Charge orders and Strange metals in Cuprates

Catherine Pépin, (IPhT, CEA-Saclay)

A. Banerjee

L. Haurie

E. Pangburn

H. Freire

S. Sarkar & M. Grandadam

College de France, June 2nd, 2022

Yvan Sidis, J. C. Séamus Davis, Mohammad Hamidian,

Alain Sacuto, Henri Alloul, Nigel Hussey, Dorothée Colson

Philippe Bourges, Victor Balédent, Dalila Bounoua, Brigitte Leridon,

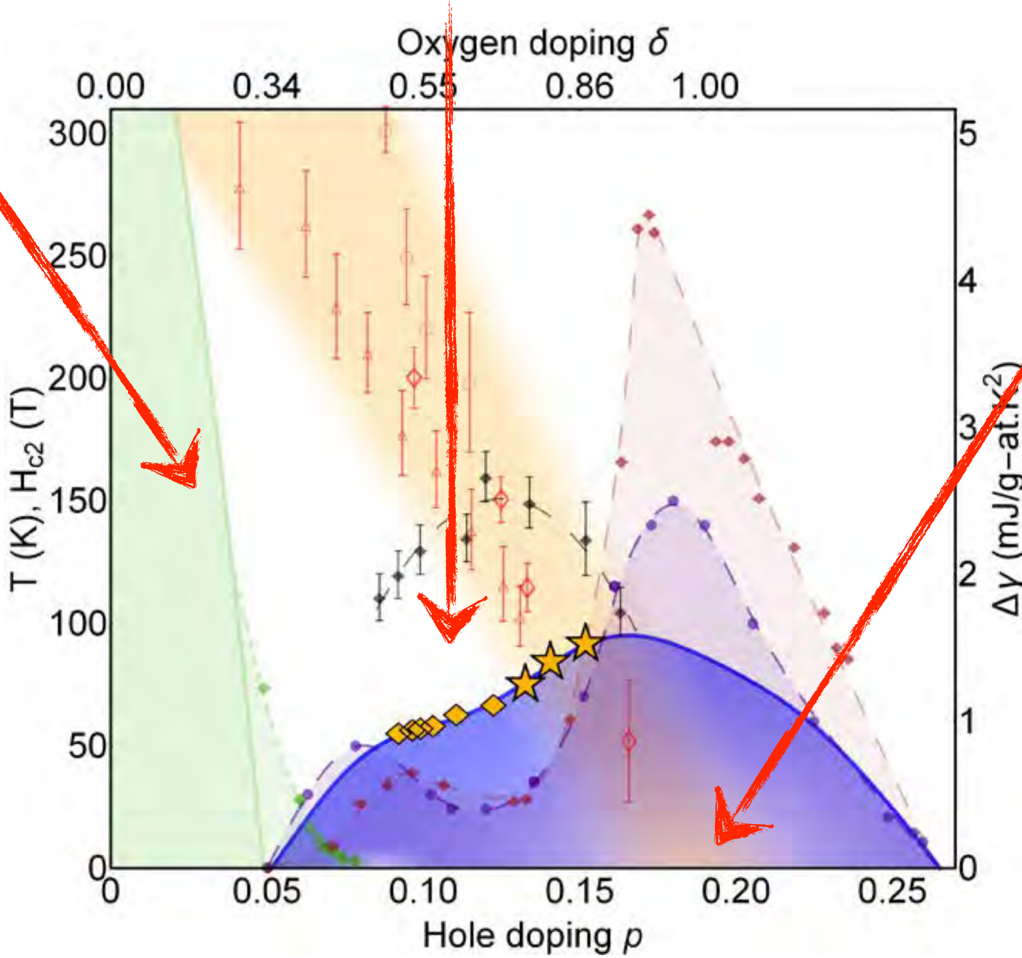
Cyril Proust, M-H Julien…

Konstantin Borisovich Efetov (April 29, 1950 – August 11, 2021) was a Russian/German theoretical physicist, recognized leader in the theory of condensed matter, and a teacher of a number of actively working theorists.

Mott transition

Fluctuations

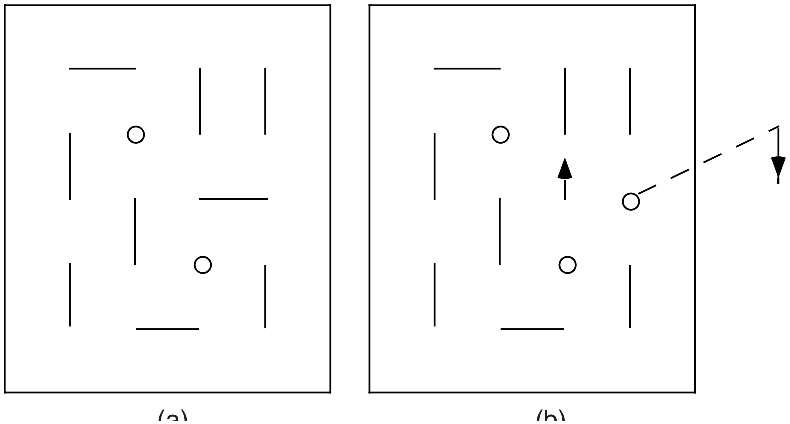
QCP under the dome



Ramshaw, 2015

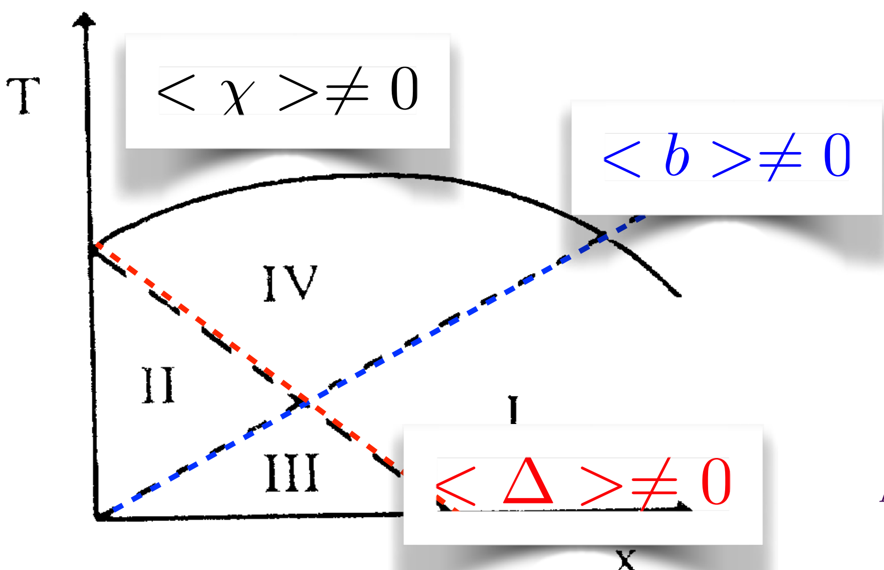
1. The context of strong coupling : doping a Mott insulator

Resonating Valence Bond (RVB) : pairs form and fluctuate



$$\chi_{ij} = \sum_{\sigma} \langle f^{\dagger}_{i\sigma} f_{j\sigma} \rangle,$$

$$\Delta_{ij} = \langle f_{i\uparrow} f_{j\downarrow} - f_{i\downarrow} f_{i\uparrow} \rangle.$$



$$c^{\dagger}_{i\sigma} = f^{\dagger}_{i\sigma} b_i$$

Spinon

Holon

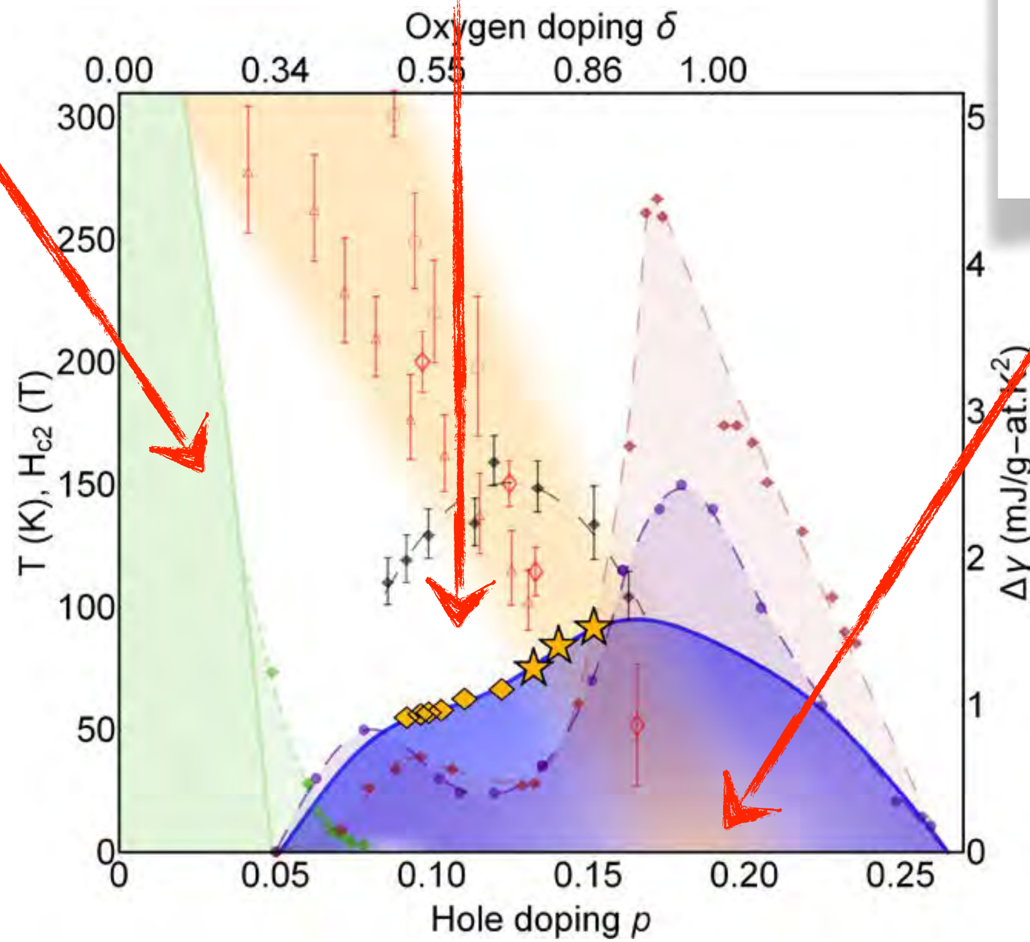
Anderson, Lee, Wen, Nagaosa, Kotliar

$$f^{\dagger}_{i\uparrow} f_{i\uparrow} + f^{\dagger}_{i\downarrow} f_{i\downarrow} + b^{\dagger}_{i} b_i = 1.$$

Mott transition

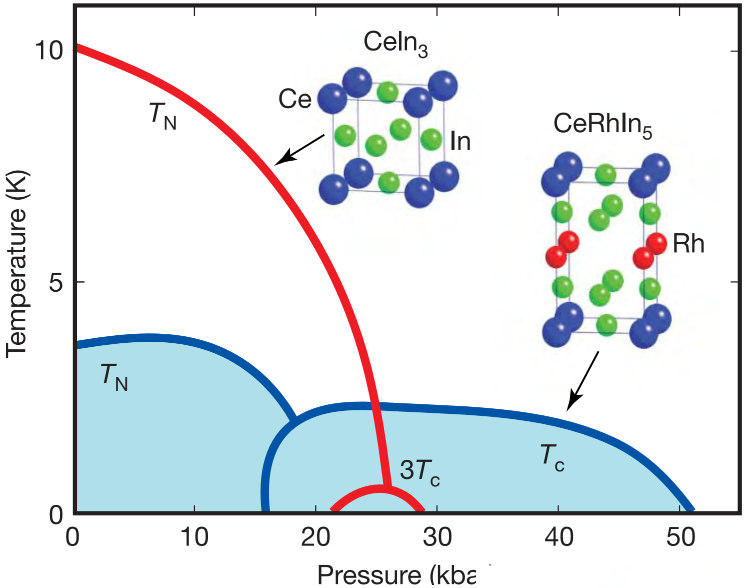
Fluctuations

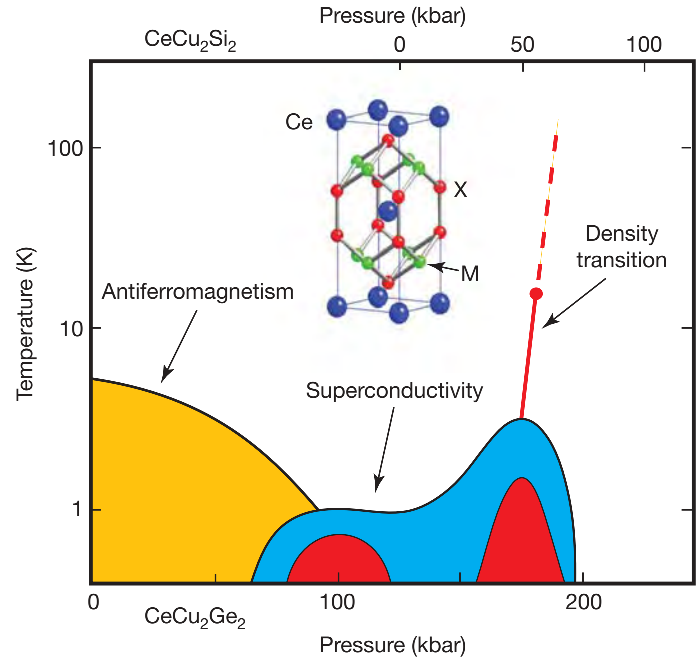
QCP under the dome

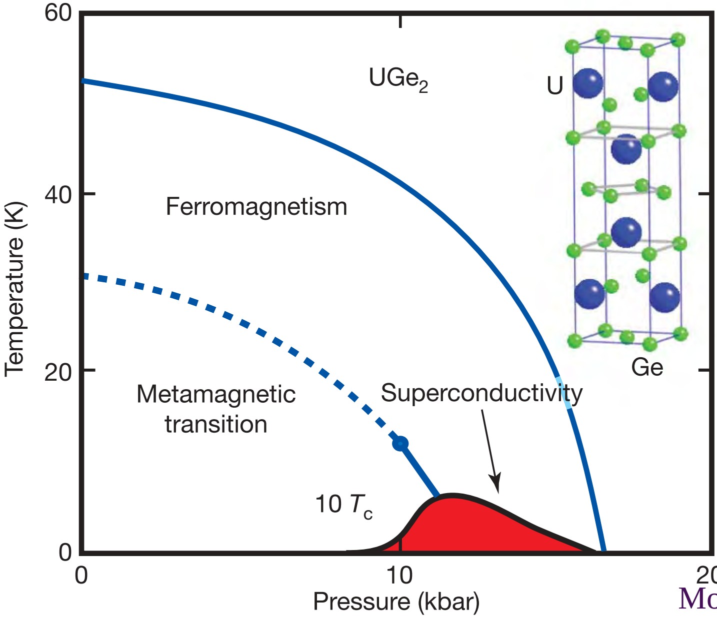


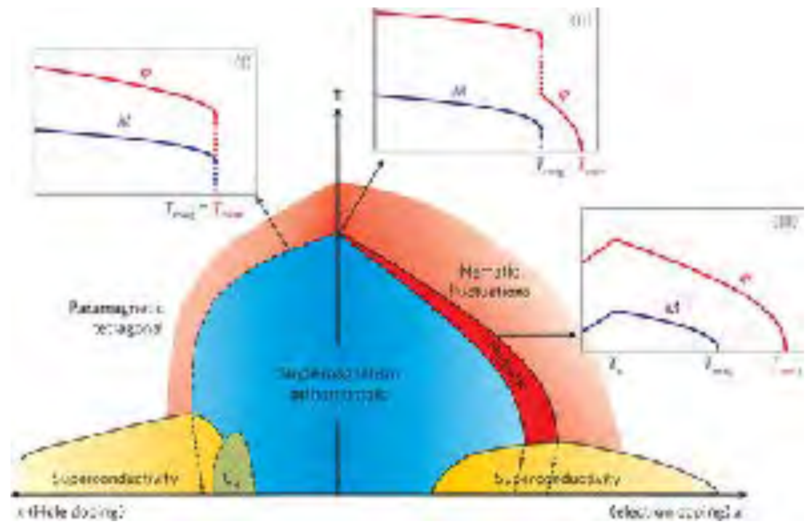
Ramshaw, 2015

2. QCP under the SC dome



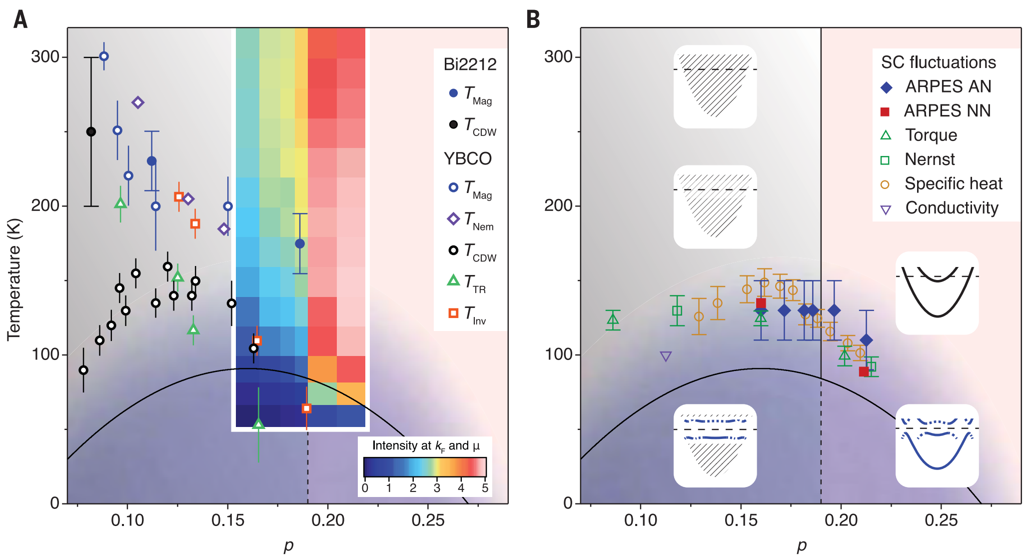


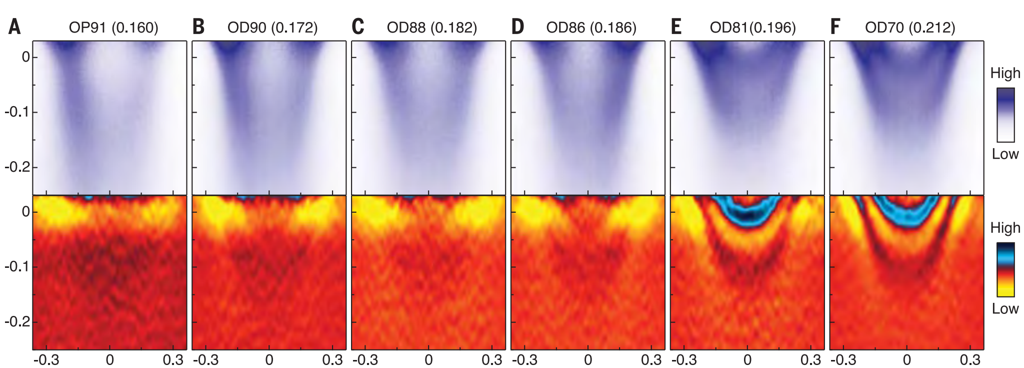




Monthoux, Pines, Lonzarich 07

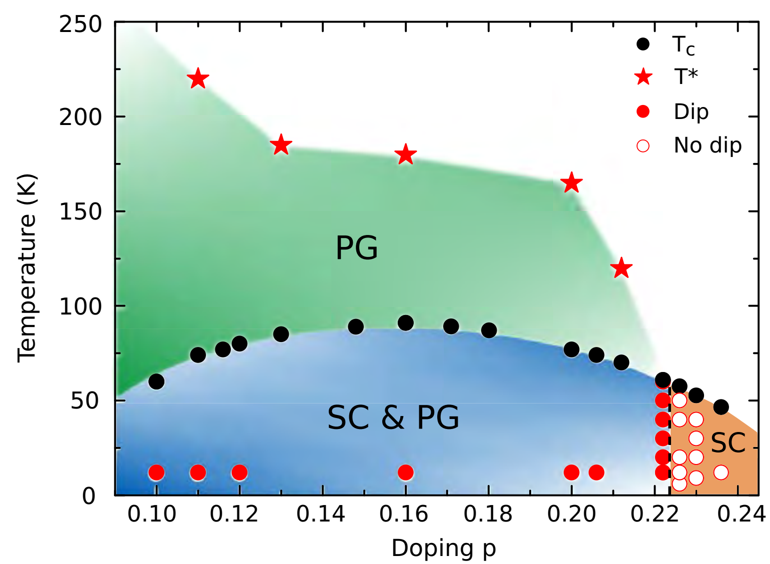
QCP questionned : an abrupt change at p ?*





