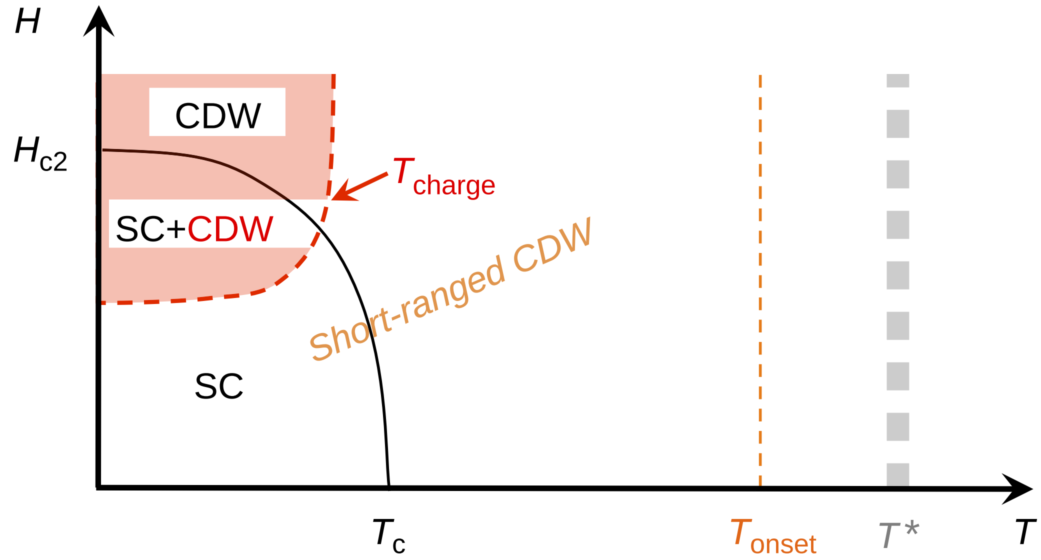


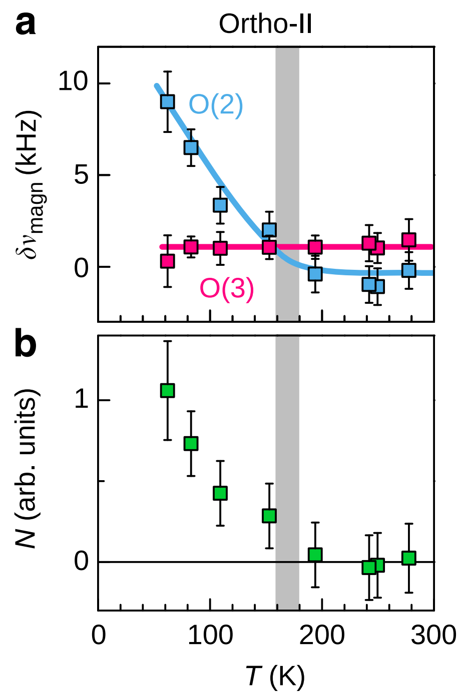
d-wave symmetry

$$b\hat{u} \quad \text{with} \quad \hat{u} = \begin{pmatrix} \Delta_- & \Delta_+ \\ -\Delta_+^* & \Delta_-^* \end{pmatrix}$$

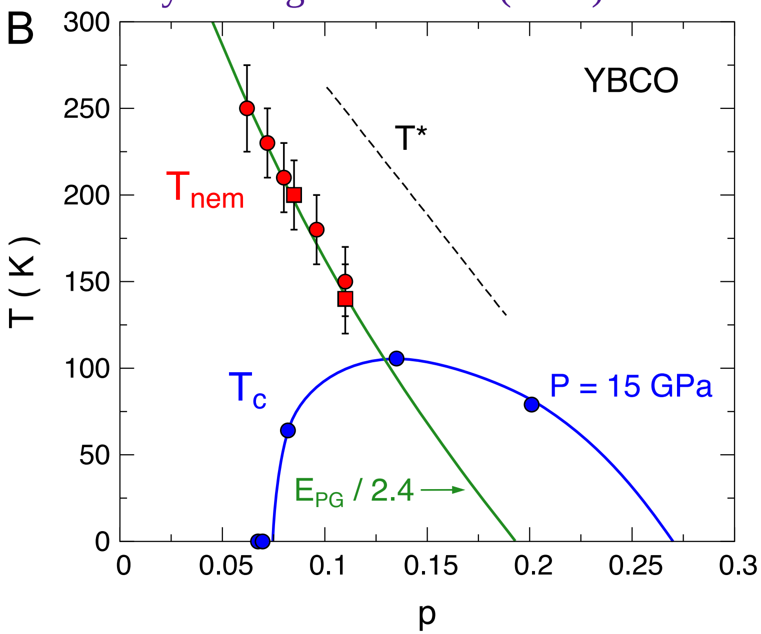
Non abelian superconductor

Wu et al. (2015)





