Strange Bosons in Strange Metals

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A. Banerjee

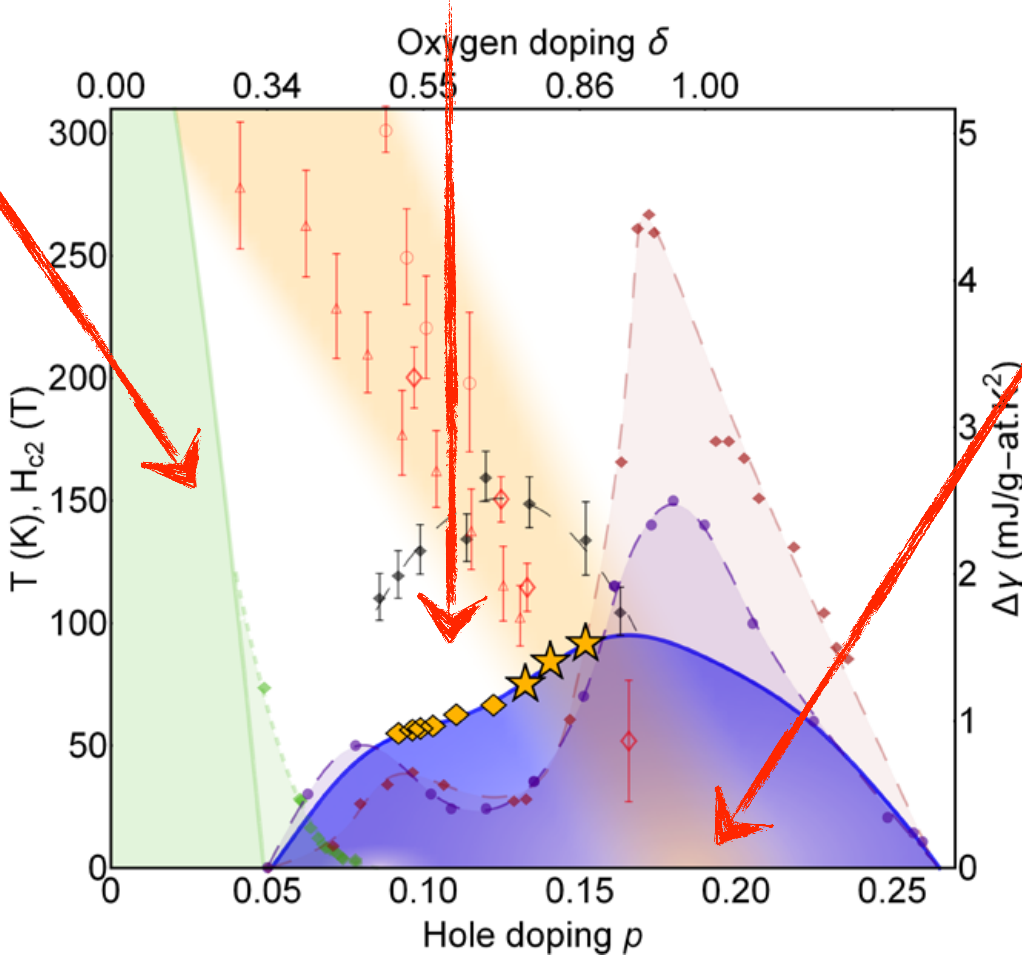
S. Sarkar & M. Grandadam

Correlated20, KITP, Oct. 13th, 2020

Mott transition

Fluctuations

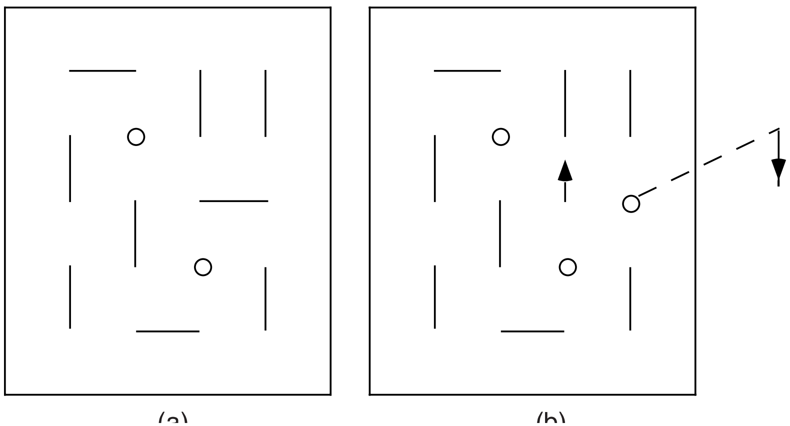
QCP under the dome



Ramshaw, 2015

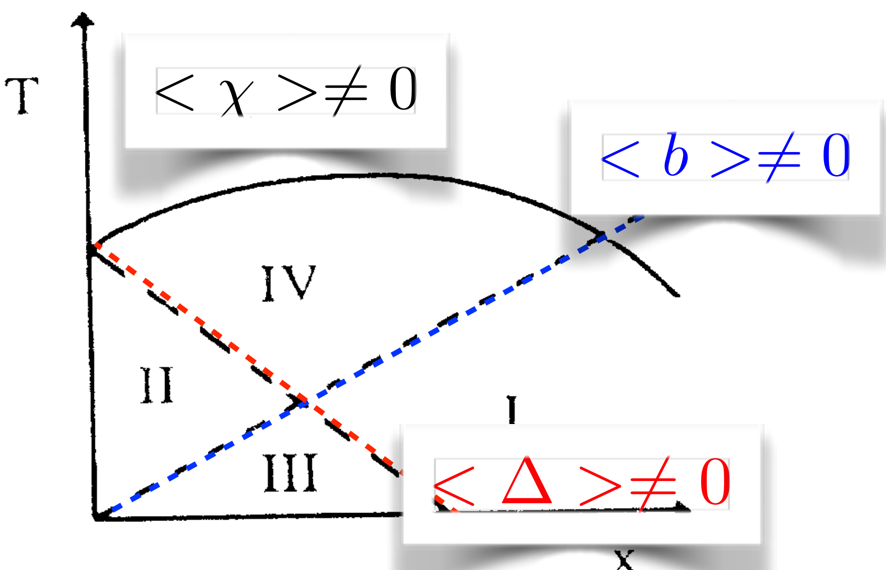