ARPES Bi2212, Chen et al. 2019

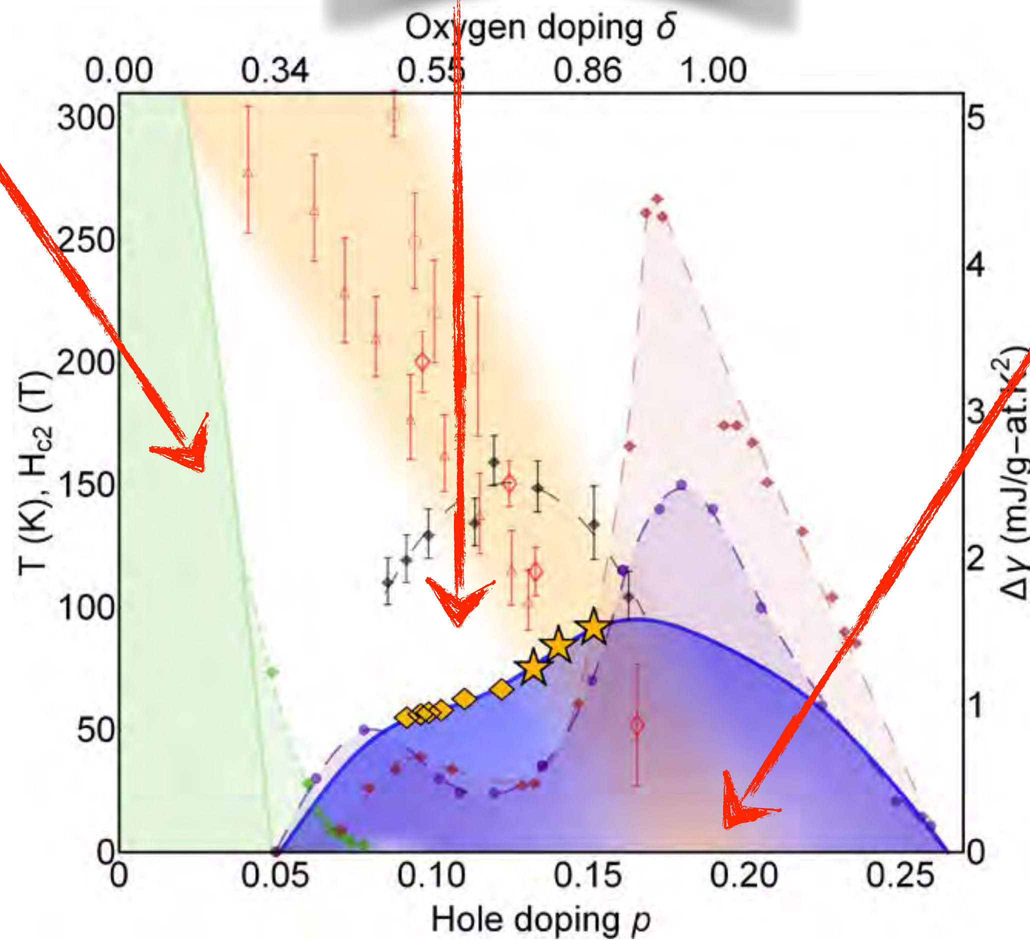
Raman Bi2212, Loret et al. 2019



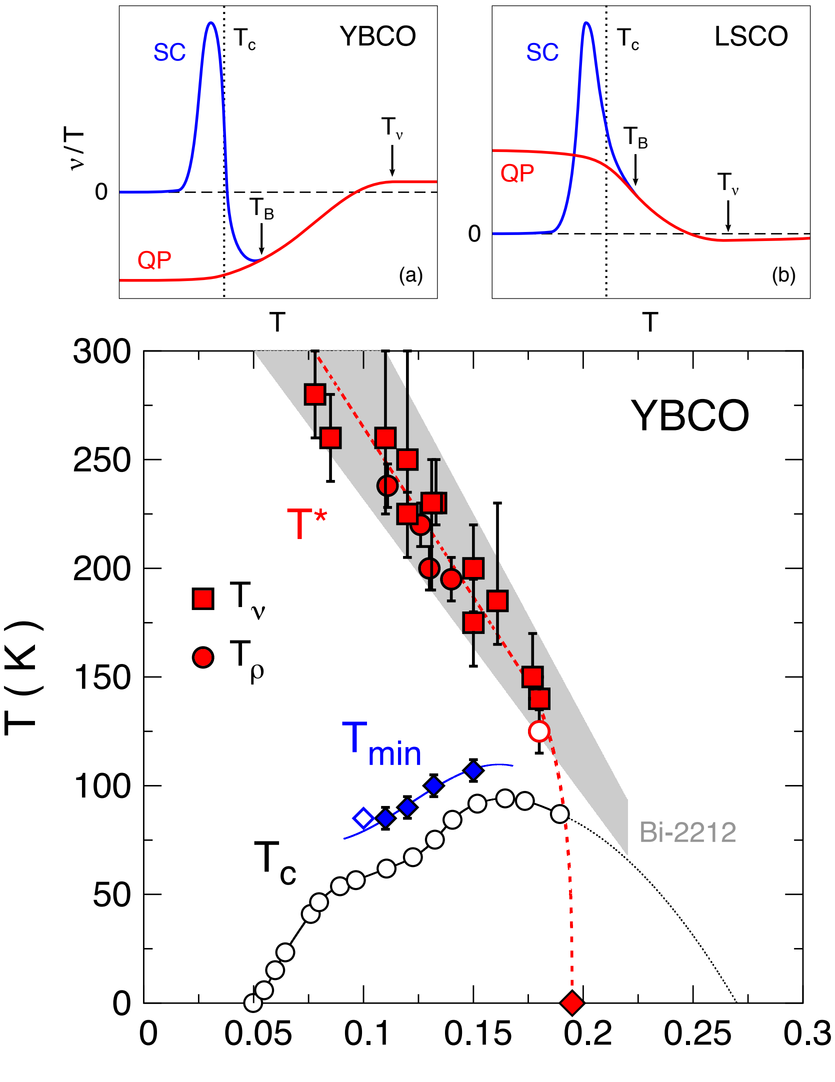
Mott transition

Fluctuations

QCP under the dome

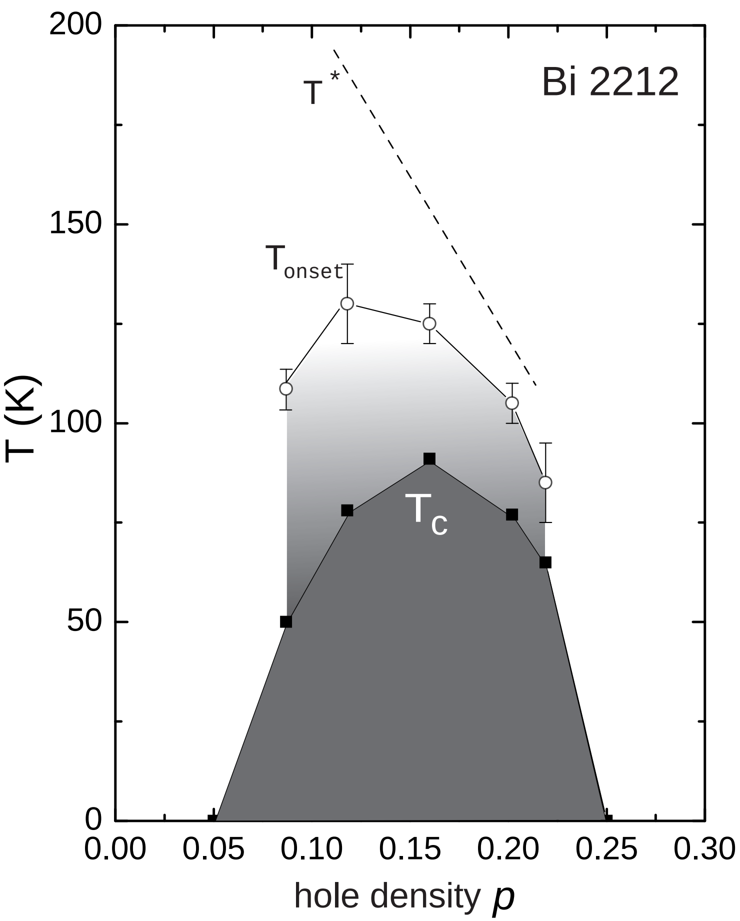


Ramshaw, 2015



Cyr-Choignière 2017

Ong 2005



Nernst effect : resolved controversy

Amplitude Fluctuations ····➤

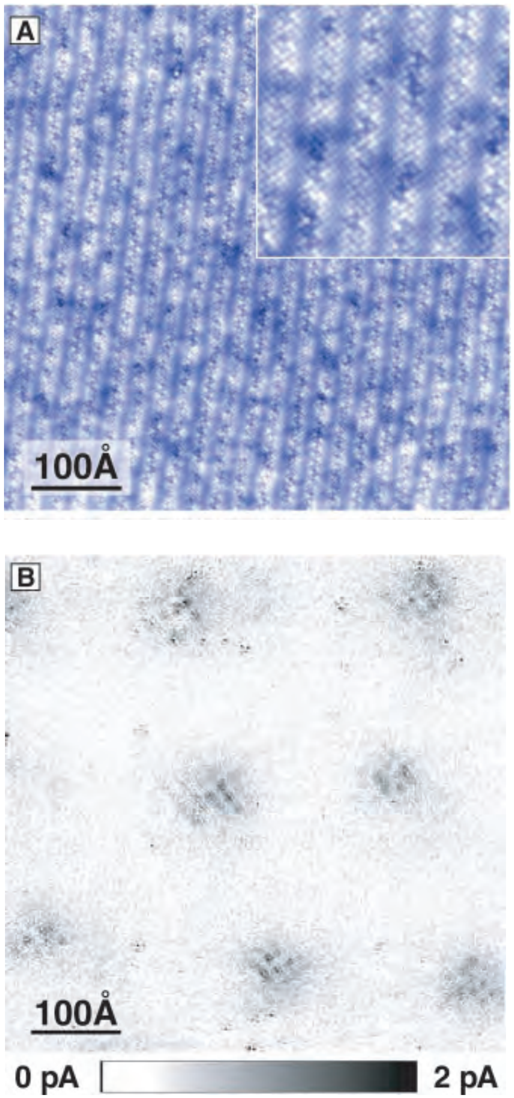
Phase fluctuations ····➤

Condensate ····➤

Recent Exp. developments
Charge Order

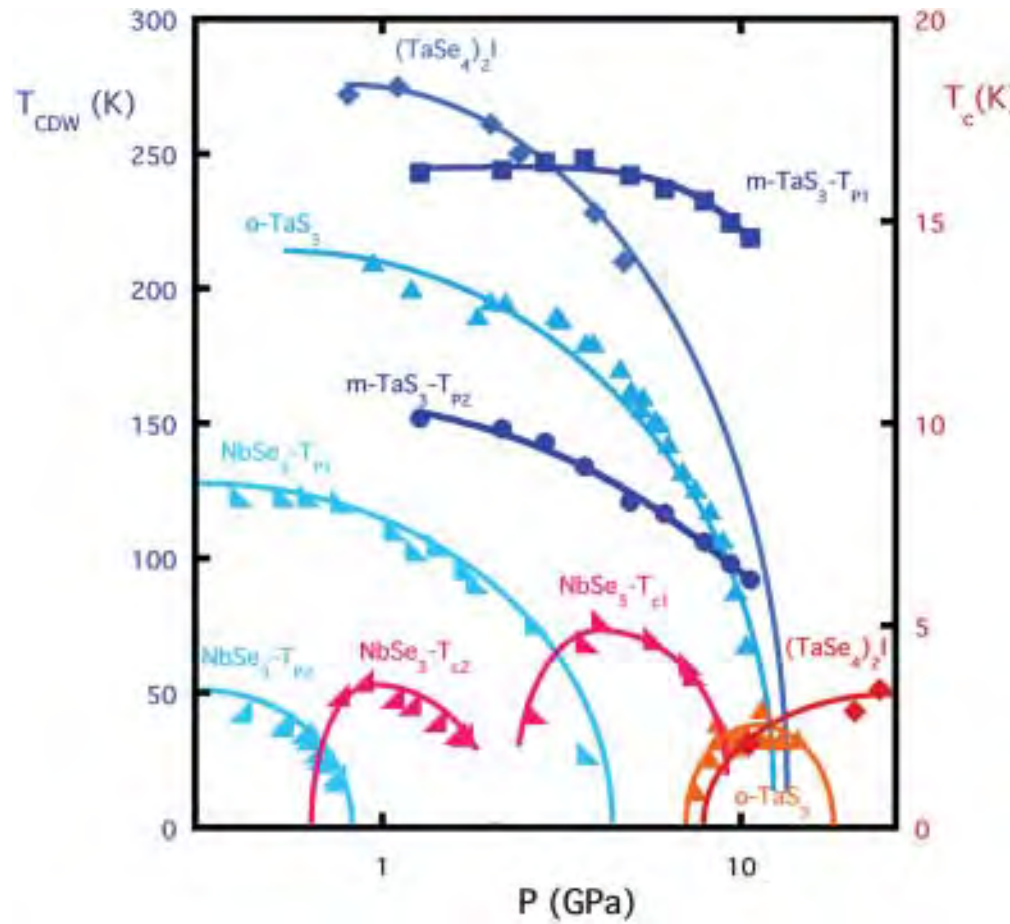
Presence of competing orders

Charge modulations in strong competition with SC state



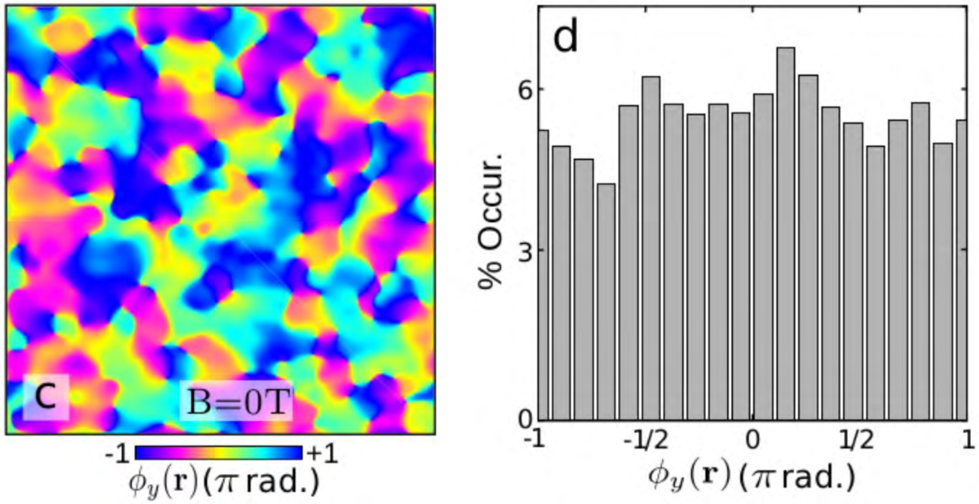
Hoffman, 2002

Kapitulnik, 2002

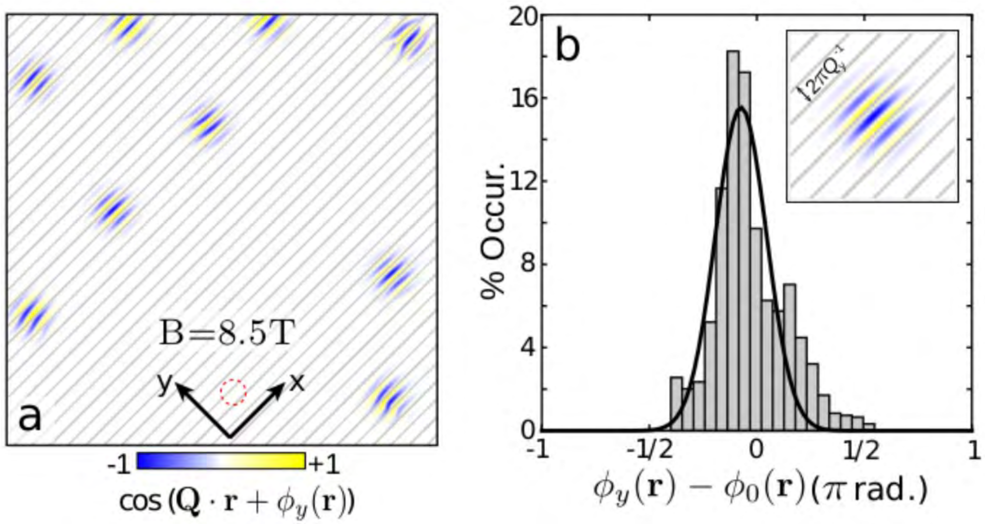


STM measurement of charge density modulation : $Re\left(\chi_{ij}\right) = \hat{d}|\chi_{ij}|cos\left(\boldsymbol{Q}\cdot\boldsymbol{r}+\phi\left(\boldsymbol{r}\right)\right)$

$B = 0\ T$ random phase distribution :



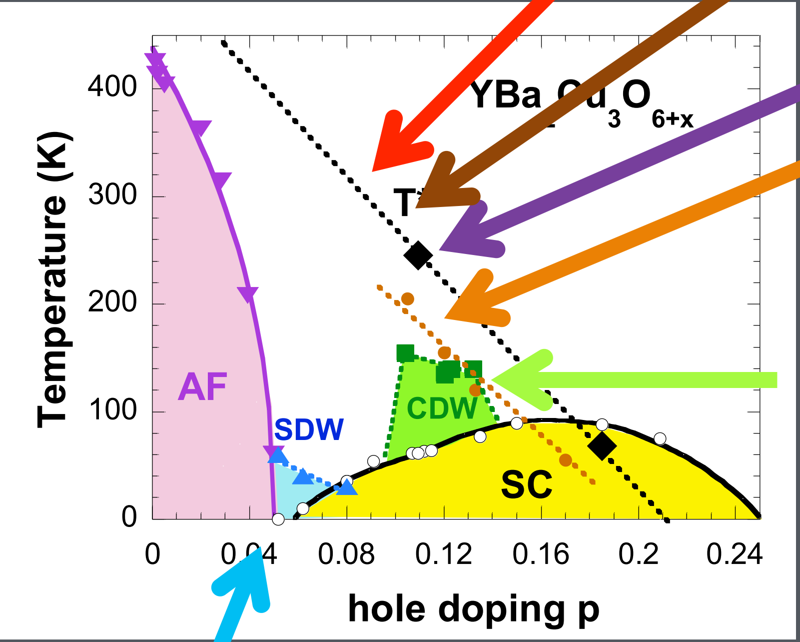
$B \neq 0\ T$ centered distribution :



M.H. Hamidian et al., Nat. Phys. **12**, 150 (2015).
M.H. Hamidian et al., arXiv:1508.00620 (2015)

Charge order Landscape

$YBa_2Cu_3O_{6+x}$



Nematicity

Inversion symmetry

loop currents

anomalous Kerr effect $T_k < T^*$

Xia, PRL 2008

Incipient CDW – $T_m < T^*$

- *$Q^* = (\delta,0)$ and $(0,\delta)$ with $\delta \sim 0.3$*

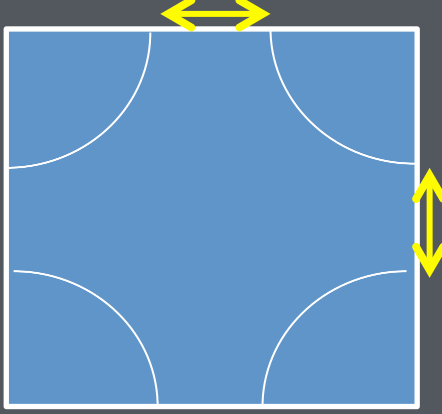
Chang , Nature Phys. 2012

Ghiringhelli, Science 2012

glassy SDW : $T_{SDW} << T^*$
(neutron, μSR, RMN)

Haug, New J. Phys. 2010

T. Wu et al., PRB 2013



Stable CDW under magnetic field &
Fermi surface reconstruction
(NMR, quantum oscillation, ultrasound)

D. LeBoeuf, *Nature* 2007.

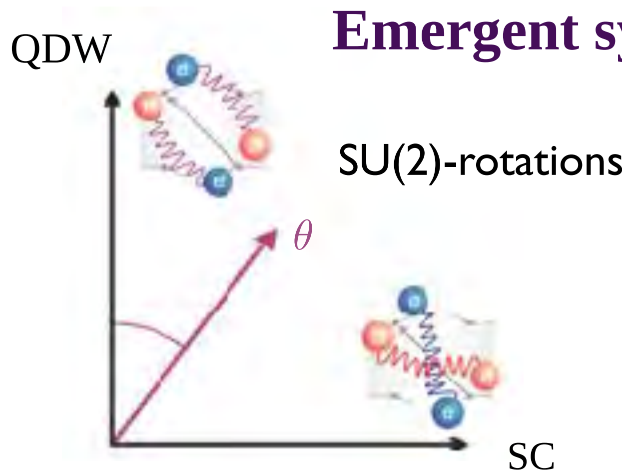
T. Wu et al., *Nature* 2011.