Cyr-Choignières et al. (2015)

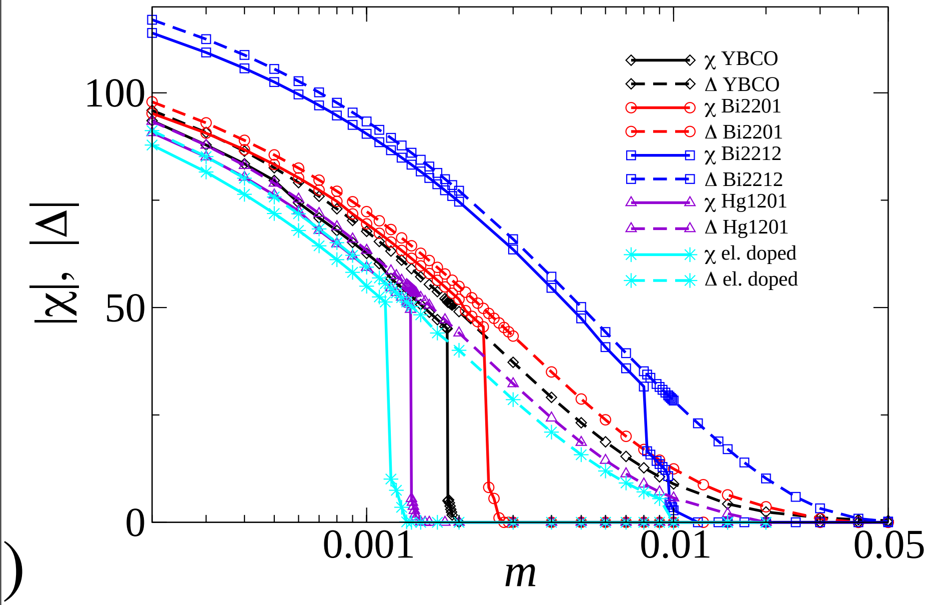


Pseudo-Gap = SU(2)
composite order parameter
=``non abelian''
superconductor

Curvature breaks the SU(2) symmetry : SC dome

How much is it broken ?

T. Kloss , X. Montiel & C.P. (2015)



$$\mathcal{L} = \chi^\dagger \left(\partial_\tau + \varepsilon(-i\hbar\nabla) + \lambda\vec{\phi}\vec{\sigma}\right)\chi$$

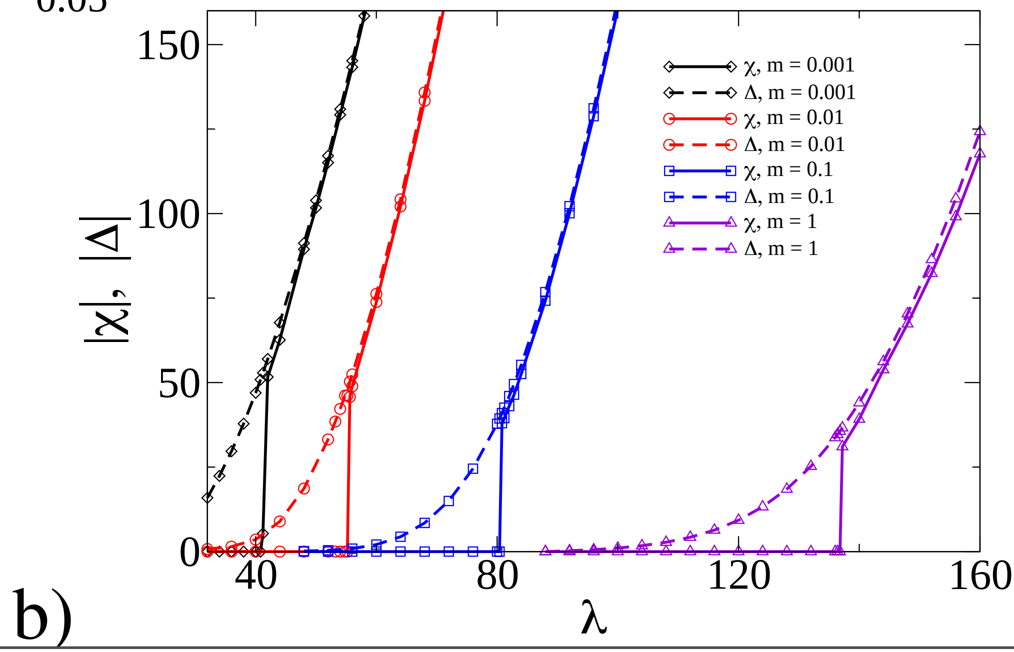
$$\langle \phi^i_{\omega,\mathbf{k}} \phi^j_{-\omega,-\mathbf{k}} \rangle \propto \frac{\delta_{ij}}{(\omega/v_s)^2 + (\mathbf{k}-\mathbf{Q})^2 + m}$$