D. LeBoeuf et al., *Nature Physics* 2013.

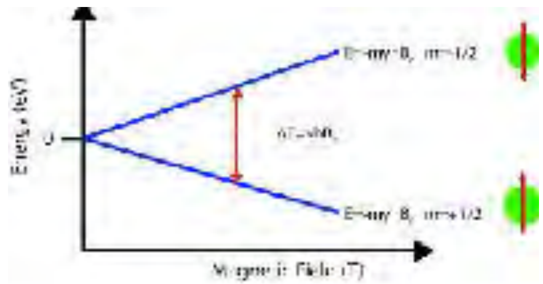
Courtesy Y. Sidis

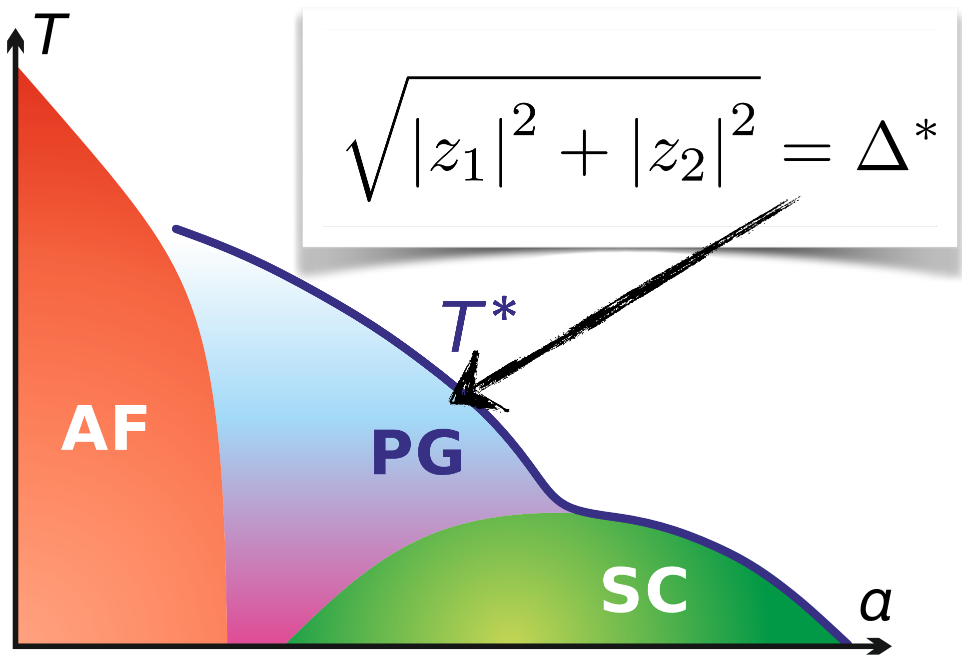
Emergent symmetry

Emergent symmetries in the under-doped regime



Degenerescence of levels:
accidental ?
symmetry related ?





$$\sqrt{|z_1|^2 + |z_2|^2} = \Delta^*$$

At some energy scale in the phase diagrams SC and Charge sectors are related by and SU(2) symmetry

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

Pseudo-gap from quantum criticality

AFM QCP in d=2

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

Dispersion linearized around 8 hot spots

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

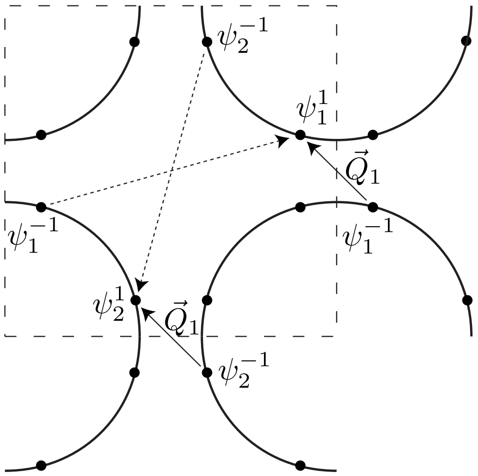
Composite order parameter

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

SU(2) symmetry and fluctuations

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

M. Metlitsky and S. Sachdev (2010)



SU(2)-symmetry

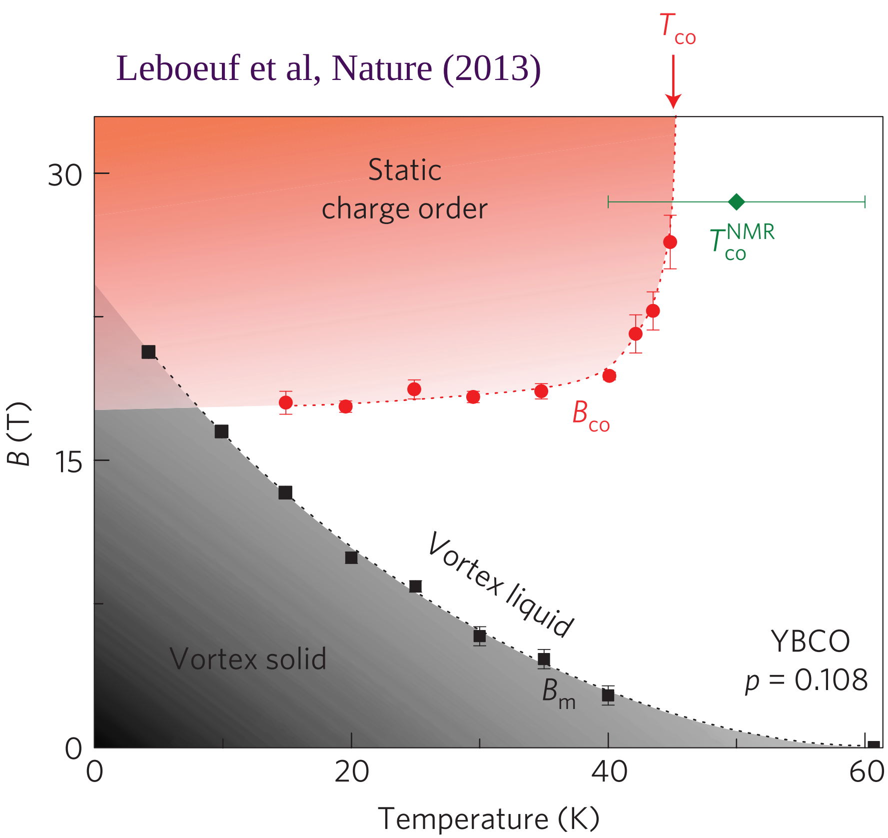
LETTER

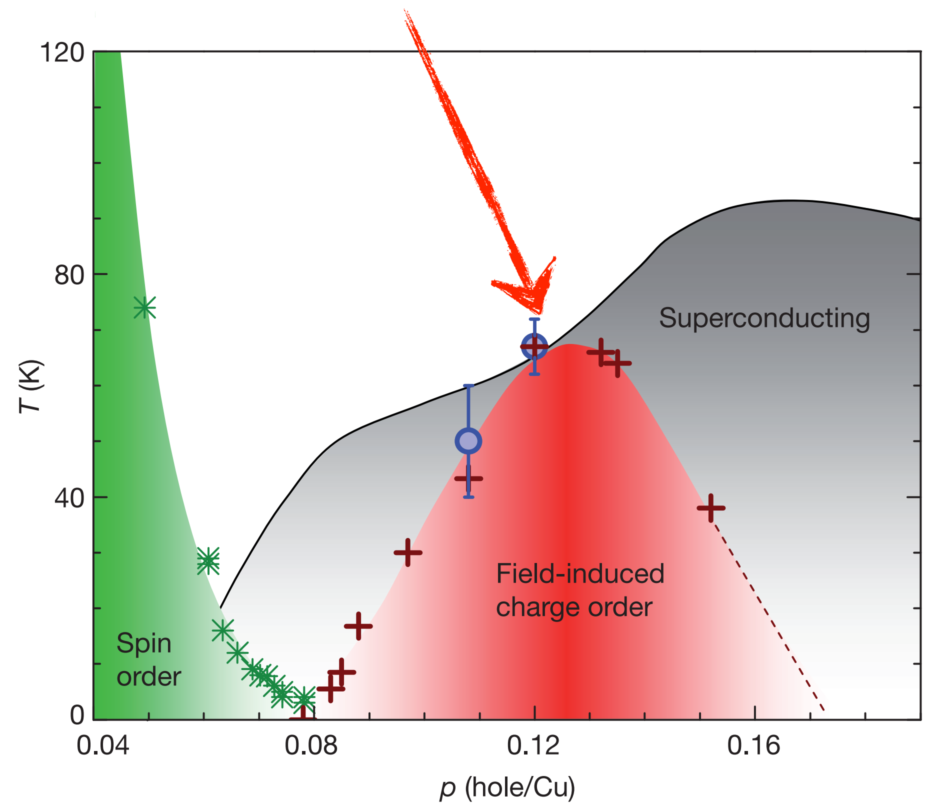
doi:10.1038/nature10345

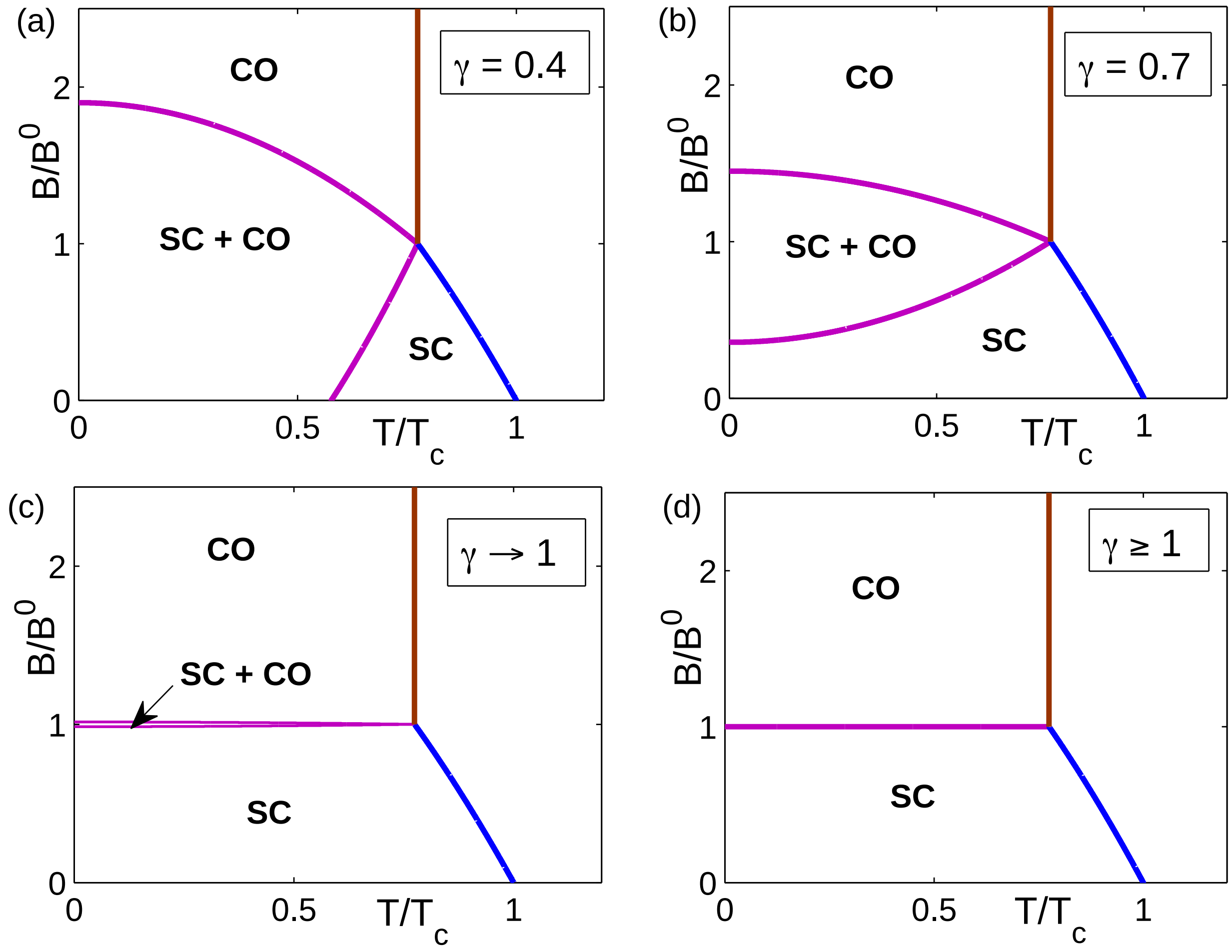
Magnetic-field-induced charge-stripe order in the high-temperature superconductor $YBa_2Cu_3O_y$

Tao Wu[1], Hadrien Mayaffre[1], Steffen Krämer[1], Mladen Horvatić[1], Claude Berthier[1], W. N. Hardy[2,3], Ruixing Liang[2,3], D. A. Bonn[2,3] & Marc-Henri Julien[1]

Leboeuf et al, Nature (2013)





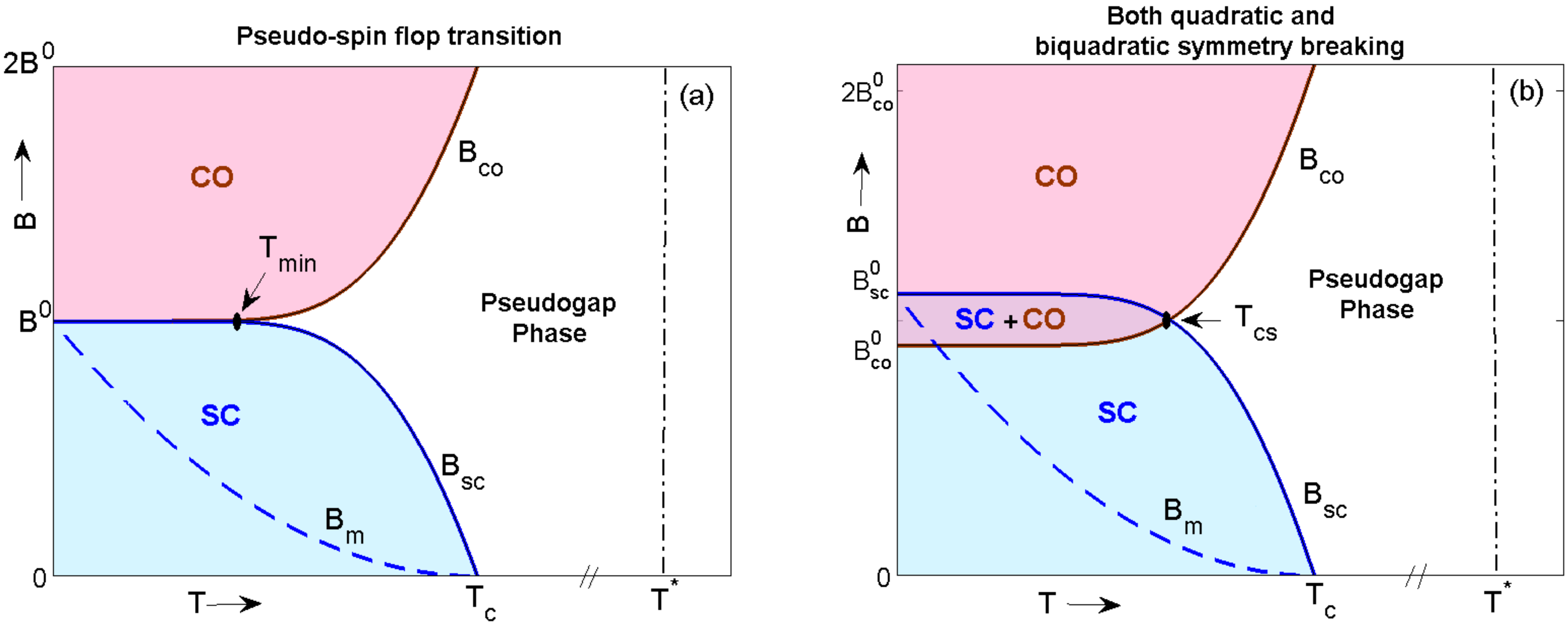


$$f[\psi,\phi] = \alpha_\psi|\psi|^2 + \frac{\beta_\psi}{2}|\psi|^4 + \alpha_\phi|\phi|^2 + \frac{\beta_\phi}{2}|\phi|^4 + \gamma|\psi|^2|\phi|^2,$$

$$\alpha_\phi = \alpha'_\phi + a_{co}T^2$$

D. Chakraborty et al, Preprint

Non Linear Sigma Model



$$\frac{F}{T} = \frac{1}{t_0} \int tr[\nabla u^\dagger \nabla u + \kappa_0 \tau_3 u^\dagger \tau_3 u] dR$$

$$\frac{F_{bq}}{T} = \frac{1}{t_0} \int z_0 \left\{ \left(tr[\tau_3 u^\dagger \tau_3 u] \right)^2 - 1 \right\} dR$$

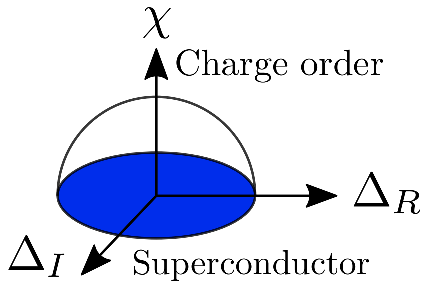
Topology and local structures

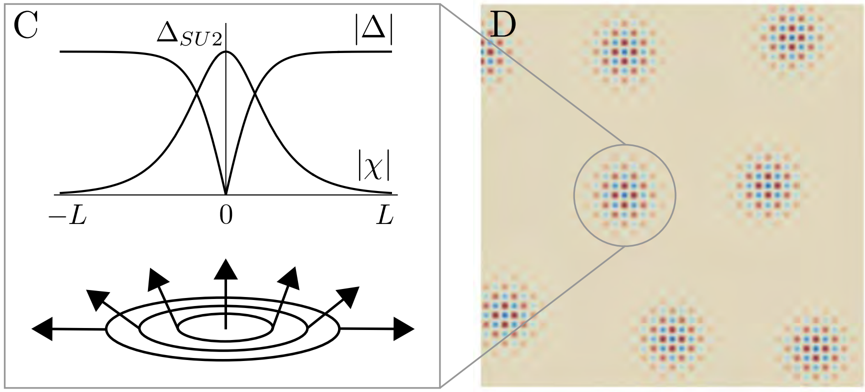
Homotopy classes

$$\Delta^2_{-,R} + \Delta^2_{-,I} + \Delta^2_{+,R} + \Delta^2_{+,I} = 1$$

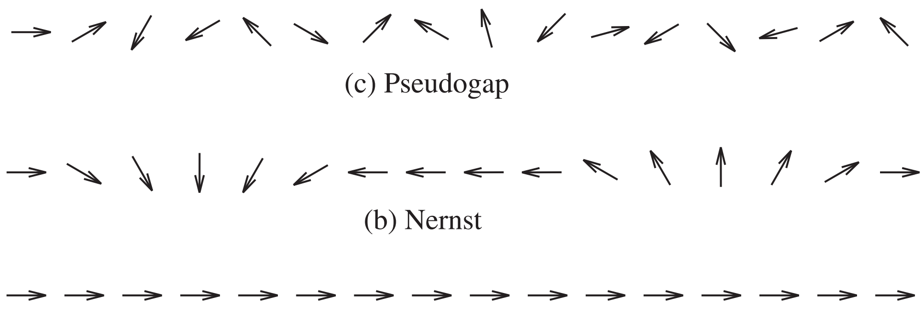
$$\pi_2(S_3) = 0$$

0(3) non linear σ-model





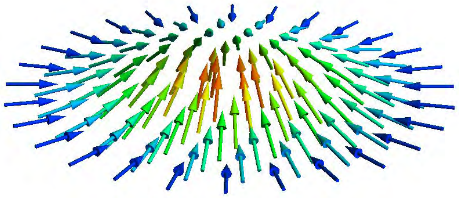
Vortex structure
Phase diagram



(c) Pseudogap

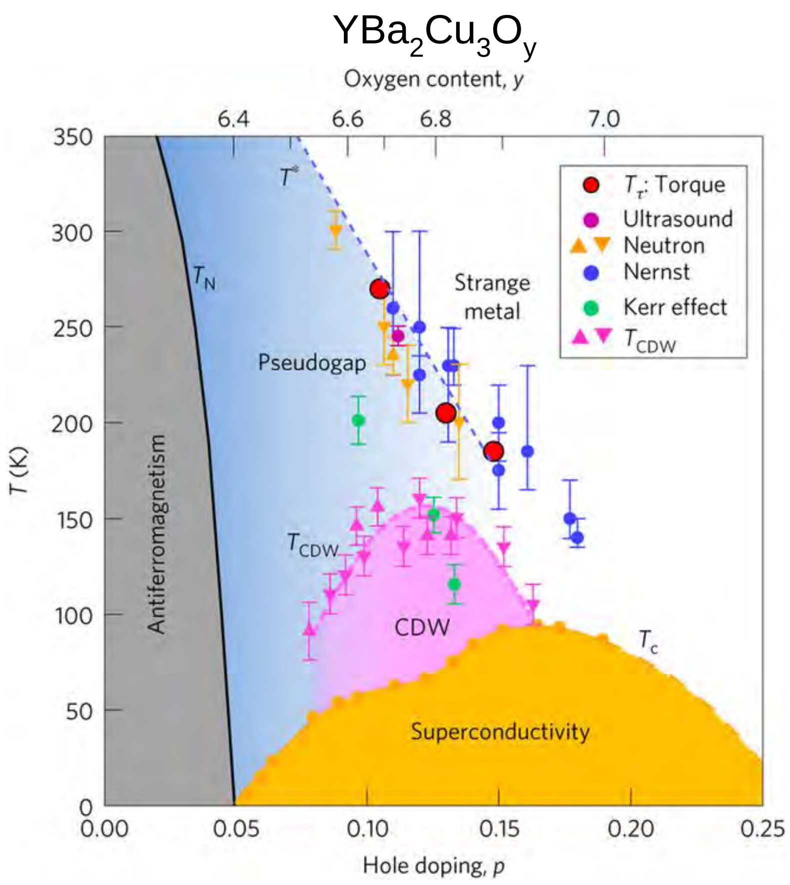
(b) Nernst

(a) Superconductor



Fractionalization of a PDW

The phase diagram



Slave-boson method :

$$c^\dagger_{i,\sigma} = b_i f^\dagger_{i,\sigma}$$

Charge (holon)

Spin (spinon)

Constraint : $$b_i b_i^\dagger + \sum_\sigma f_{i,\sigma} f^\dagger_{i,\sigma} = 1$$

Fictitious gauge transformation : $$\begin{cases} f_{i\sigma} \to e^{i\theta} f_{i\sigma} \\ b_i \to e^{i\theta} b_i \end{cases}$$

Fractionalization of a Pair Density Wave

Modulated particle-particle pair : $\Delta_{ij}^{PDW} = \left\langle c_{i,\sigma} c_{j,\bar{\sigma}} e^{i\boldsymbol{Q}\cdot\boldsymbol{r}_{ij}} \right\rangle$

PDW fractionalization : $\Delta_{ij}^{PDW} = \left[\Delta_{ij}, \chi_{ij}^*\right]$

$$\Delta_{ij}^* \Delta_{ij} + \chi_{ij}^* \chi_{ij} = 1$$

Uniform particle-particle pair : $\Delta_{ij} = \langle c_{i,\sigma} c_{j,\bar{\sigma}} \rangle$ → Charge (2)