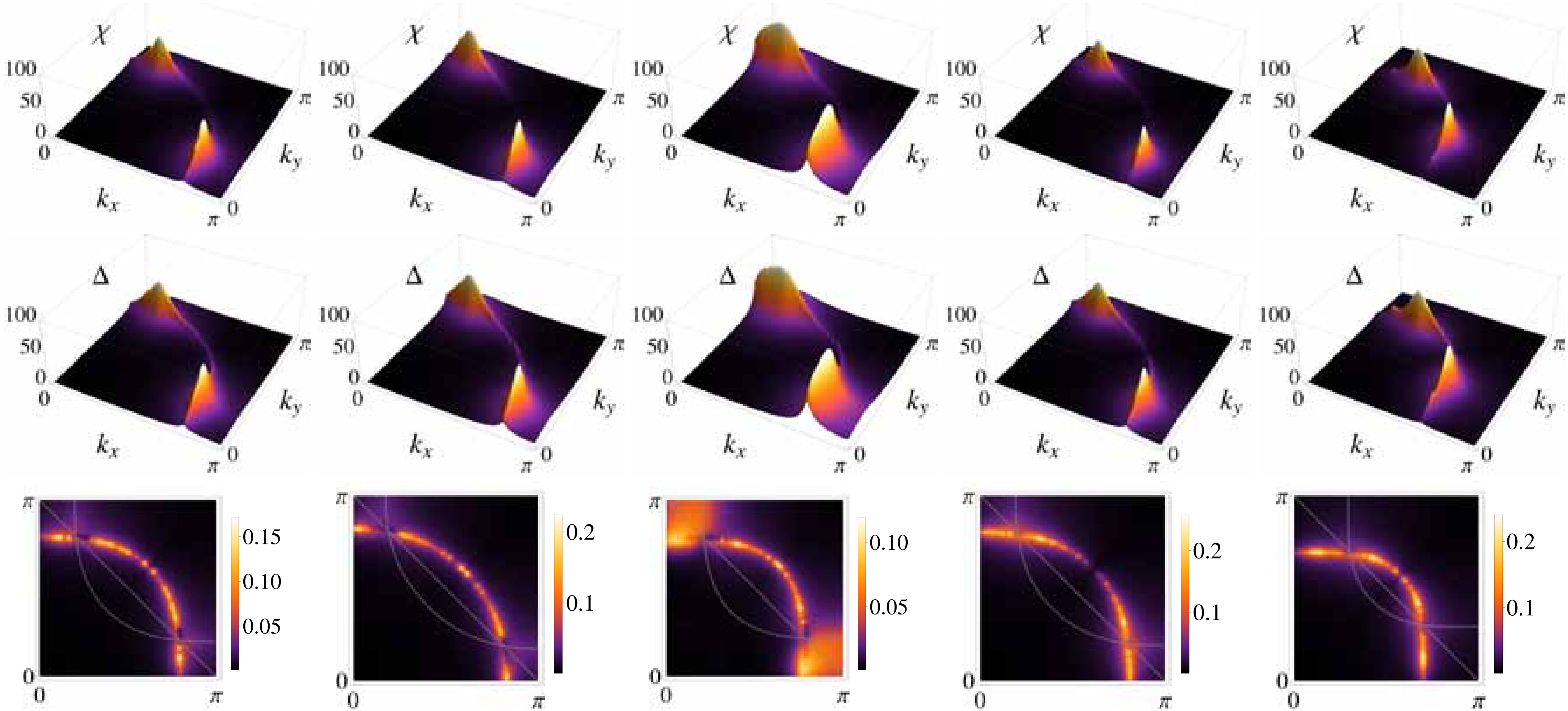
***SU(2) symmetry** is*

optimal when

AF correlations

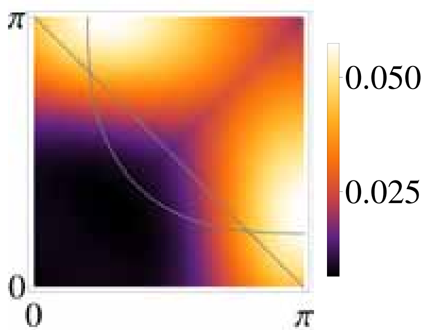
are maximum





YBCO Bi2201 Bi2212 Hg1201 $NdCeCu0_4$

$\lambda = 44,\ m = 10^{-3}$

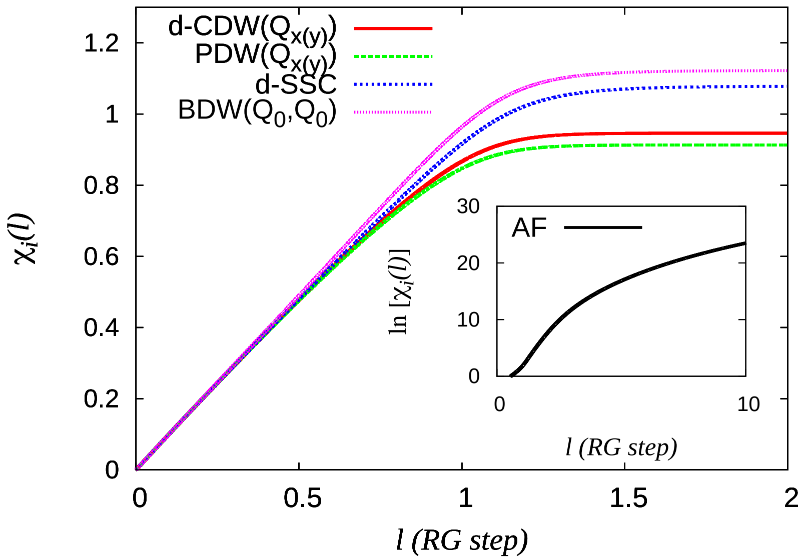


$\lambda = 160,\ m = 1$

$$0.02 \leq \Delta E \leq 0.3$$

Confirmation by other techniques ?