Modulated particle-hole pair : $\chi_{ij} = \left\langle c_{i,\sigma}^\dagger c_{j,\sigma} e^{i\boldsymbol{Q}\cdot\boldsymbol{r}_{ij}} \right\rangle$ → Translation symmetry

Phase transformation : $\begin{cases} \Delta_{ij} \rightarrow e^{i\theta} \Delta_{ij} \\ \chi_{ij} \rightarrow e^{i\theta} \chi_{ij} \end{cases}$

Ansatz : $|PG\rangle = \left(\hat{\chi}_{ij} + \hat{\Delta}_{ij}\right)|0\rangle$ + constraint

The phase diagram

$$S = \frac{1}{2} \int d^2x \sum_{a,b=1}^{2} |\omega_{ab}|^2 , \text{ with } \omega_{ab} = z_a \partial_\mu z_b - z_b \partial_\mu z_a ,$$

$$z_1 = \Delta, \; z_2 = \chi, \; z_1^* = \Delta^*, \; z_2^* = \chi^* .$$

Emerging gauge field : confining transition

Freezing of all phases

Incoherent bosons

$T = T^*$

θ gets to fluctuate

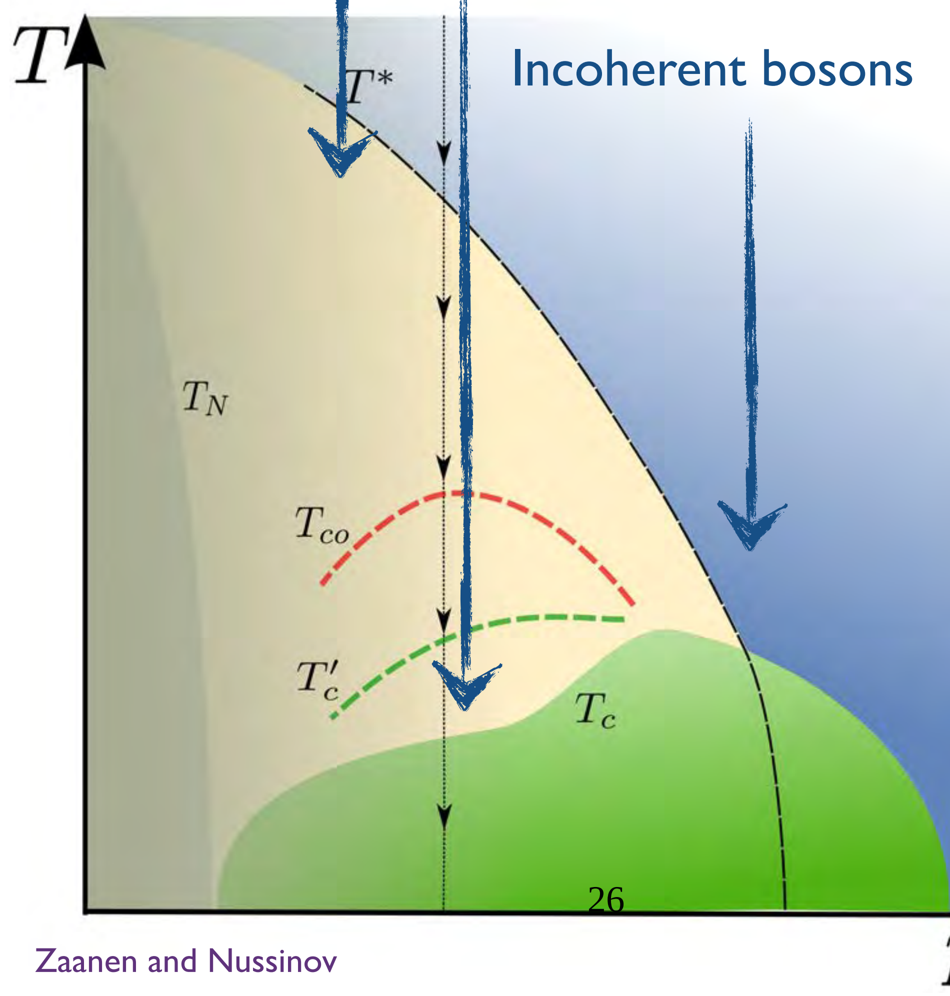
We obtain the constraint

$$|\Delta_{ij}|^2 + |\chi_{ij}|^2 = (E^*)^2$$

$T = T_c$

ϕ gets frozen and we have global phase coherence.

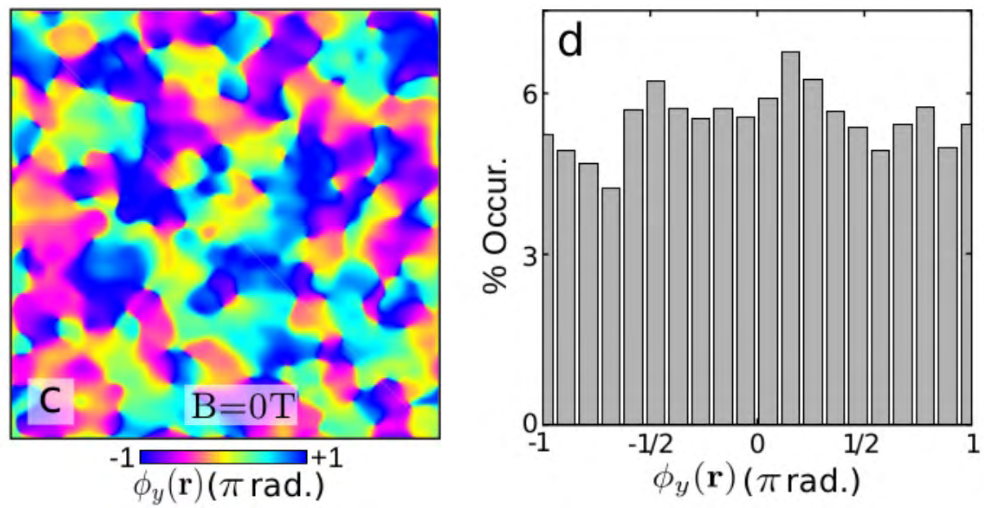
Meissner effect.



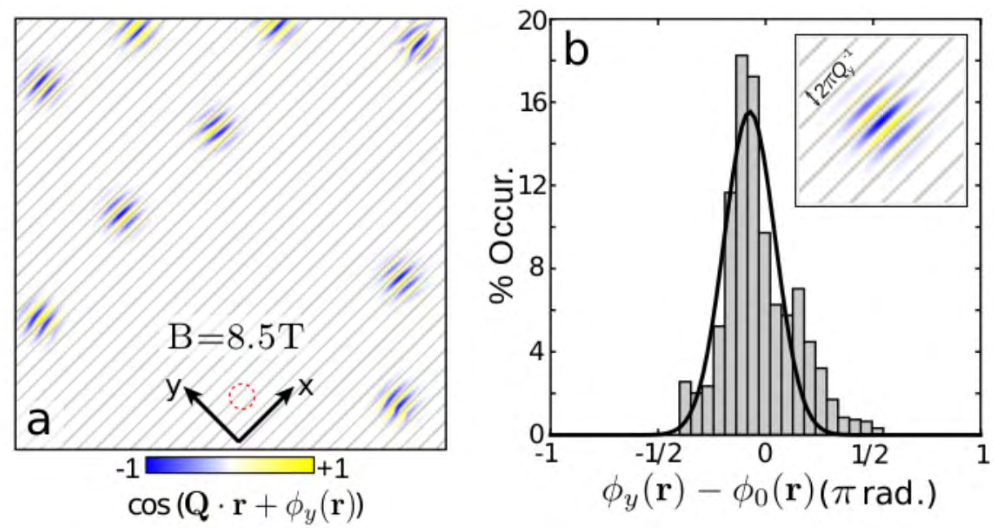
Zaanen and Nussinov

STM measurement of charge density modulation : $Re\left(\chi_{ij}\right) = \hat{d}|\chi_{ij}|cos\left(\boldsymbol{Q}\cdot\boldsymbol{r}+\phi\left(\boldsymbol{r}\right)\right)$

$B = 0\ T$ random phase distribution :



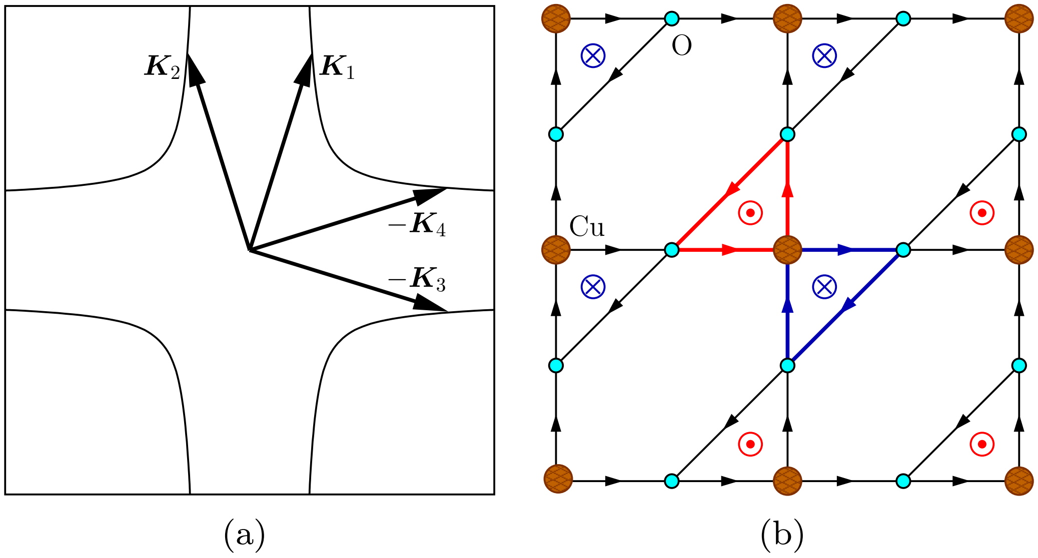
$B \neq 0\ T$ centered distribution :



M.H. Hamidian et al., Nat. Phys. **12**, 150 (2015).
M.H. Hamidian et al., arXiv:1508.00620 (2015)

Original idea: Loop Current

(C.M. Varma)



Agterberg (2015)

L. Mangin-Thro et al, Nat. Comm 6, 7705 (2015)

Symmetries of a PDW order

$$\Delta_{\boldsymbol{Q}} \xrightarrow{\mathcal{T}} \Delta^*_{-\boldsymbol{Q}} \qquad \Delta_{\boldsymbol{Q}} \xrightarrow{\mathcal{P}} \Delta_{-\boldsymbol{Q}}.$$

The fractionalized PDW supports the symmetry of the Q=0 loop currents as a precursor order parameter

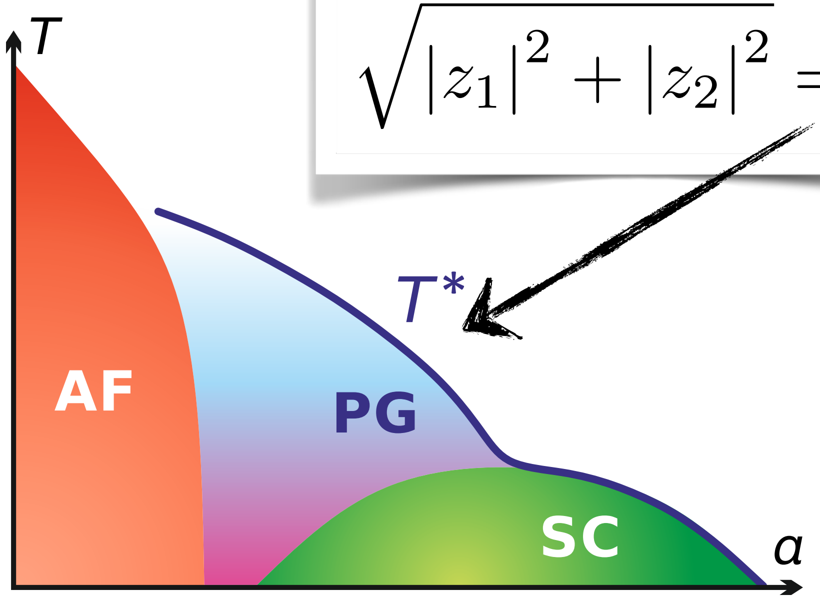
$$l = (|\Delta_Q|^2 - |\Delta_{-Q}|^2)$$

Analogy with SU(2) emergent symmetry

$$\psi = (z_1, z_2) \qquad \mathcal{L}_{CP^1} = \frac{1}{2g}\left|D_\mu \psi\right|^2 + V(\psi)$$

$$\sqrt{|z_1|^2 + |z_2|^2} = \Delta^*$$

Same Anstaz of entangled states



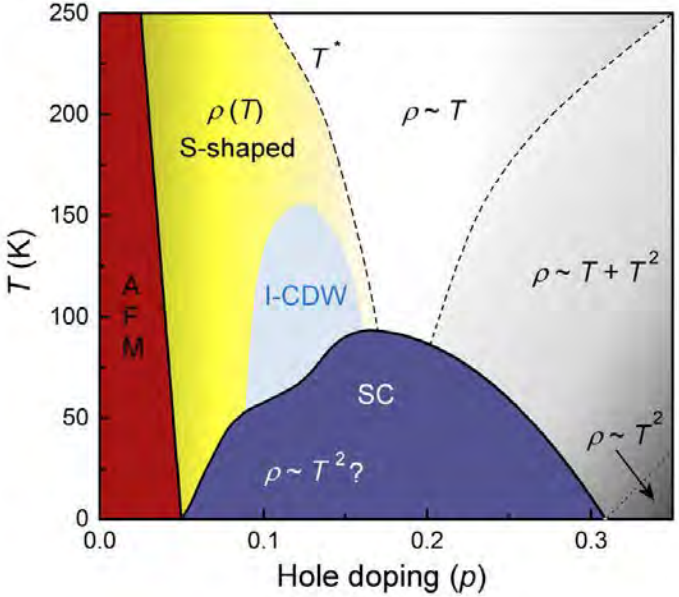
Same constraint !

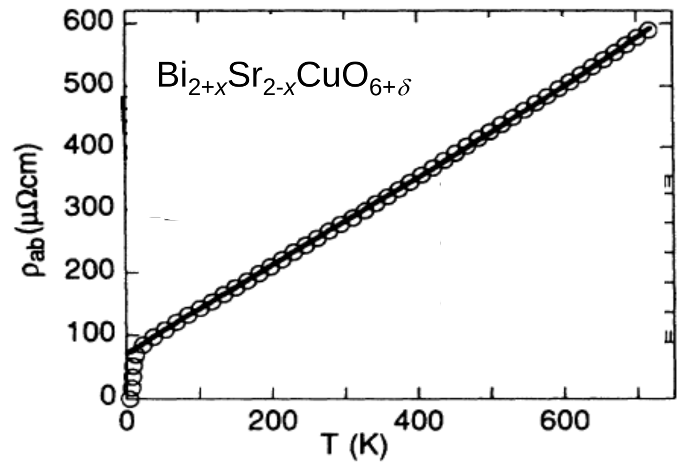
$$|PG\rangle = \left(\hat{\chi}_{ij} + \hat{\Delta}_{ij}\right)|0\rangle$$

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

Strange metals

Most strongly Correlated/ Entangled QCP ?

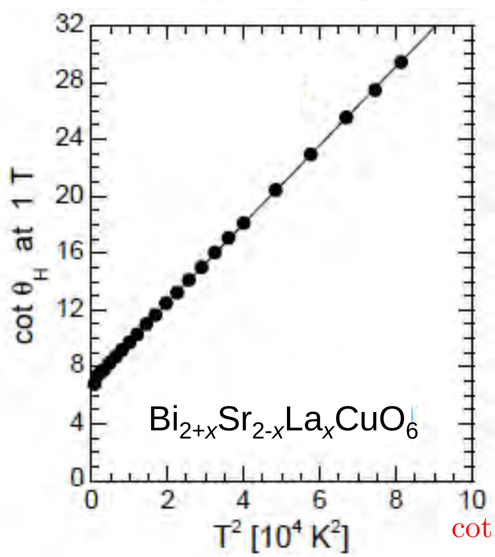




Martin *et al.*, *Phys. Rev. B* (1990)

Planckian regime for the resistivity, minimal viscosity

Zaanen 2019
Black hole models, SYK etc…



$$\cot\theta_H = \frac{\sigma_{xx}}{\sigma_{xy}} = \frac{ne^2\tau}{m}$$

At the same time Drude like optical conductivity driven by T

$$\sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau}$$

Van der Marel 90

$$\tau \propto 1/T$$

$$\sigma_{xx} = \frac{ne^2\tau}{m}$$

$$\cot\theta_H = \frac{\sigma_{xx}}{\sigma_{xy}} = \frac{ne^2\tau}{m}$$

$$\sigma_{xy} = \frac{ne^3B\tau^2}{cm}$$

$$R_H = \frac{\sigma_{xy}}{\sigma_{xx}^2} = \frac{Bm}{ne}$$

$\longrightarrow$

$$\tau^{-1} \sim T^2$$

$$n \sim T \; ?$$

Transport in the Strange Metal

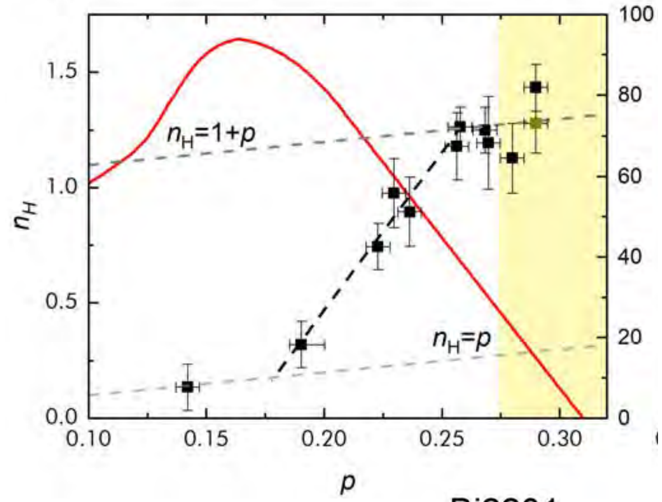
Recent controversy

Spectral weight missing in the Strange Metal regime ?

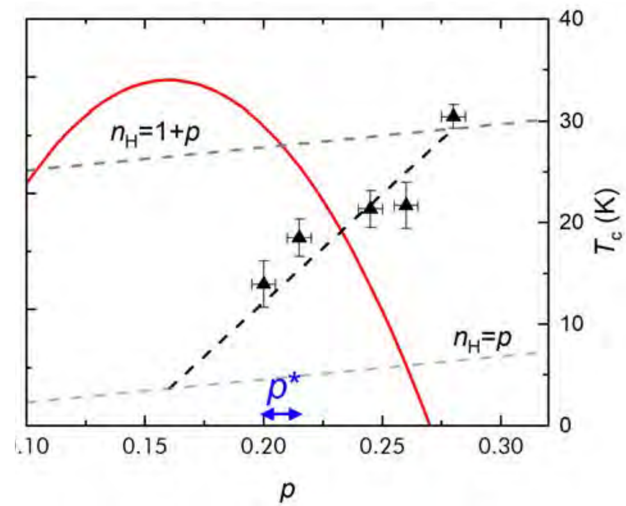
Our answer : **two types of carriers, fermions and charge-2 bosons with finite momentum**

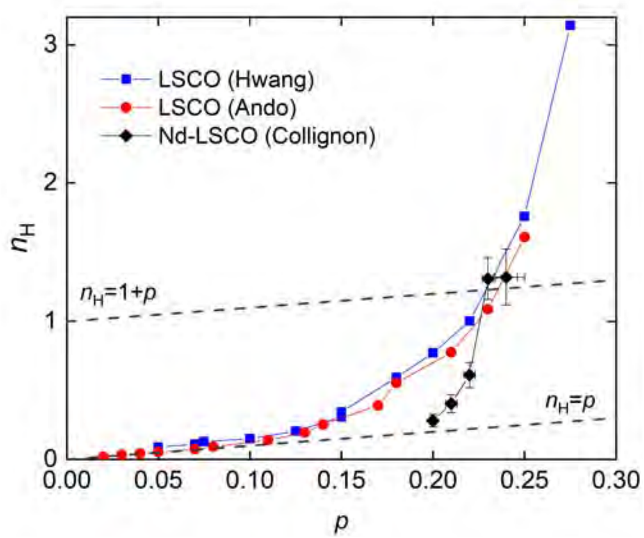
Prutzke, et al.

Tl2201



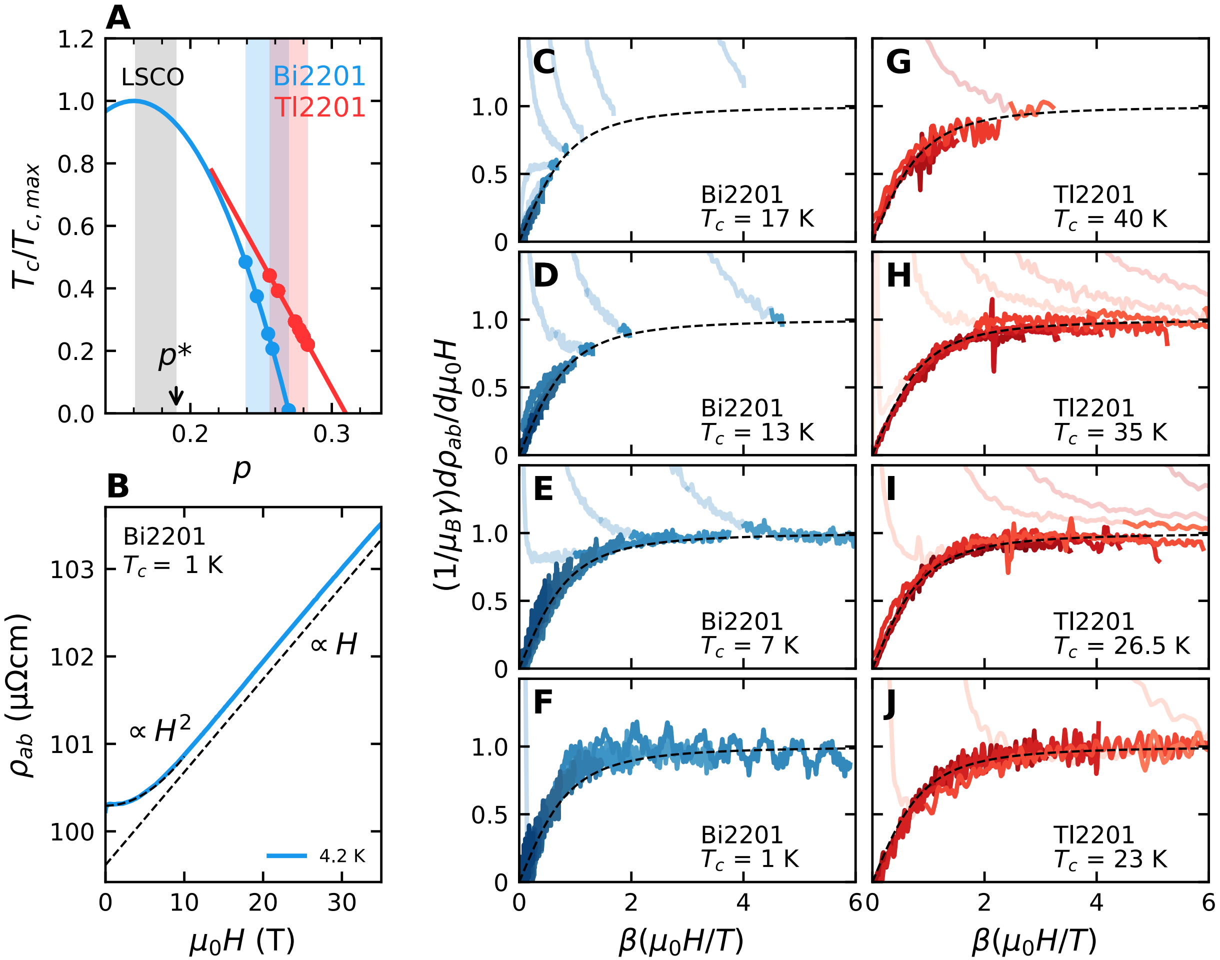
Bi2201





H/T scaling in the SM phase

$$\rho(H,T) - \rho(0,0) = \sqrt{(\alpha k_B T)^2 + (\gamma \mu_B \mu_0 H)^2}$$



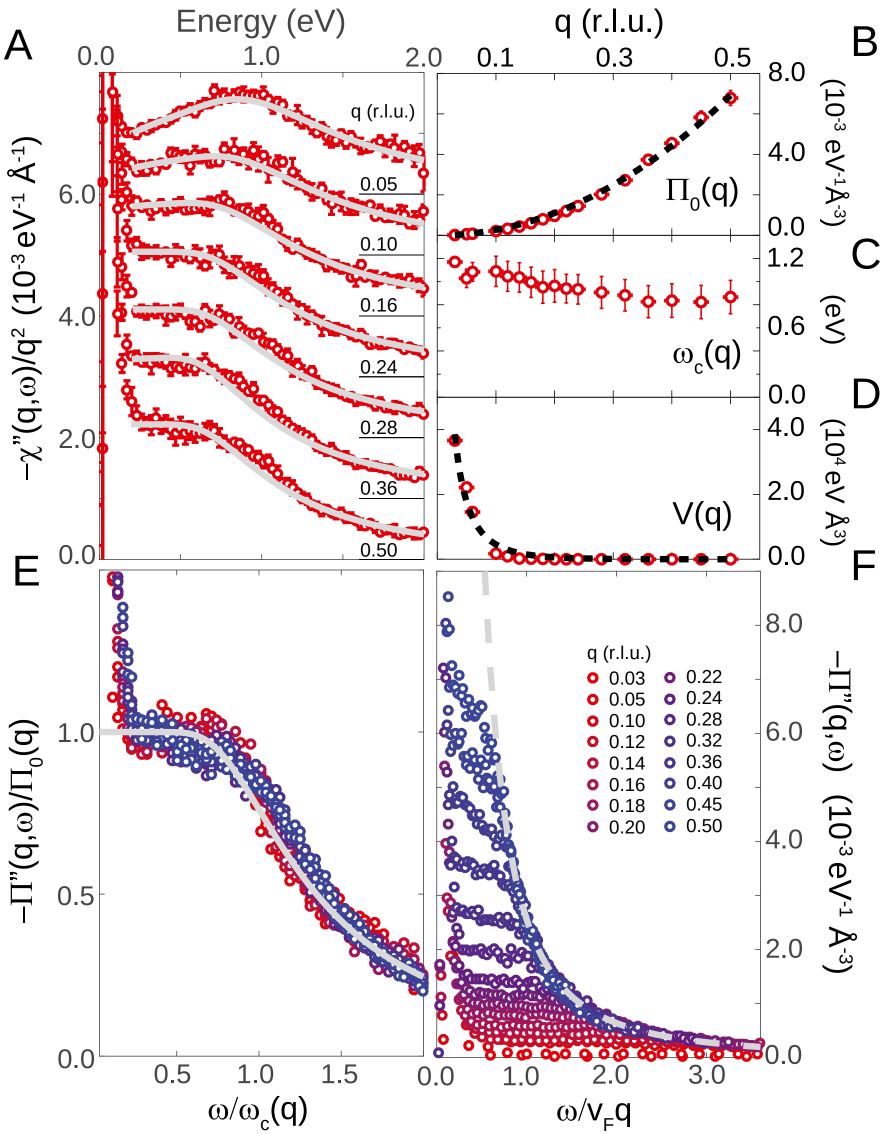
- *Isotropic*
- *Incoherent*

$$\sigma_{xy} = 0$$

- *Planckian limit*

Ayres et al., preprint 2020, courtesy N.Hussey

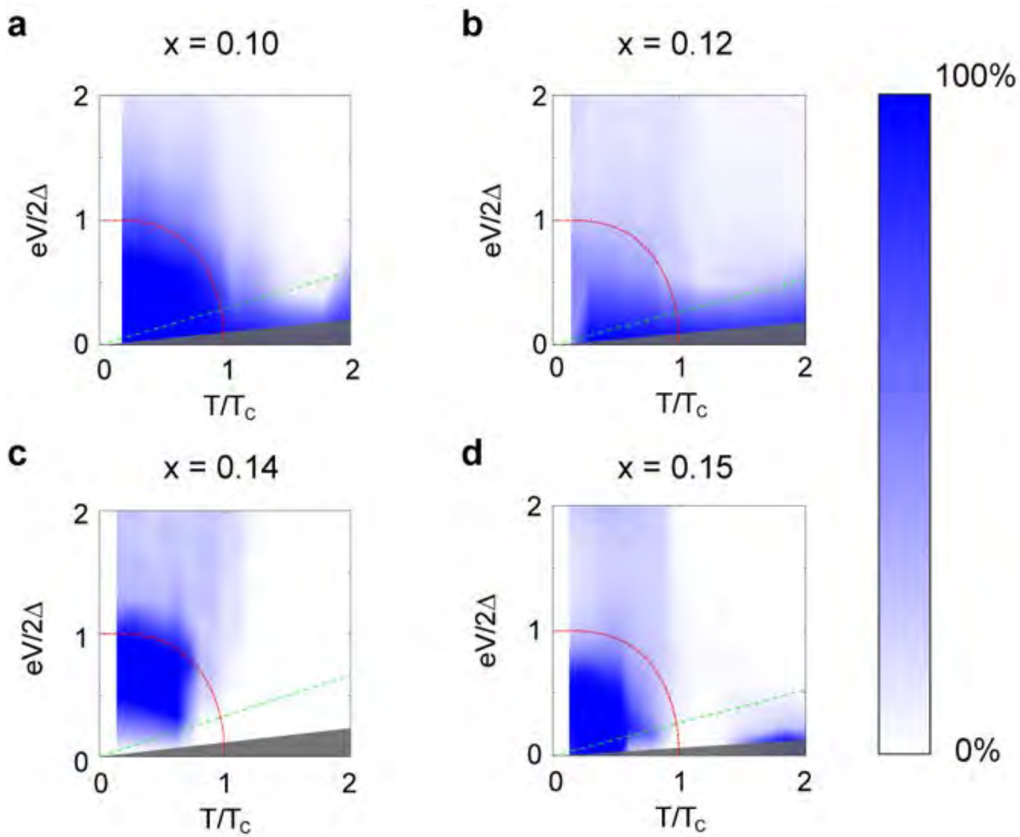
Presence of « another species » in this regime : MEELS experiment



Mitrano et al., 2018

Jamming transition

Pair tuneling in LSCO : noise measurement

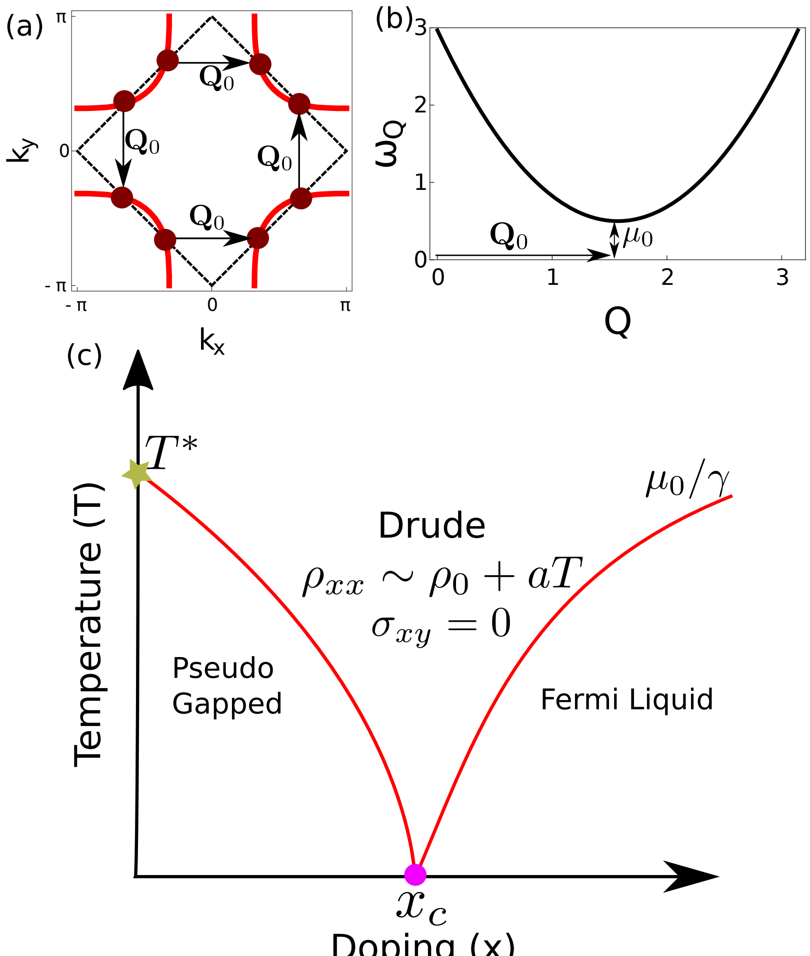


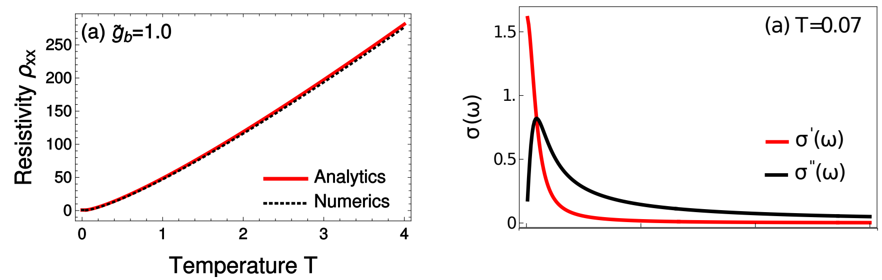
Zhou et al., 2019

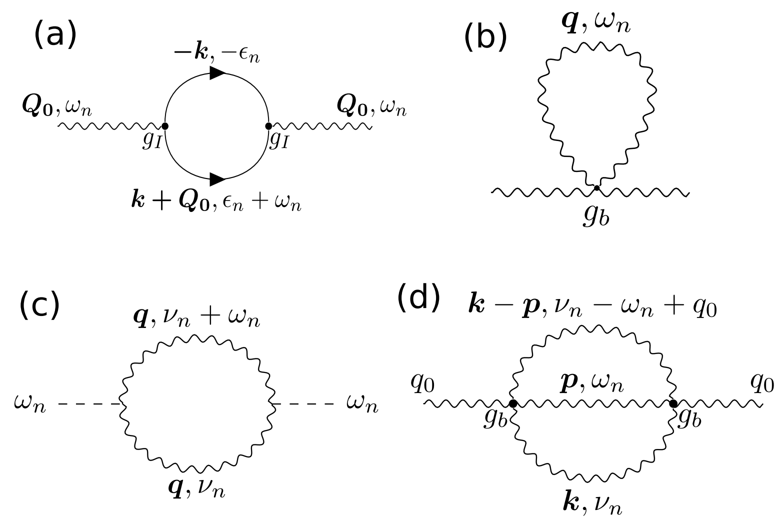
Our proposal : Charged bosons in the Strange Metal phase

$$\mathcal{D}^{-1}(\mathbf{q}, i\omega_n) = \gamma\,|\omega_n| + \mathbf{q}^2 + \mu(T)$$

$$\sigma_{xx}\left(i\omega \to \omega + i\delta\right) = \frac{\sigma_0^b \tau}{\left(1 - i\frac{\gamma\omega}{2\mu}\right)},$$





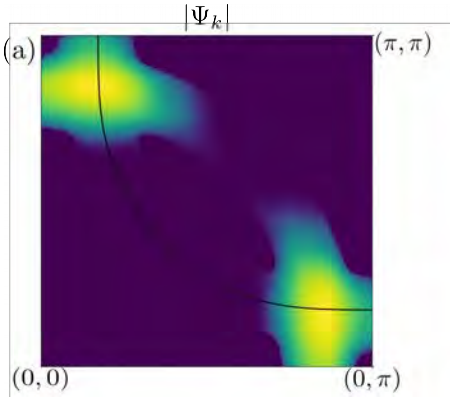


A. Banerjee et al. (2020)

$$\sigma_{xx} = \frac{ne^2}{m}\tau_{xx}$$

$$\cot\theta_H = \frac{\sigma_{xx}}{\sigma_{xy}} = \frac{c}{eB}\frac{\tau_x}{\tau_{xy}^2}$$

$$\sigma_{xy} = \frac{ne^3B}{cm}\tau_{xy}^2$$



$$\tau_{xx}^{-1} \sim T$$

$\longrightarrow$

$$\tau_{xy}^{-1} \sim T^{1.5}$$

Averaging the Hall conductivity around the Fermi surface with hot and cold spots

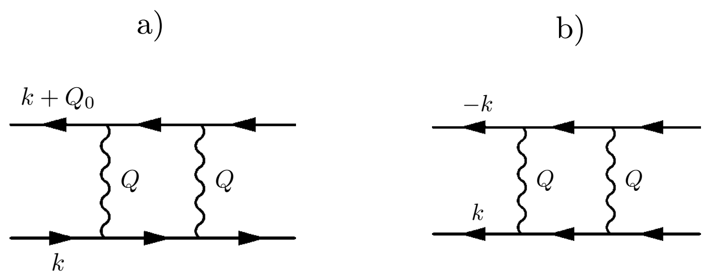
Kokalj, McKenzie and Hussey, 2012

Predictions ARPES

Why the system would want to do this ?

$$H = \sum_{i,j,\sigma} c^{\dagger}_{i,\sigma} t_{ij} c_{j,\sigma} + J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

$$+V \sum_{<i,j>} n_i n_j$$



$$\chi_{ij} = \frac{1}{2} < c^{\dagger}_{i\sigma} c_{j\sigma} > \qquad \Delta^*_{ij} =< c^{\dagger}_i \uparrow c^{\dagger}_j \downarrow>$$

$$\Psi_{ij} = (\hat{\Delta}_{ij}, \hat{\chi}_{ij})^t \qquad |\Psi_{ij}| = E^*$$

<u>Mean-field decoupling</u>

$$\Delta_k = \sum_{\sigma} \sigma c_{k,\sigma} c_{-k,\bar{\sigma}}$$

$$\chi^Q_k = \sum_{\sigma} c^{\dagger}_{k,\sigma} c_{k+Q,\sigma}$$

Condensation energy

$$E_{PG} = \frac{1}{2\tilde{J}} |\Psi_{k=k_F}|^2 = 0.017\, eV,$$

$$E_{SC} = \frac{1}{2J_-} |\Delta_{k=k_F}|^2 = 0.014\, eV,$$

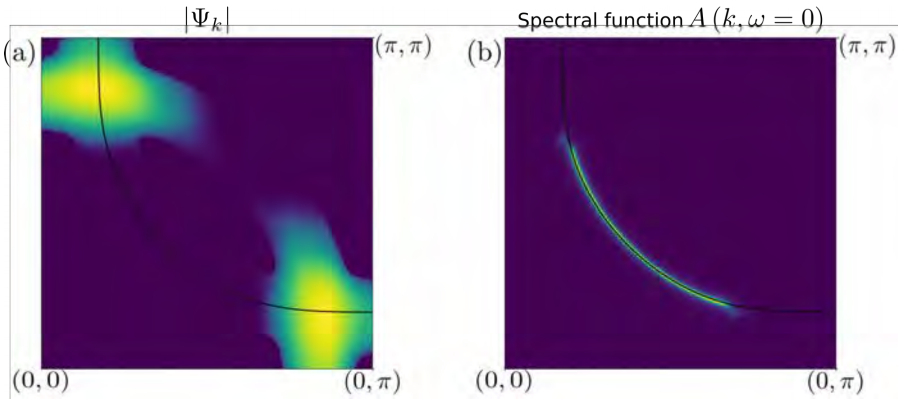
$$E_{CDW} = \frac{1}{2J_+} |\chi_{k=k_F}|^2 = 0.011\, eV.$$

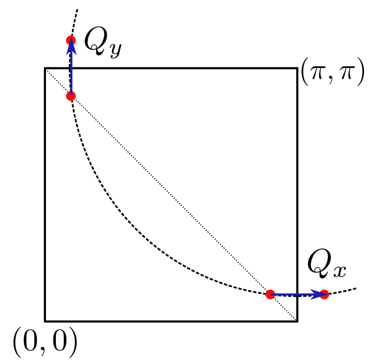
<u>Energy scales :</u>

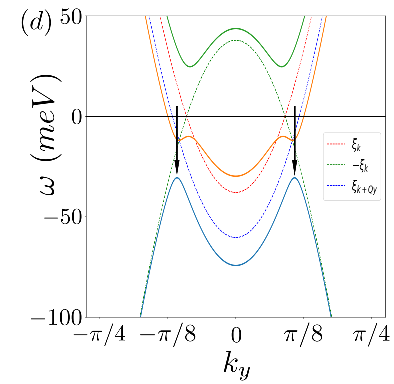
$$\Delta_k \sim 3J - V$$

$$\chi^Q_k \sim 3J + V$$

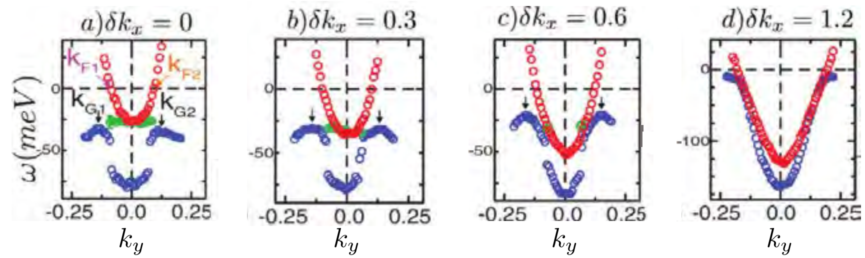
Opening a gap in the Fermi surface



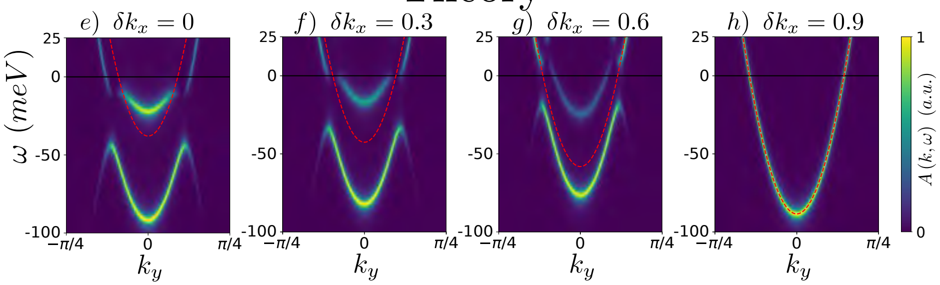




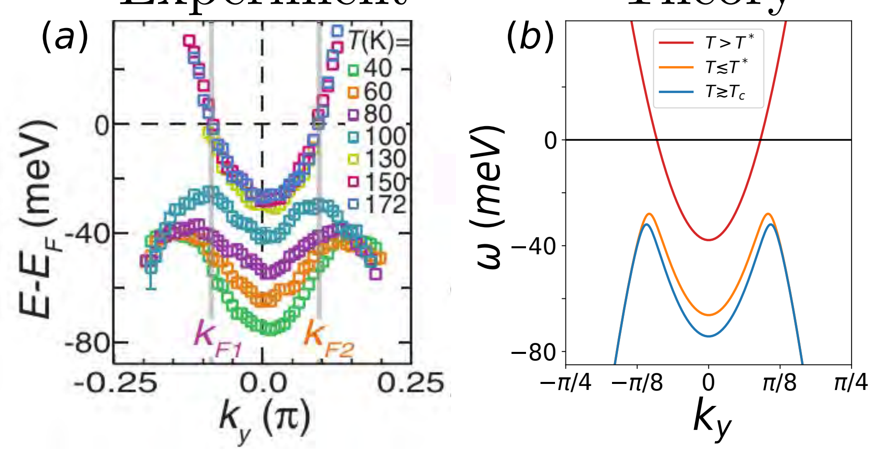
Experiment



Theory



Experiment Theory



M. Grandadam et al. PRB (2020)

ARPES, Bi2201

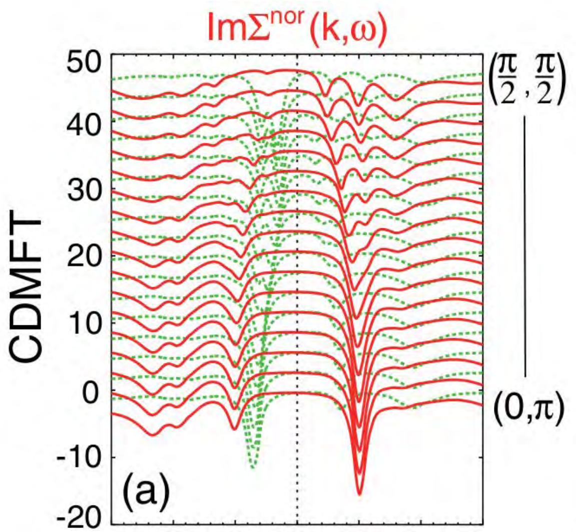
Comparison with CDMFT : « hidden fermion»