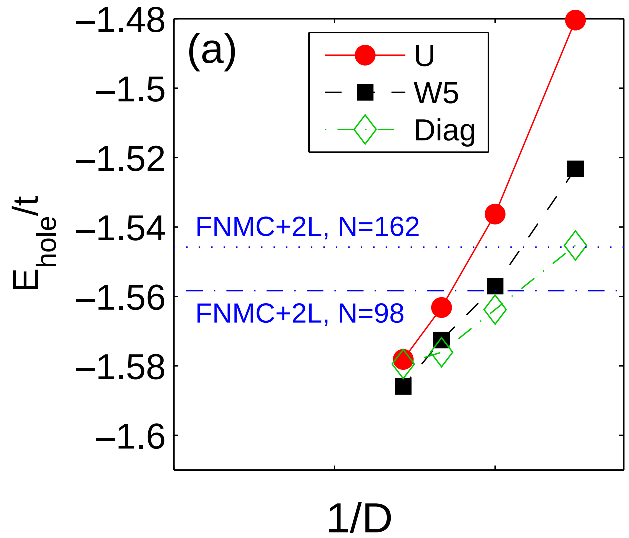
2 loops RG

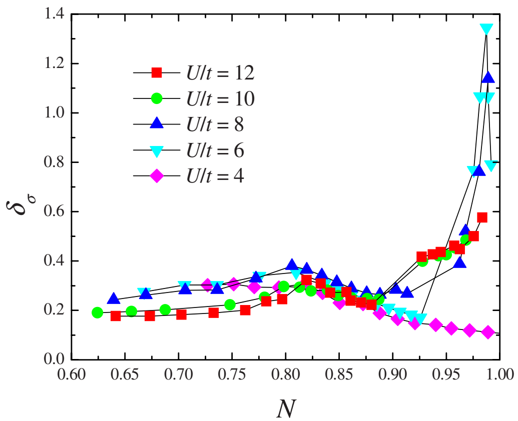


Freire, Carvalho & C.P. (2015)

SU(2) partner of axial CDW is PDW

Exact diag



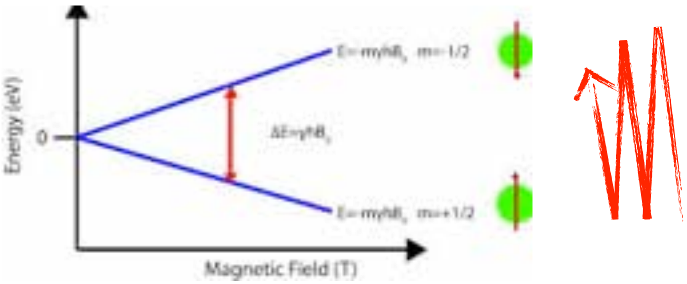


C-DMFT ?
Nematic response

Okamoto et al (2010)

Corboz et al. (2014)

In search for the collective mode...



Collective mode

Raman Scattering, X-Rays,
Electron Energy Loss
Sspectroscopy

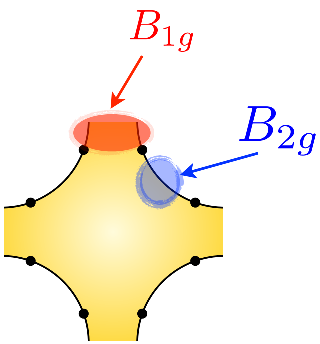
- *charge 2*
- *singlet*
- *around* $q \simeq 2k_F$

$$|" \downarrow " >= c^{\dagger}_{k,\uparrow} c_{k-2k_F,\uparrow} |0>$$

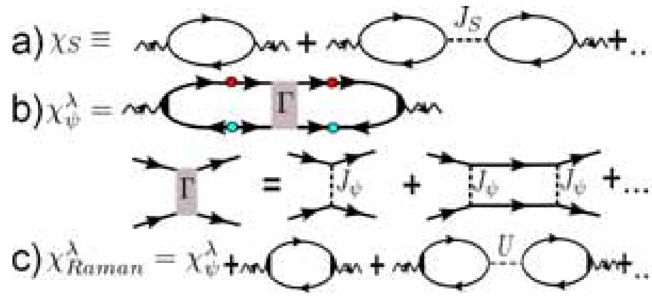
$$|" \uparrow " >= c^{\dagger}_{k,\uparrow} c^{\dagger}_{-k,\downarrow} |0>$$

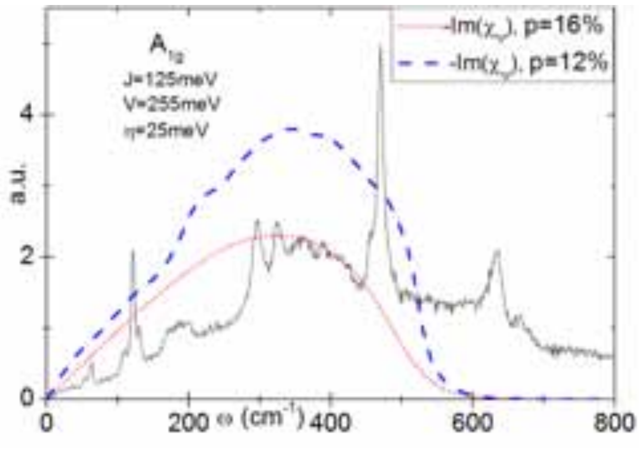
$$\hat{\rho} = \sum_k c_{-k,\downarrow} c_{k-2k_F,\uparrow}$$

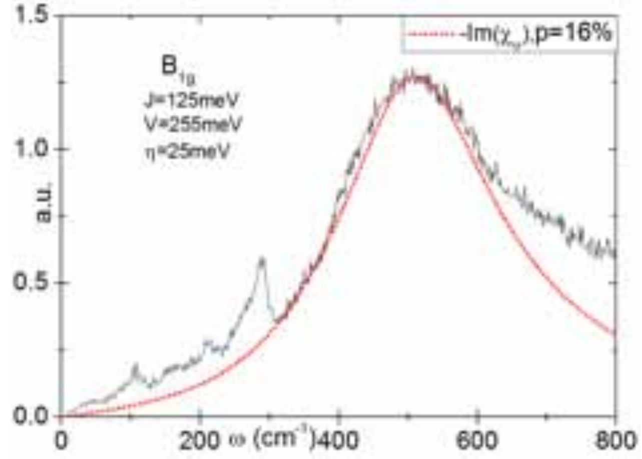
X. Montiel, T. Kloss,
Y. Gallais, A. Sacuto, CP, preprint