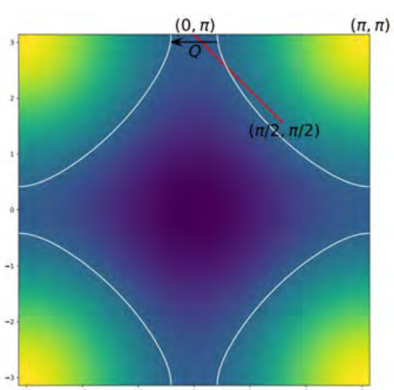
$$H = \sum_{k,\sigma} \epsilon_k c^\dagger_{k,\sigma} c_{k,\sigma} + \sum_{k,\sigma} \left(\sigma \Delta^*_k c^\dagger_{k,\sigma} c^\dagger_{-k,-\sigma} + h.c.\right)$$
$$+ \sum_{\alpha,k,\sigma} \epsilon^{f,\alpha}_k f^{\alpha\dagger}_{k,\sigma} f^{\alpha}_{k,\sigma} + \sum_{\alpha,k,\sigma} \left(\sigma \Delta^{f,\alpha^*}_k f^{\alpha\dagger}_{k,\sigma} f^{\alpha\dagger}_{-k,-\sigma} + h.c\right)$$
$$+ \sum_{\alpha,k,\sigma} \left(V^\alpha_k c^\dagger k,\sigma f^\alpha k,\sigma + h.c\right)$$

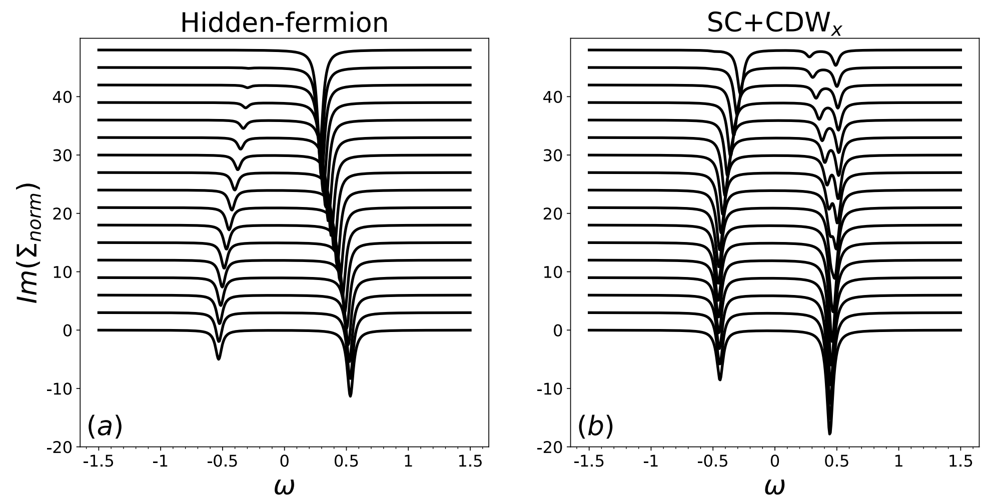
$$f_{k,\sigma} = c_{k+Q,\sigma}$$

CDMFT $\mathbf{Q} = (\pi,\pi)$ (AF)

Fract. PDW $\mathbf{Q} = \mathbf{Q}_0$ (CDW)







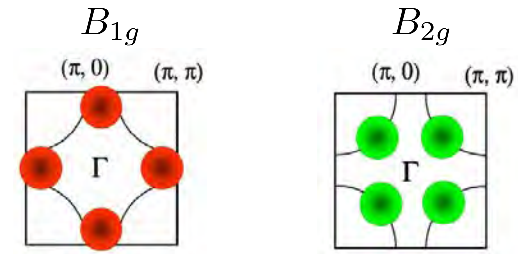
S. Sakai et al. 2021

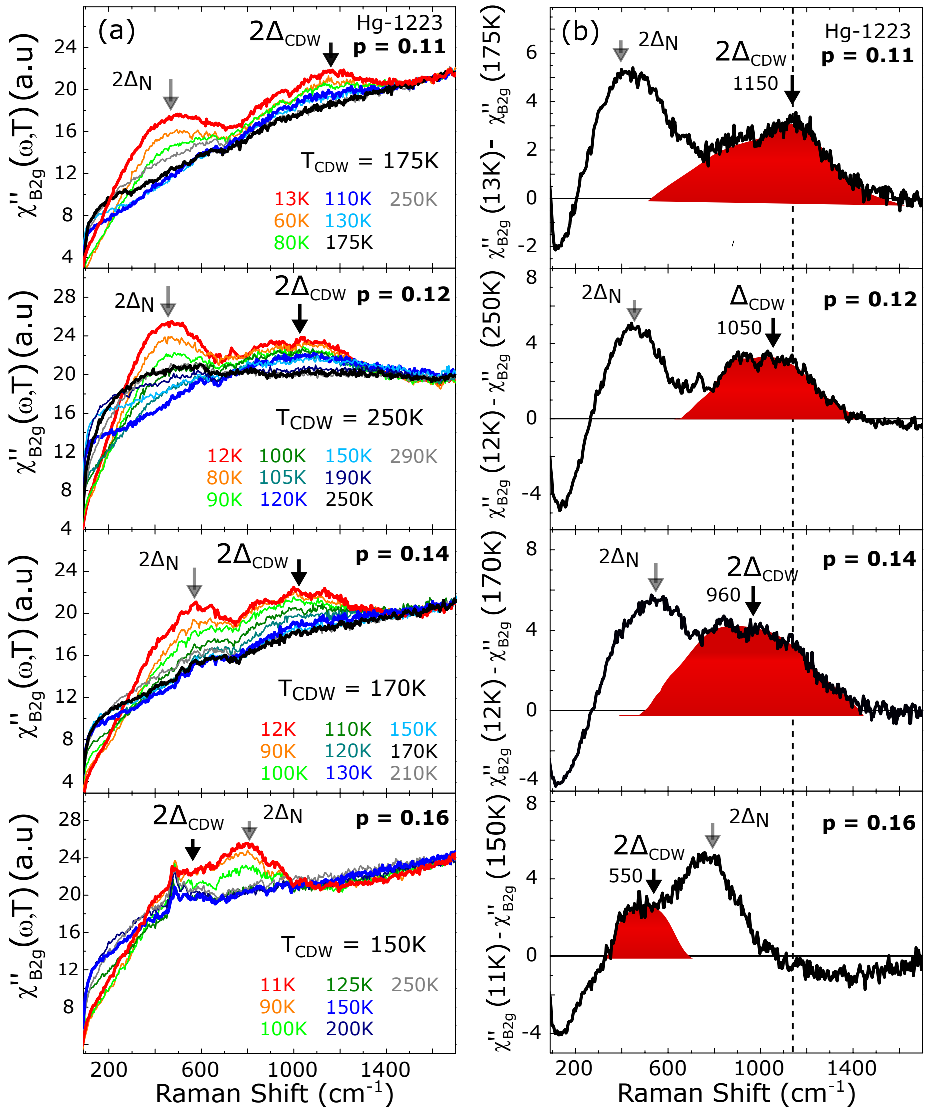
M. Grandadam et al. 2021

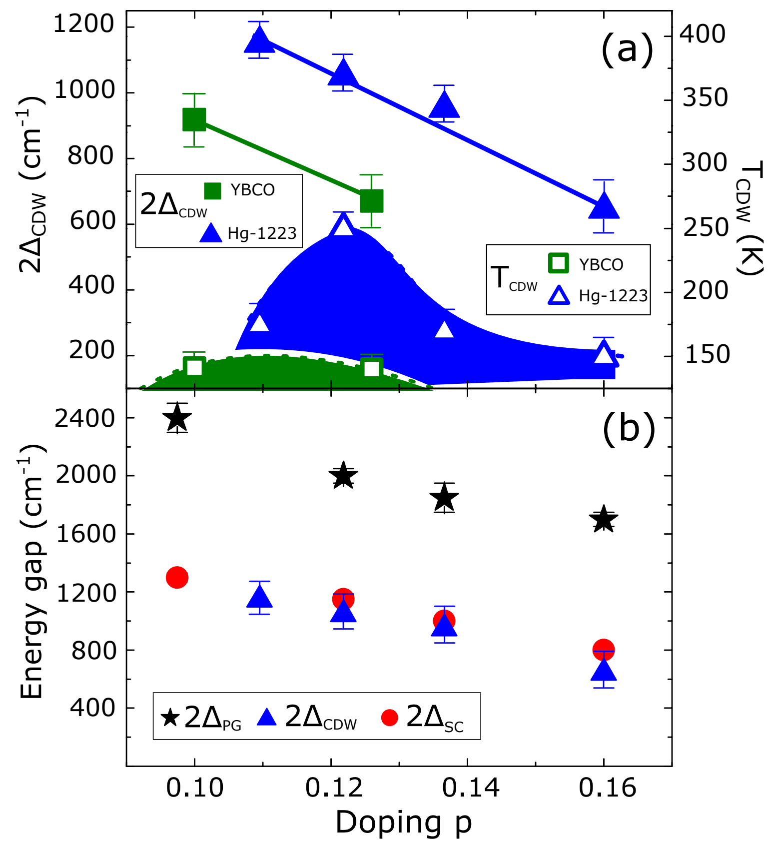
Raman scattering

Raman Scattering   B2g, T < Tco

Loret et al. Nat. Physics (2019)



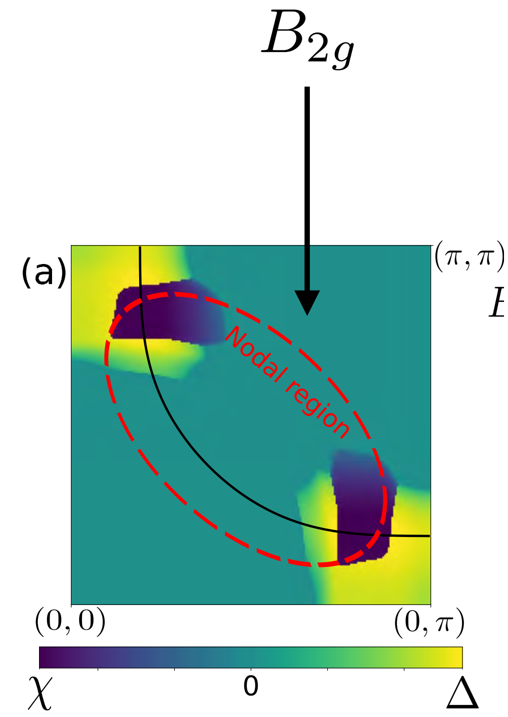


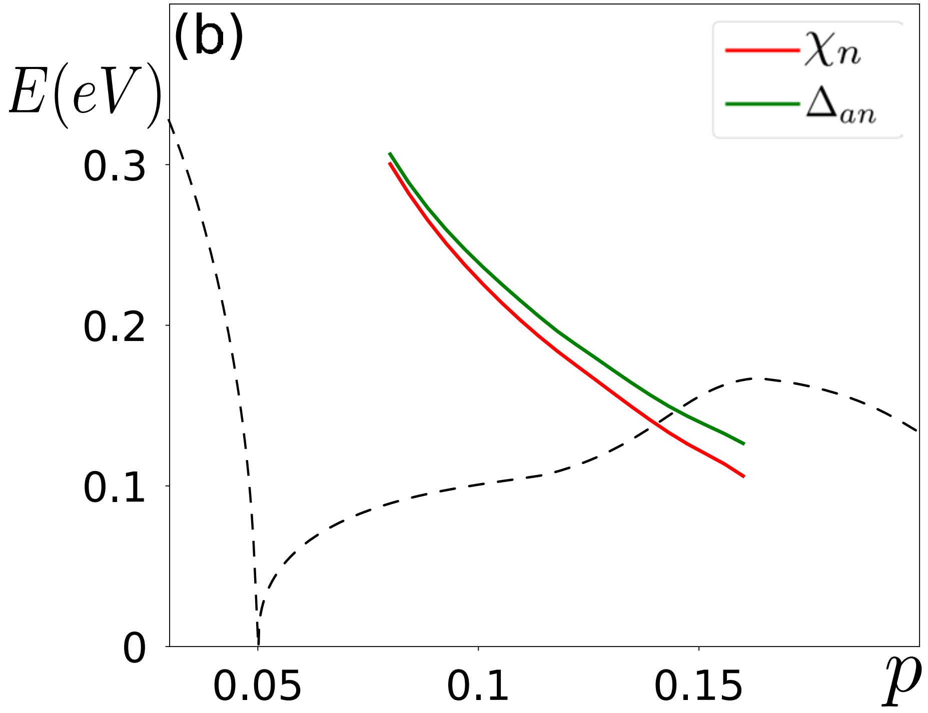


Solving gap equations

$$\Delta_{k,\omega} = -\frac{1}{\beta}\sum_{q,\Omega}\frac{J_{-}\left(q,\Omega\right)\Delta_{k+q}}{\left(\omega+\Omega\right)^{2}-\xi_{k+q}^{2}-\Delta_{k+q}^{2}},$$

$$\chi_{k,\omega} = -\frac{1}{\beta}\sum_{q,\Omega}\frac{J_{+}\left(q,\Omega\right)\chi_{k+q}}{\left(\omega+\Omega-\xi_{k+q}\right)\left(\omega+\Omega-\xi_{k+Q+q}\right)-\chi_{k+q}^{2}};$$





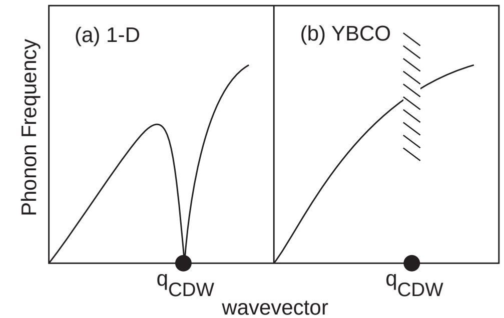
Same order of magnitude for
Δ and χ

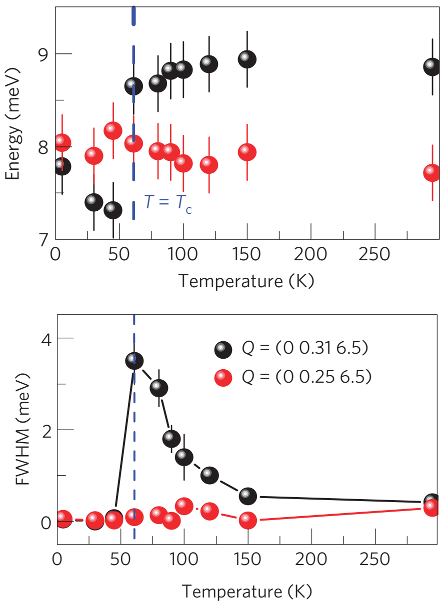
M. Grandadam et al. PRB (2019)

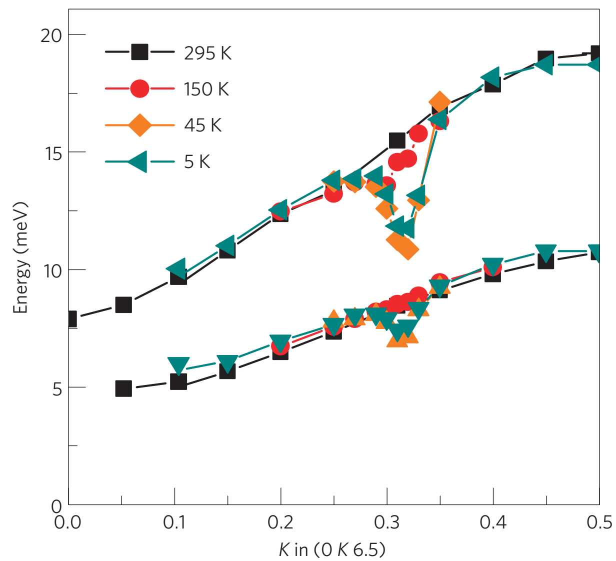
Phonon Softening

Anomalous softening of phonons

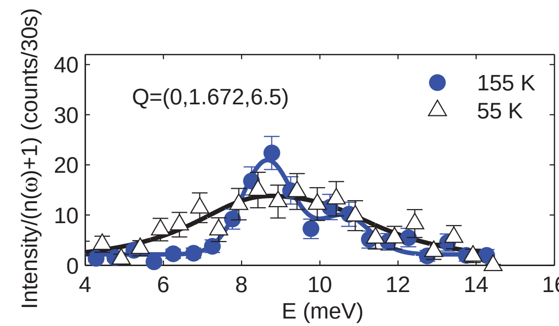
Blackburn, 2013

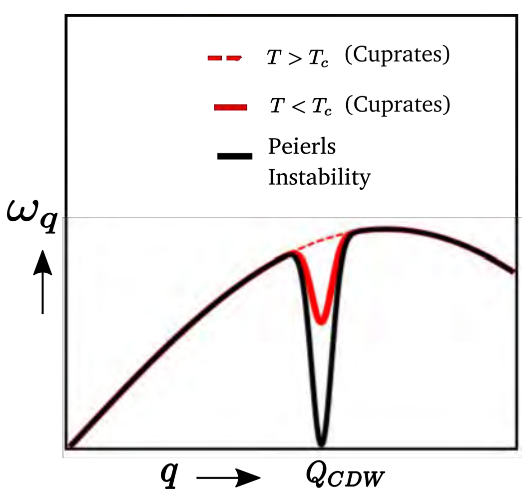




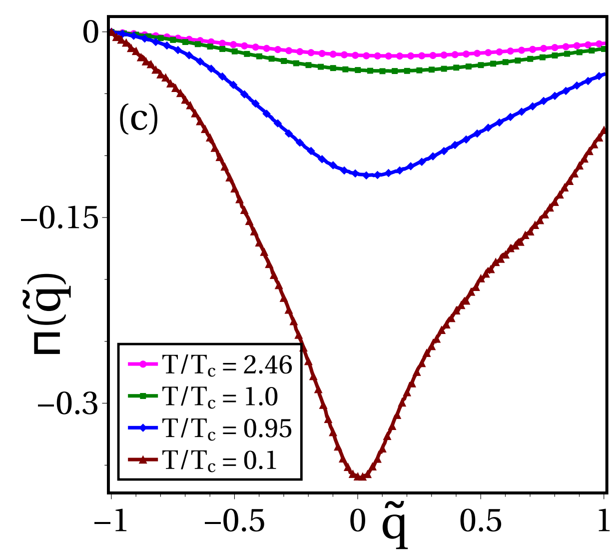


Le Tacon, 2013

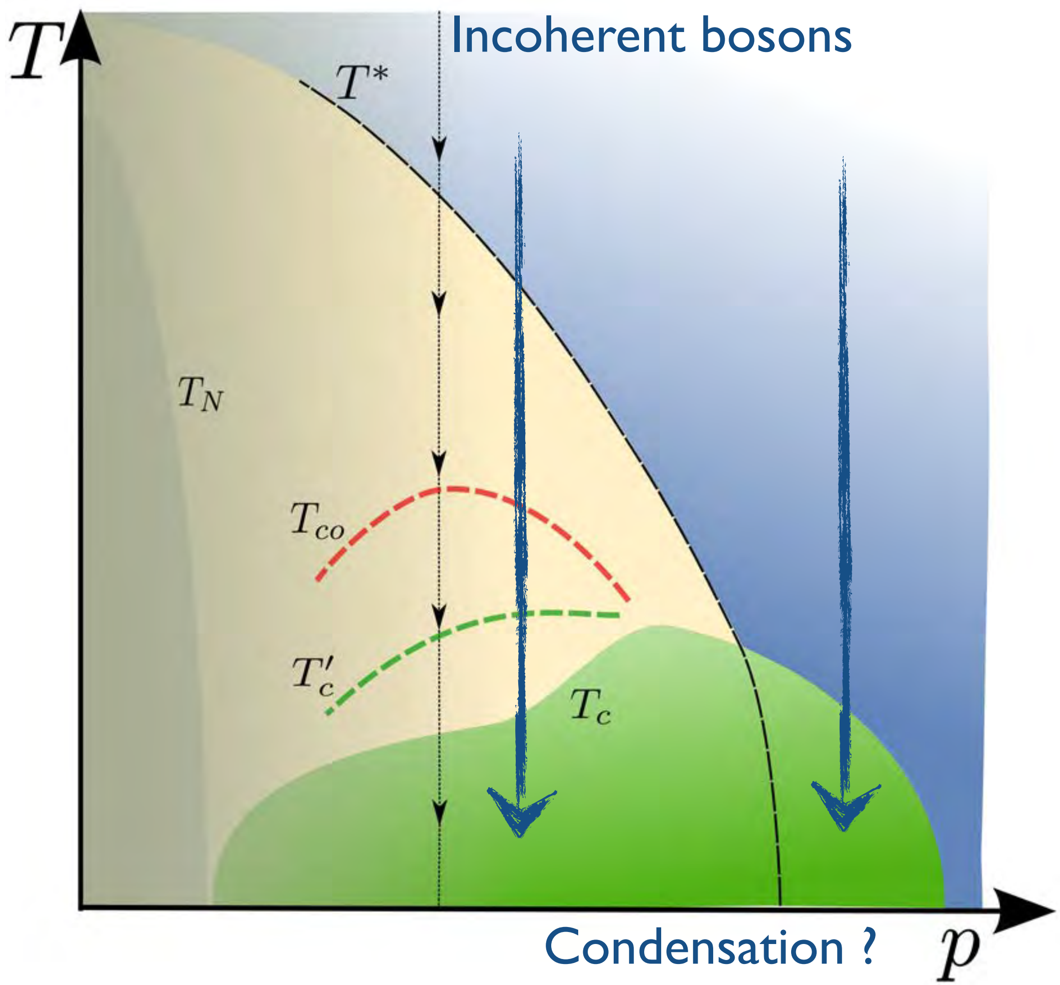




- *Phases lock at Tc*
- *Fluct. Quench at Tc*



S. Sarkar et al. (2020)


Incoherent bosons
T
T^*
T_N
T_{co}
T'_c
T_c
Condensation ?
p

Conclusions

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

- Fractionalizing a PDW or a more complex boson

- Entangling particle-hole and particle-particle pairs at T*

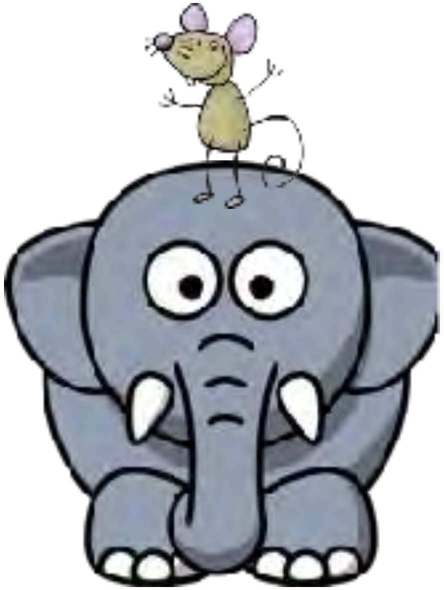
- Explains recent Raman, phonon softening

- ARPES : back-bending, poles in self-energy (cf. DMFT studies)

- Can a charge-2 boson explain the mystery of strange metal and Hall resistivity ?