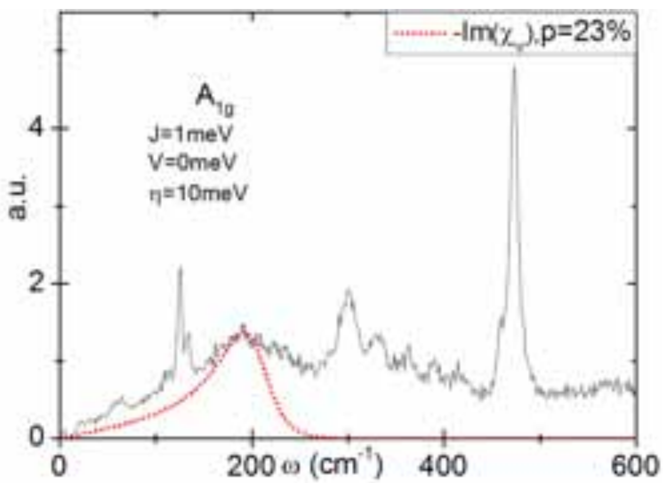


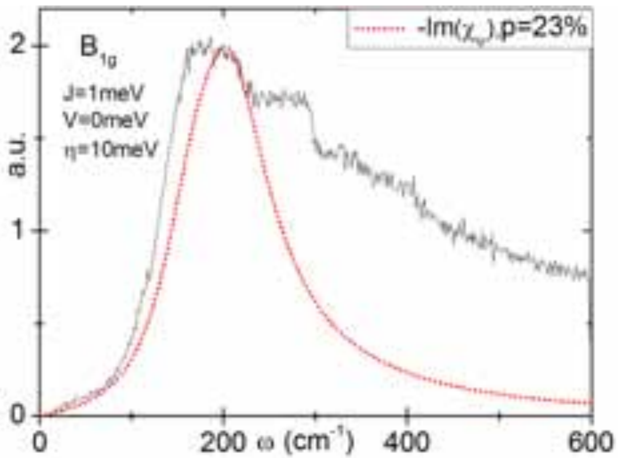
$$H = \sum_{\mathbf{k},\sigma} \xi_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} \left(J_{\mathbf{q}} c^{\dagger}_{\mathbf{k},\alpha} \sigma^{T}_{\alpha\beta} c_{\mathbf{k}+\mathbf{q},\beta} c^{\dagger}_{\mathbf{k}'+\mathbf{q},\gamma} \sigma_{\gamma\delta} c_{\mathbf{k}',\delta} \right) + \sum_{\mathbf{k},\mathbf{k}',\sigma,\sigma'} V_{\mathbf{q}} c^{\dagger}_{\mathbf{k},\sigma} c_{\mathbf{k}+\mathbf{q},\sigma} c^{\dagger}_{\mathbf{k}',\sigma'} c_{\mathbf{k}'-\mathbf{q},\sigma'},$$