- Exp. predictions with mesoscopic noise, Josephson effects

- Numerical check in strong coupling approaches



Discussions of the data and a few Refs

Maxence Grandadam, Catherine Pépin arXiv:2012.11226

Anurag Banerjee, Maxence Grandadam, Hermann Freire, Catherine Pépin arXiv:2009.09877

Saheli Sarkar, Maxence Grandadam, Catherine Pépin arXiv:2009.02975

Maxence Grandadam, Debmalya Chakraborty, Xavier Montiel, Catherine Pépin arXiv:2002.12622

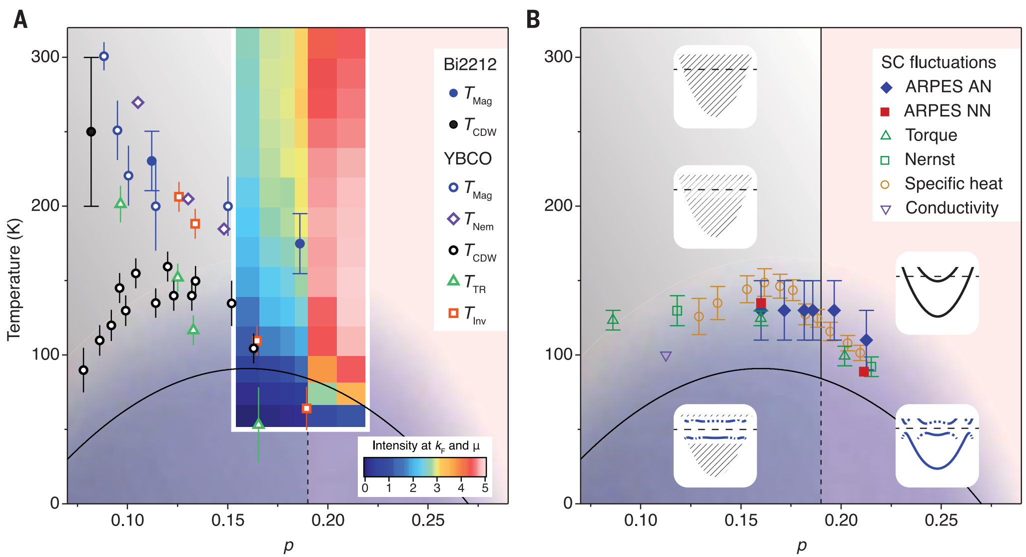
D. Chakraborty, M. Grandadam, M. H. Hamidian, J. C. S. Davis, Y. Sidis, C. Pépin arXiv:1906.01633

Saheli Sarkar, Debmalya Chakraborty, Catherine Pépin arXiv:1906.08280

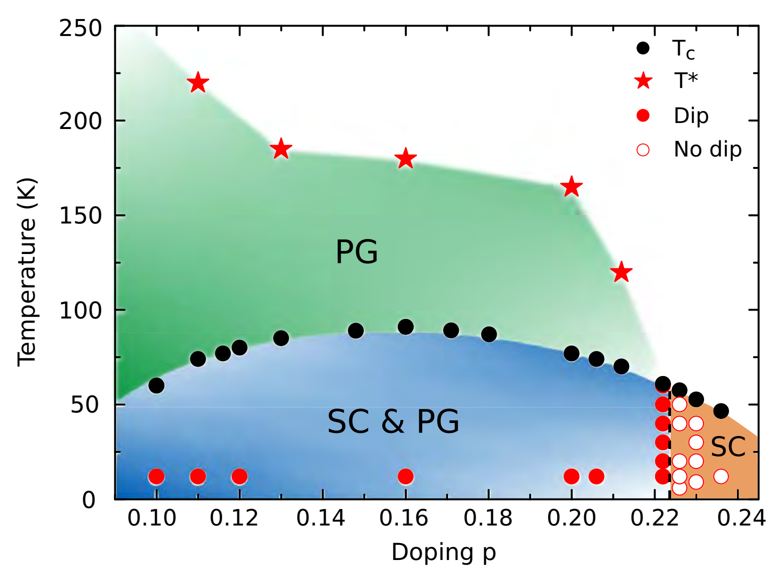
C. Pépin, D. Chakraborty, M. Grandadam, S. Sarkar arXiv:1906.10146

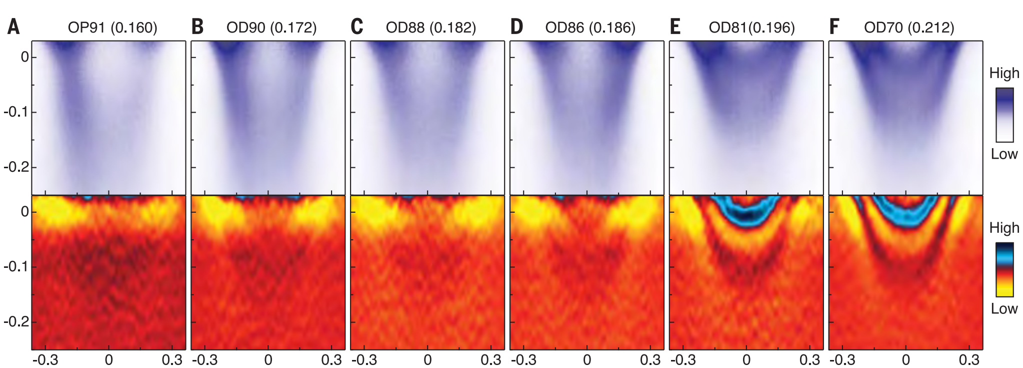
Quantum Criticality
Or
Cross-Over ?

QCP questioned : an abrupt change at p ?*



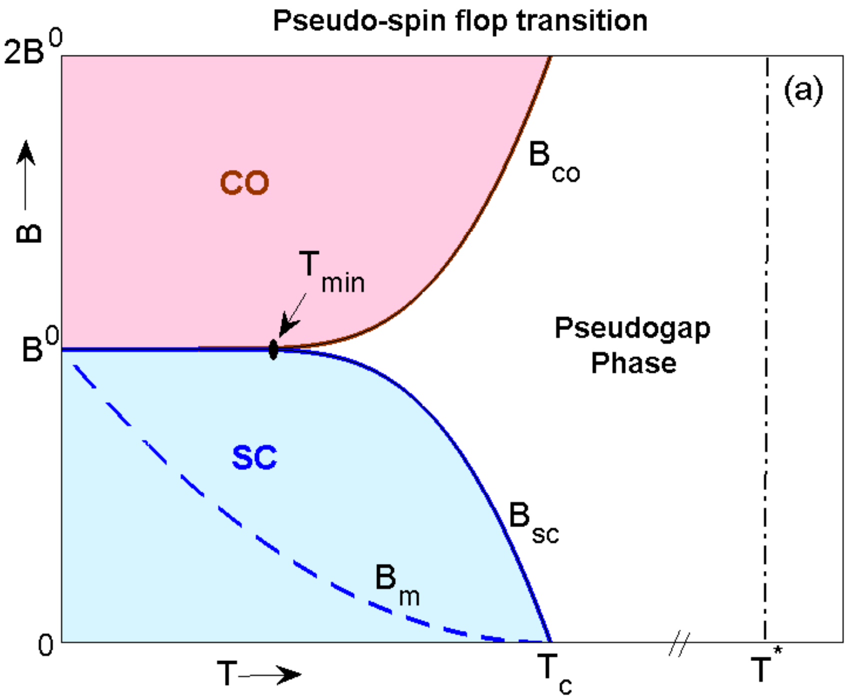
Raman Bi2212, Loret et al. 2019

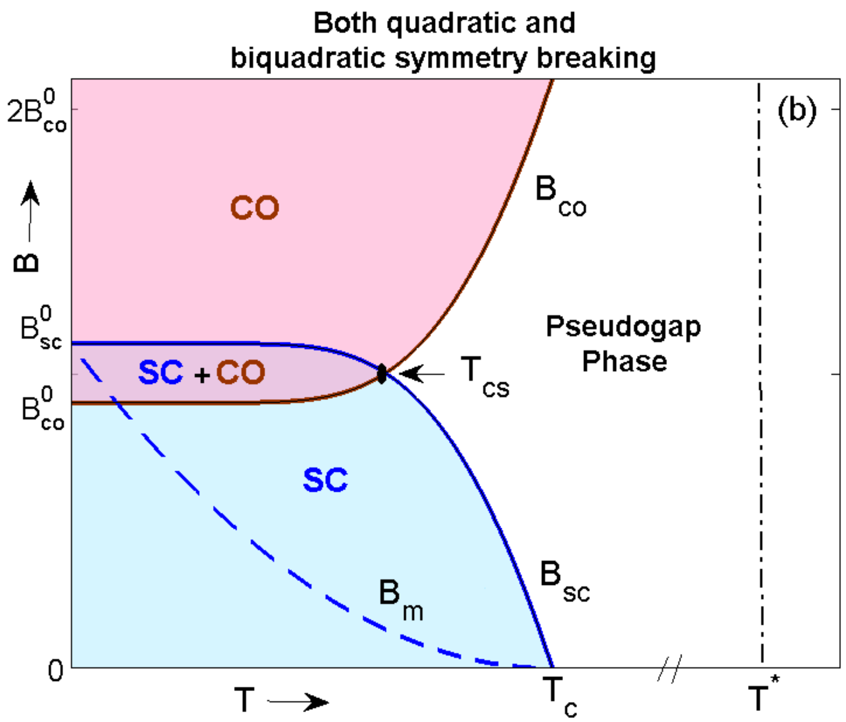




ARPES Bi2212, Chen et al. 2019

O(3) Non Linear Sigma Model





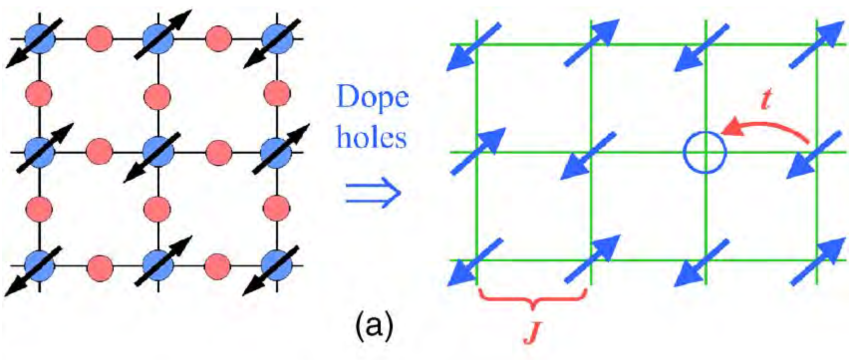
$$\frac{F}{T} = \frac{1}{t_0} \int tr[\nabla u^\dagger \nabla u + \kappa_0 \tau_3 u^\dagger \tau_3 u] dR$$

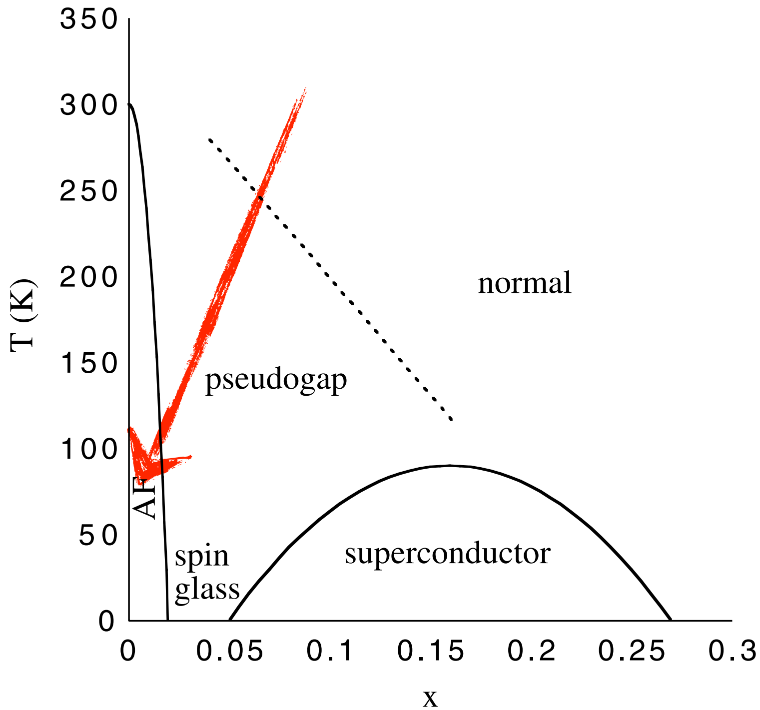
$$\frac{F_{bq}}{T} = \frac{1}{t_0} \int z_0 \left\{ \left(tr[\tau_3 u^\dagger \tau_3 u] \right)^2 - 1 \right\} dR$$

D. Chakraborty et al. PRB (2018)

The context of strong coupling : doping a Mott insulator

Resonating Valence Bond (RVB)





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

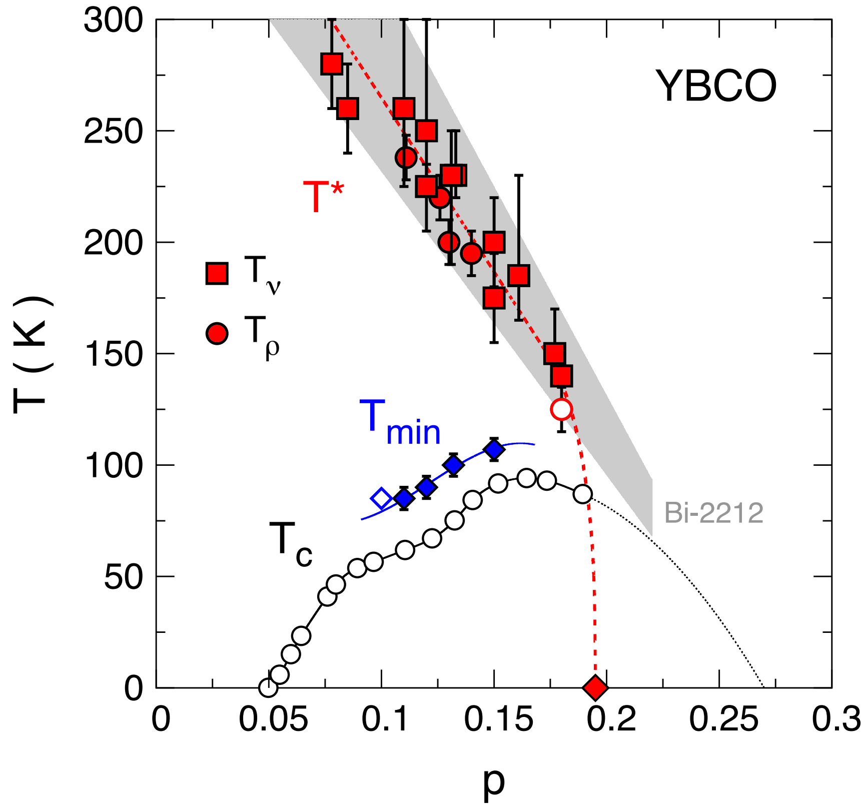
Anderson, Lee, Nagaosa, Rice etc…

P: projection on no double occupancy

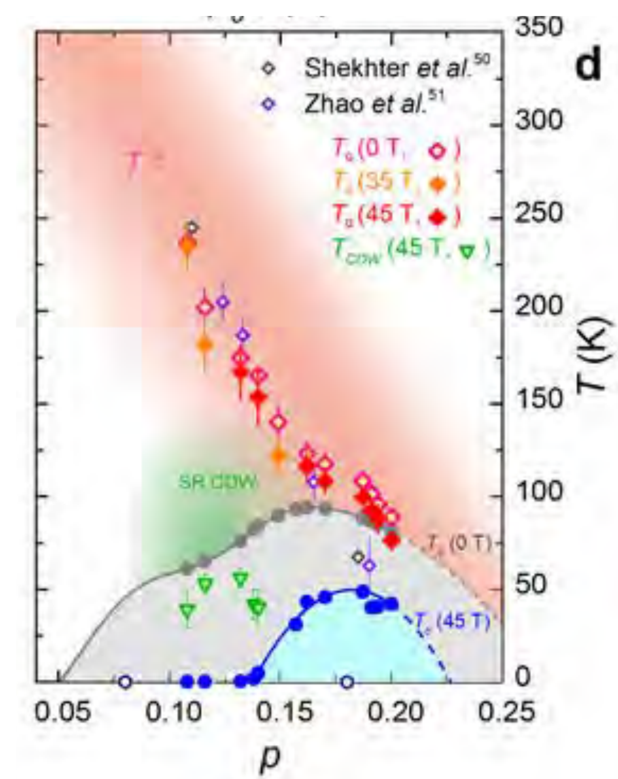
The extend of the Cooper pairs phase fluctuations regime
Nernst effect (Ong, Behnia), transport (Rullier-Albenque, Sebastian), Squid spectroscopy (Lesueur)…

The presence of a partner to SC pairing inhibits the visibility of phase fluctuations in transport and Nernst effect (Orgard, 2017)

Cyr-Choignière et al , (2017)



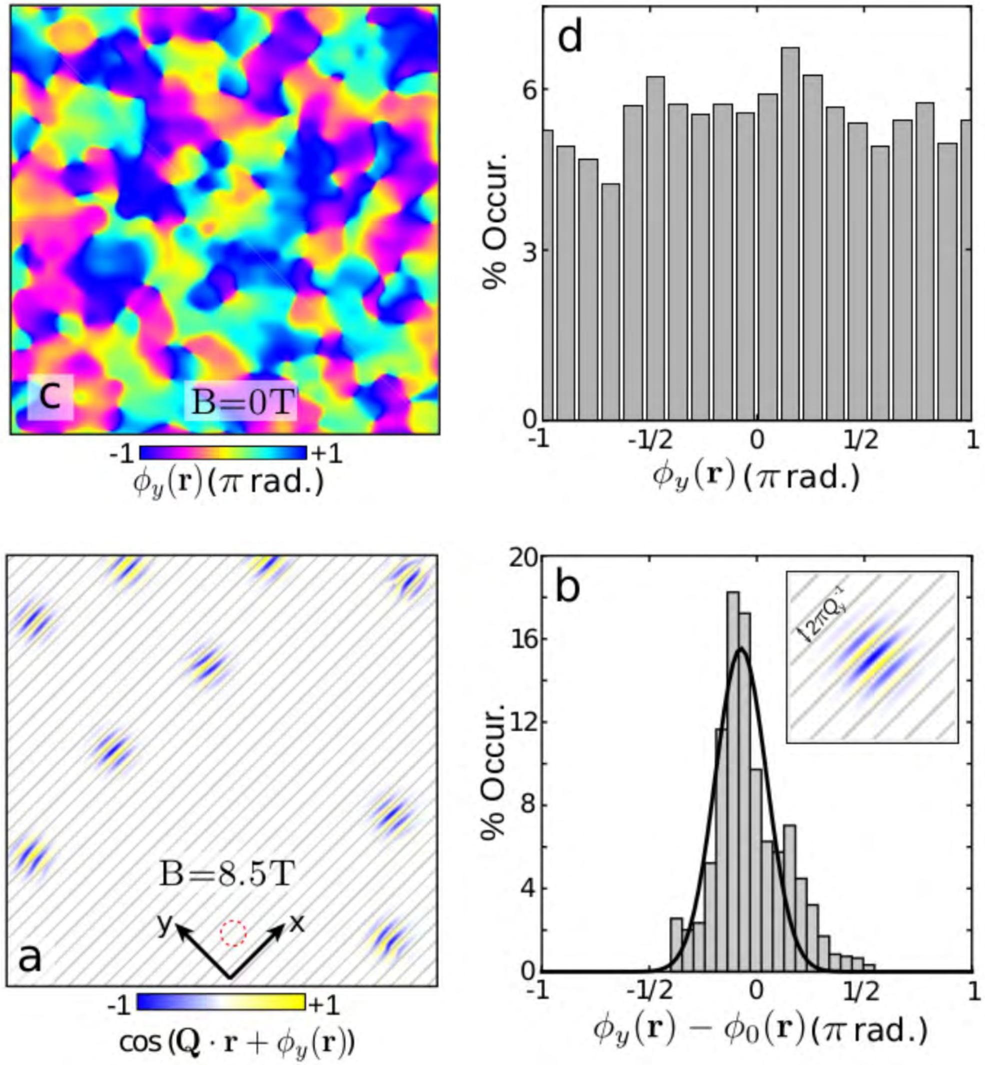
Hsu et al , (2017)