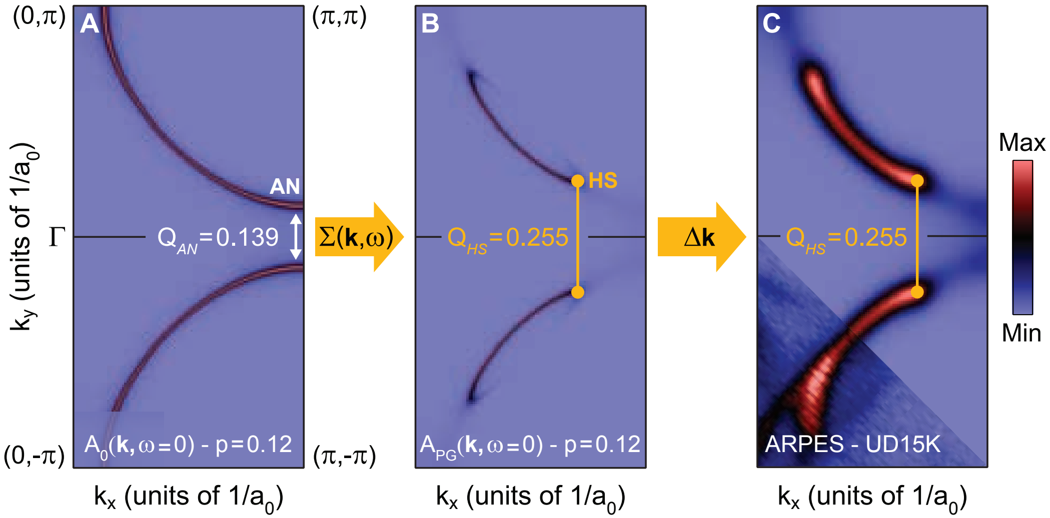


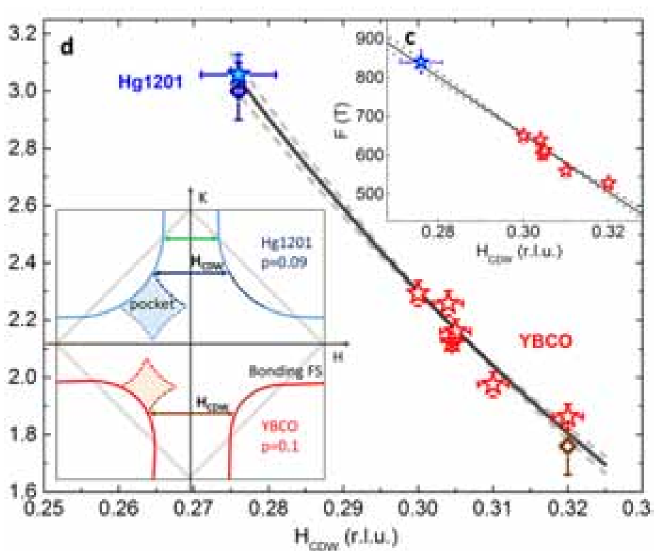
$$V_{\mathbf{q}} = V$$

$$J_{\mathbf{q}} = -J$$

Controversy with the CDW wave vector

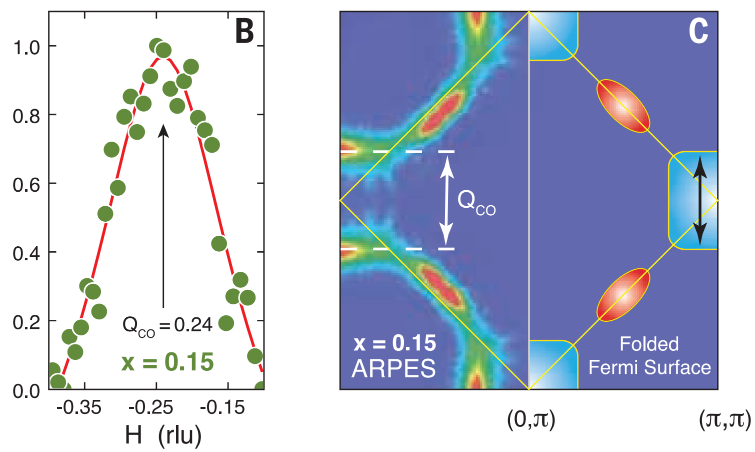
Damascelli : (2013)





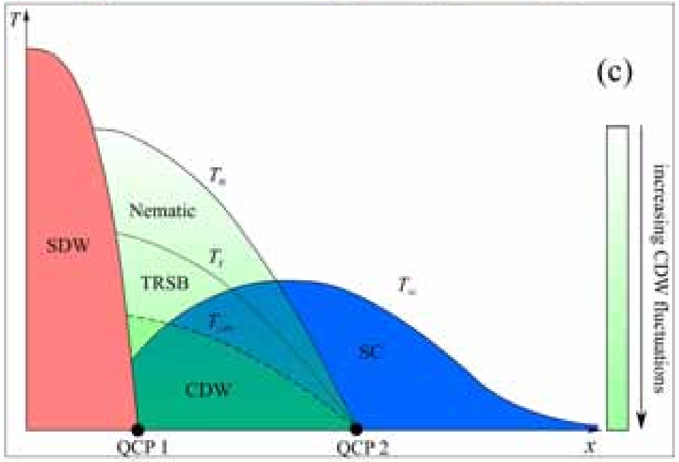
Greven (2014)

$\mathrm{Nd}_{2-x}\mathrm{Ce}_x\mathrm{CuO}_4$



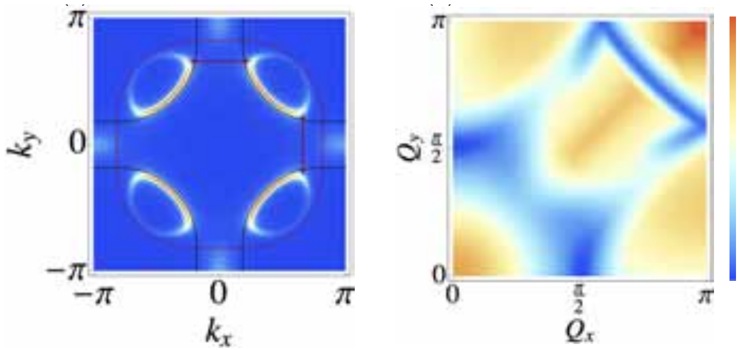
da Silva Neto et al. (2015)

Y. Wang, A. Chubukov (2014)

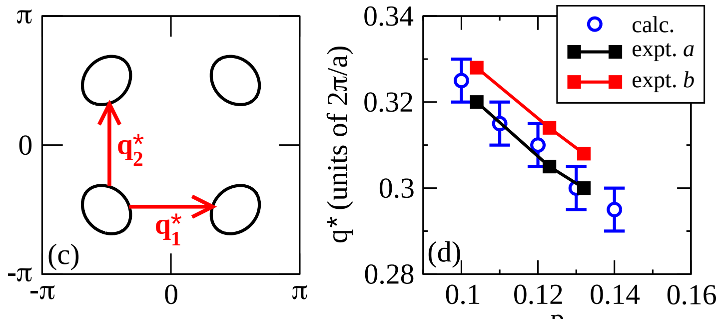


Pre-emptive order breaking TR

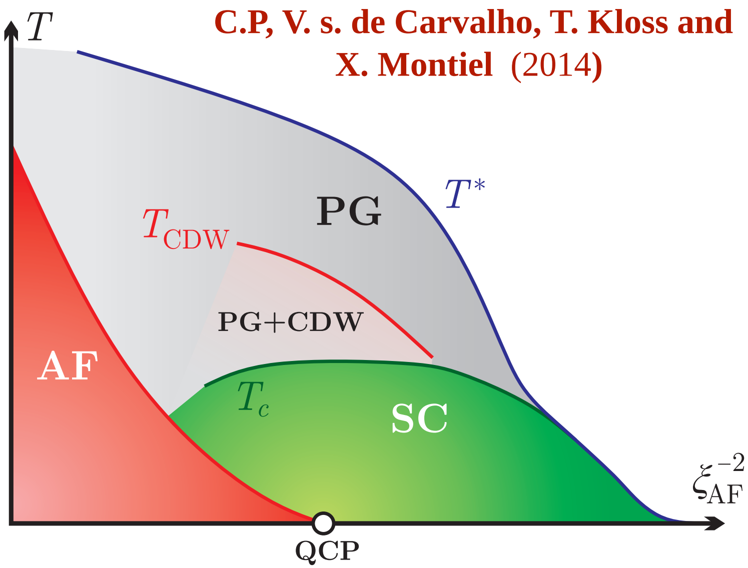
S. Sachdev, D. Chowdhury (2014)