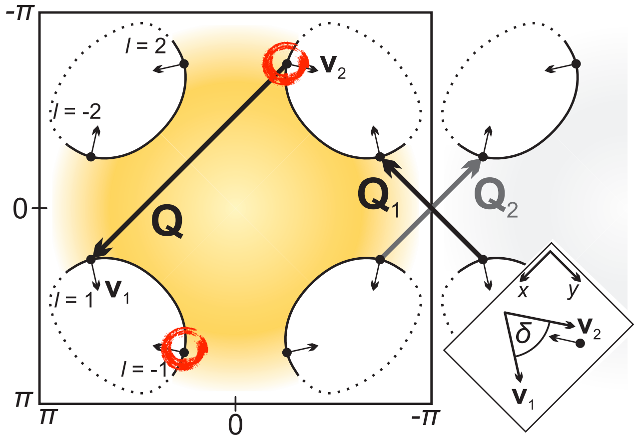
STM measurement of charge density modulation : $Re\left(\chi_{ij}\right) = \hat{d}|\chi_{ij}|cos\left(\boldsymbol{Q}\cdot\boldsymbol{r}+\phi\left(\boldsymbol{r}\right)\right)$

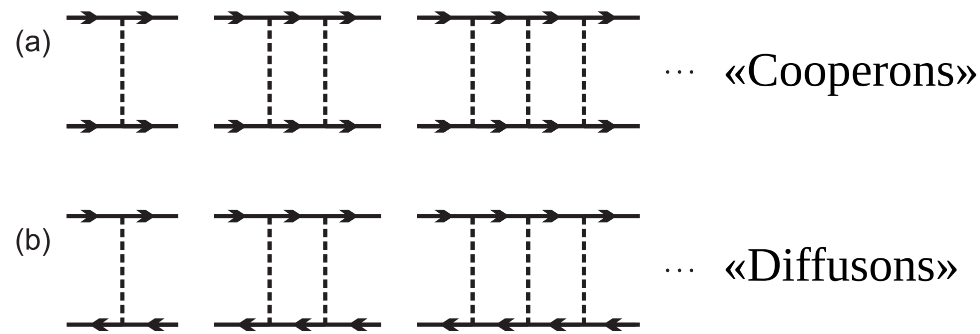
$B = 0\ T$ random phase distribution :

$B \neq 0\ T$ centered distribution :

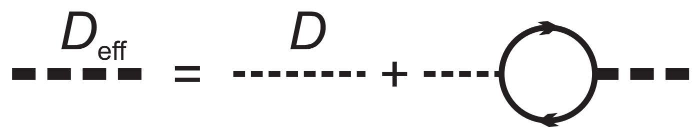


M.H. Hamidian et al., Nat. Phys. **12**, 150 (2015).
M.H. Hamidian et al., arXiv:1508.00620 (2015)





$$\delta \ll 1$$



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

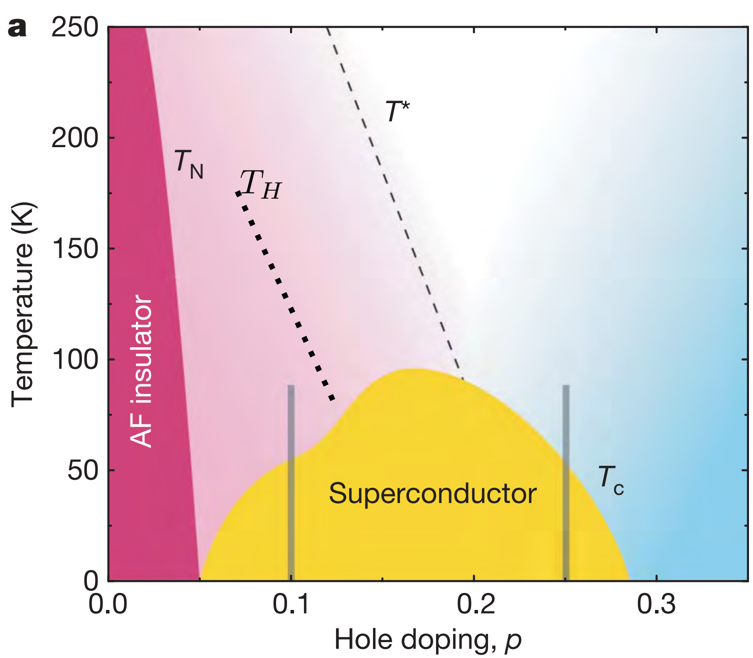
$$u = \begin{pmatrix} \Delta_- & \Delta_+ \\ -\Delta_+^* & \Delta_-^* \end{pmatrix} \quad \text{with} \quad |\Delta_+|^2 + |\Delta_-|^2 = 1$$

^{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)

We report NMR shift ΔK and T_1 data of ^{89}Y taken from 77 to 300 K in $YBa_2Cu_3O_{6+x}$ for $0.35 < x < 1$, from the insulating to the metallic state. A Korringa law and therefore a Fermi-liquid picture is found to apply for the spin part K_s of ΔK. The spin contribution $\chi_s(x,T)$ to χ_m is singled out, as the T variation of ΔK scales linearly with the macroscopic susceptibility χ_m. This implies that Cu(3d) and O(2p) holes do not have independent degrees of freedom. Their hybridization, which has a σ character, hardly varies with doping. These results put severe constraints on theoretical models of high-T_c cuprates.

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



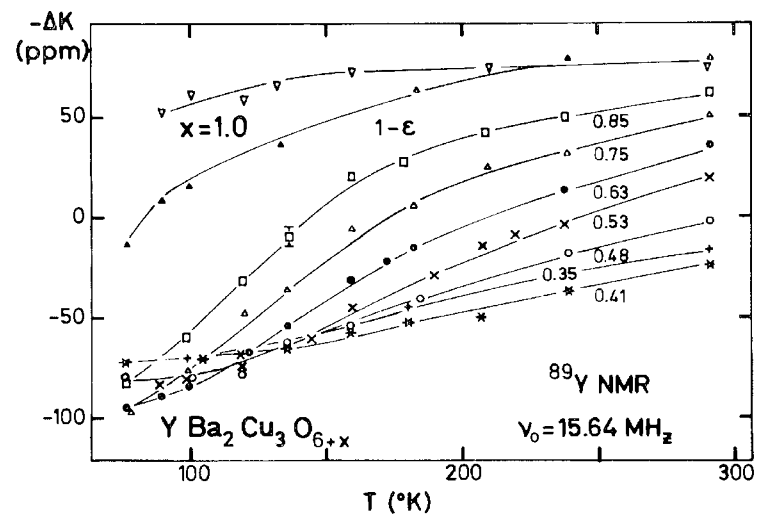
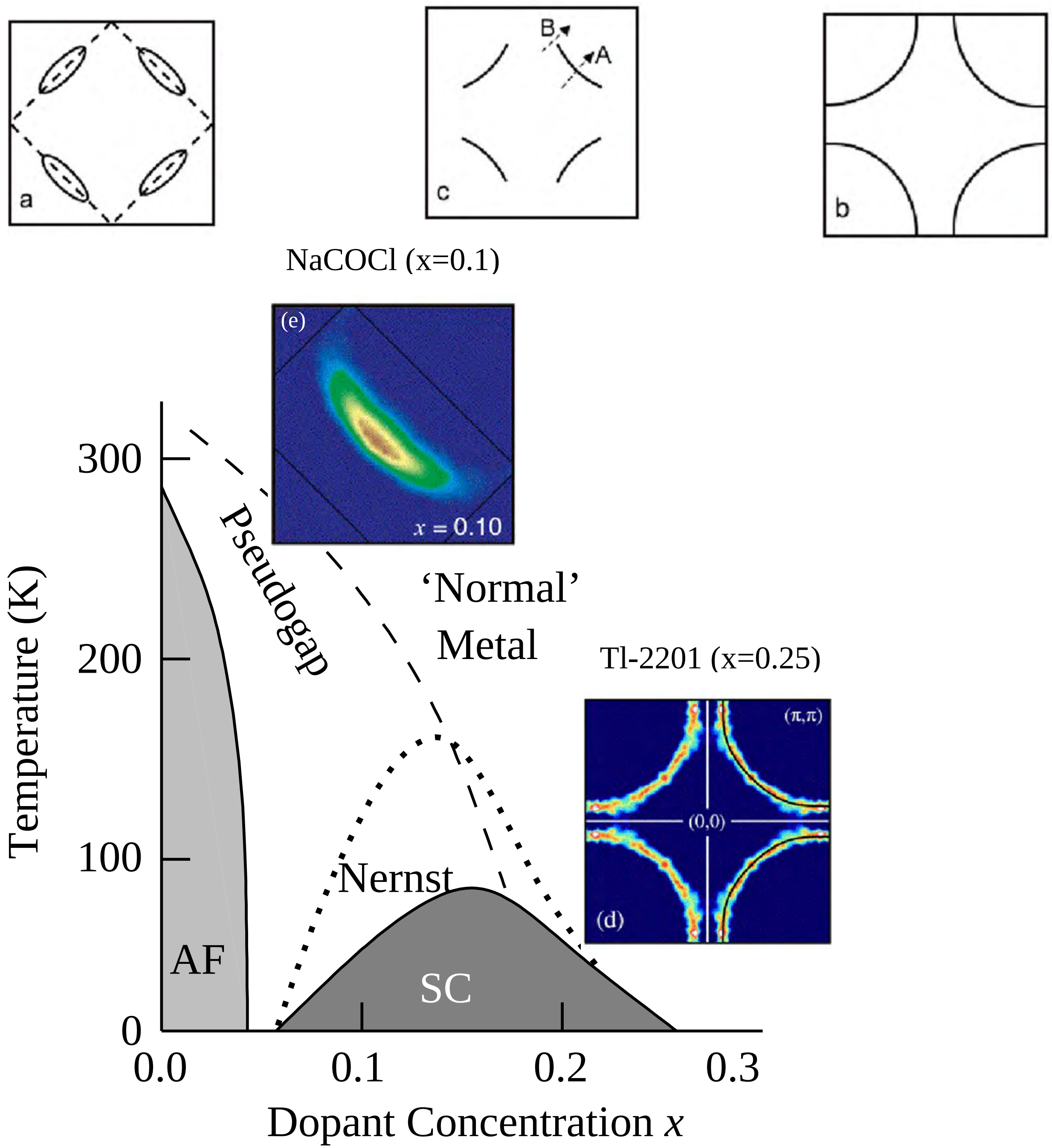
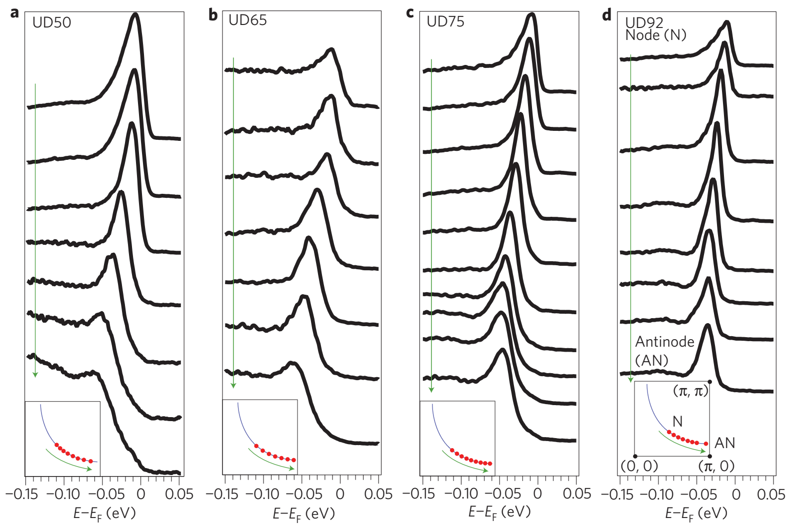


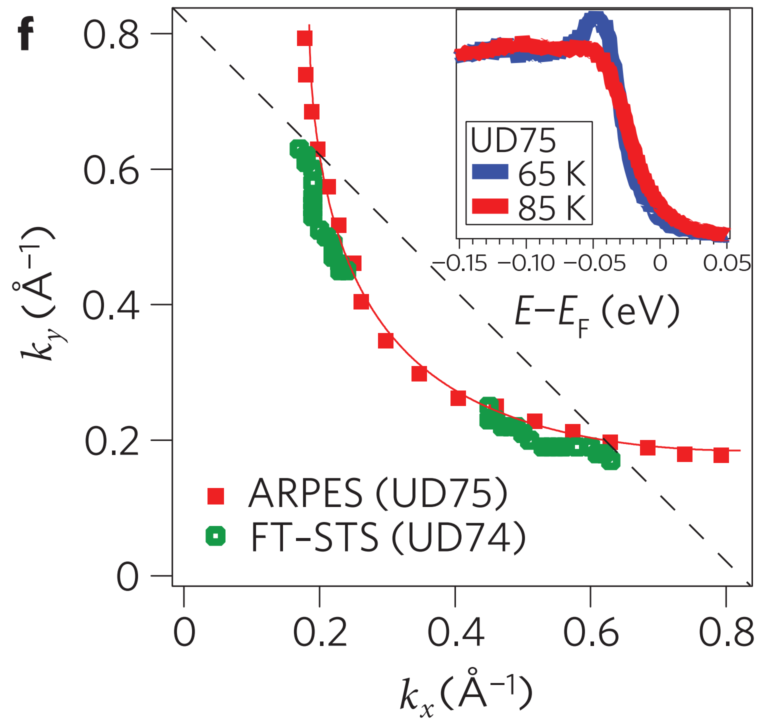
FIG. 1. The shift ΔK of the ^{89}Y line, referenced to YCl_3 plotted vs T, from 77 to 300 K. The lines are guides to the eye.

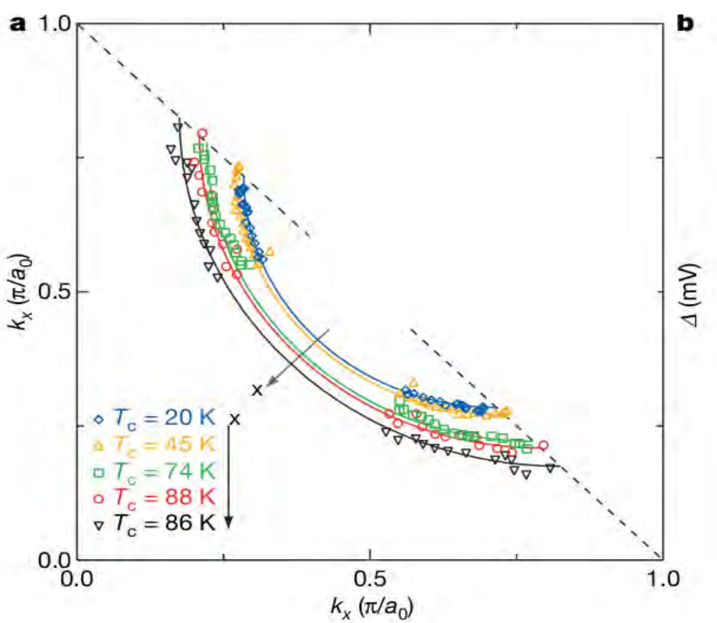


a
c
B
A
b
NaCOCl (x=0.1)
(e)
x = 0.10
Pseudogap
'Normal'
Metal
Tl-2201 (x=0.25)
(π,π)
(0,0)
(d)
Nernst
AF
SC
300
200
100
0
0.0
0.1
0.2
0.3
Temperature (K)
Dopant Concentration x

Fractionalization in the PG phase ?







Is fractionalization compatible with the observation of Bogoliubov QP in the anti-nodal region ?

Coherence of the electrons ?

Amplitude Fluctuations ....➤

Phase fluctuations ....➤

Condensate ....➤

The concept of SU(2) symmetry

C.N.Yang & S-C. Zhang (1989)

Pseudo-Spins

$$\eta^{+} = \sum_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}+\mathbf{Q}\downarrow}$$

$$\eta_{z} = \sum_{\mathbf{k}} \left(c^{\dagger}_{\mathbf{k}\uparrow} c_{\mathbf{k}\uparrow} + c^{\dagger}_{\mathbf{k}+\mathbf{Q}\downarrow} c_{\mathbf{k}+\mathbf{Q}\downarrow} - 1 \right)$$

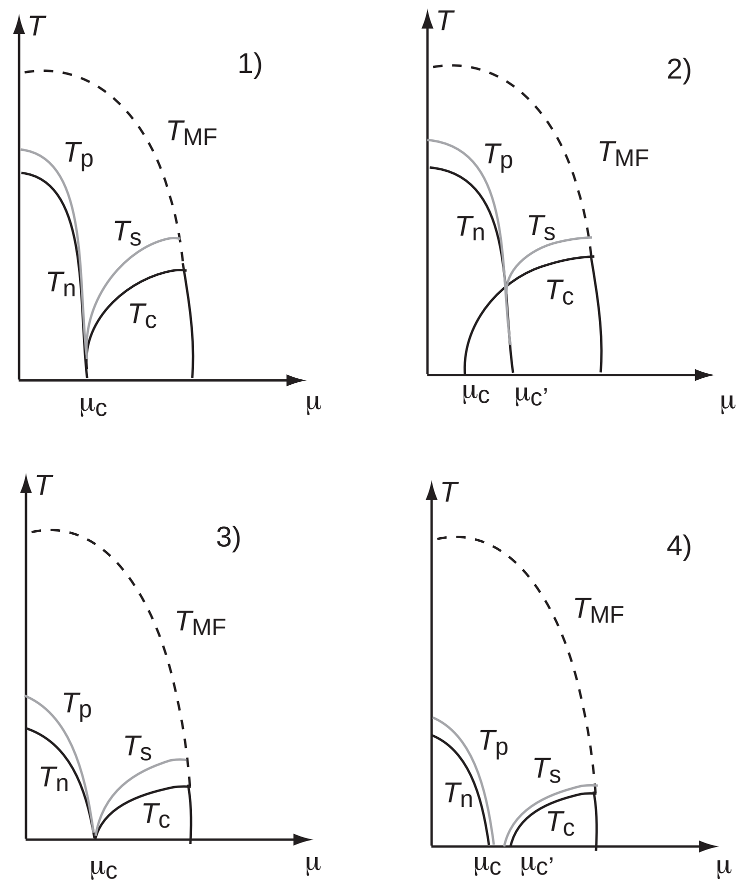
l=1 representation

$$\Delta_1 = -\frac{1}{\sqrt{2}} \sum_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k}\downarrow},$$

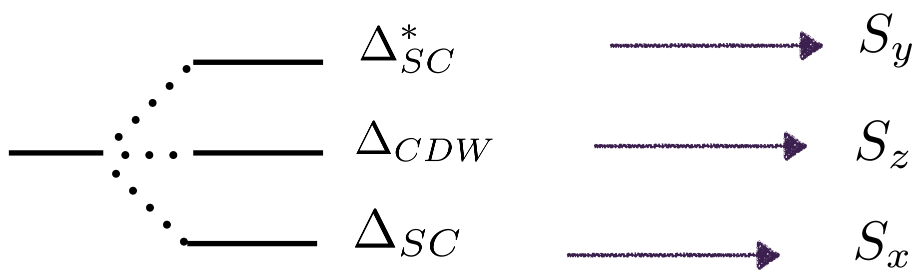
$$\Delta_0 = \frac{1}{2} \sum_{\mathbf{k},\sigma} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}+\mathbf{Q}\sigma},$$

$$\Delta_{-1} = -\Delta_1^{\dagger},$$

$$[\eta^{\pm}, \Delta_m] = \sqrt{l\,(l+1) - m\,(m \pm 1)}\,\Delta_{m\pm 1},$$
$$[\eta_z, \Delta_m] = m\Delta_m.$$



0(3) non linear σ-model



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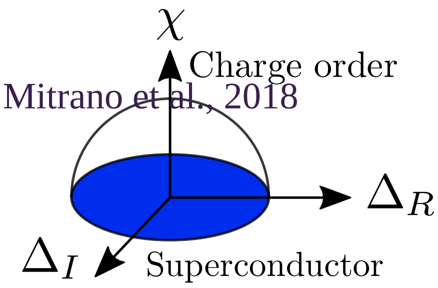

Mitrano et al., 2018

Topological structure:
Skyrmions in the pseudo spin space