Atkinson, A. Kampf (2013)



C.P, V. s. de Carvalho, T. Kloss and X. Montiel (2014)



Secondary order at the tip of the arcs

Co-existence : PG + Qx, Qy CDW

Re-examination of the SF model

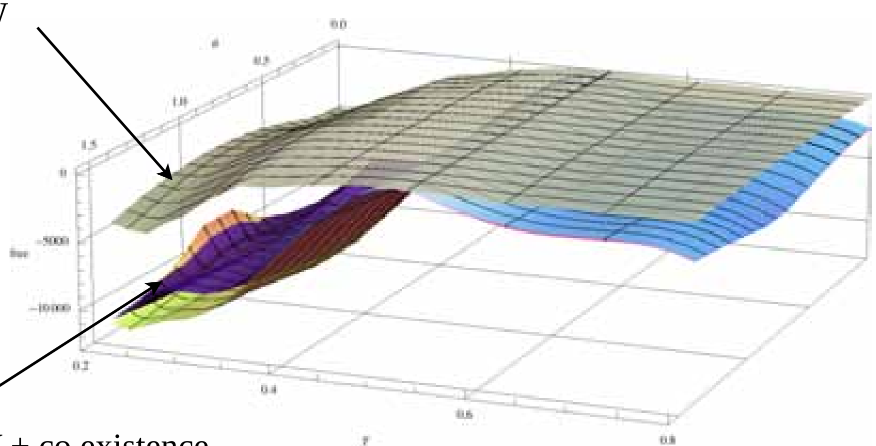
pure CDW

co-existence ?

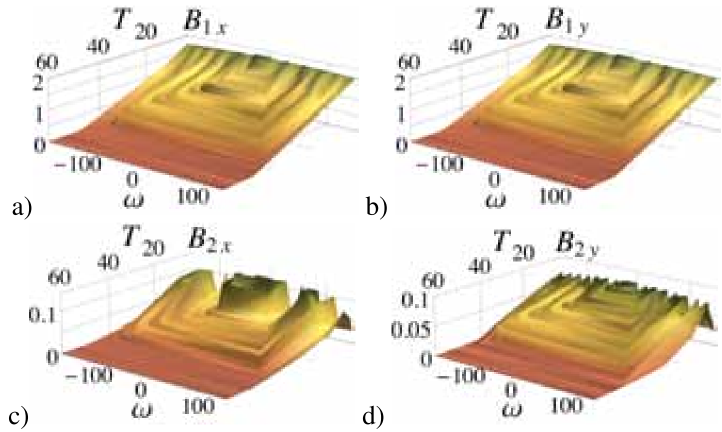
SC/QDW

Small nematic term needed to get the CDW below T* $u\rho_{\mathbf{Q}_x}\rho_{-\mathbf{Q}_x}\langle\rho_{\mathbf{Q}_y}\rho_{-\mathbf{Q}_y}\rangle$

pure CDW



SC/QDW + co existence



$B_{1,x/y} = QDW$ $B_{2,x/y} = CDW$

Free energy for the three cases

$QDW \gg CDW$

C.P, V. s. de Carvalho, T. Kloss and X. Montiel (2014)

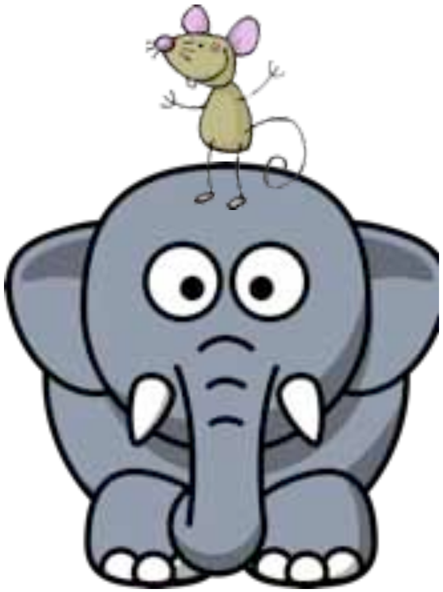
Conclusions

- Charge orders are a key players in cuprate physics: natural competitor of superconductivity.

- SU(2) symmetry present in the under-doped region of the phase diagram

- Pseudo-gap with SU(2) symmetry and charge orders are precursors of the AFM order

- One can stabilize axial-CDW in co-existence with composite Peierls-SC phase



- SU(2) rotation of axial CDW=PWD