1. The context of strong coupling : doping a Mott insulator

Resonating Valence Bond (RVB) : pairs form and fluctuate



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

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



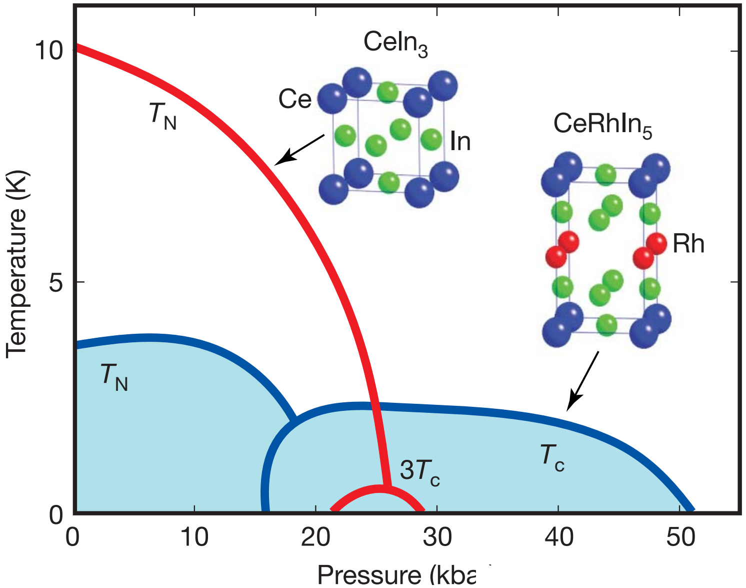
$$c_{i\sigma}^\dagger = f_{i\sigma}^\dagger b_i$$

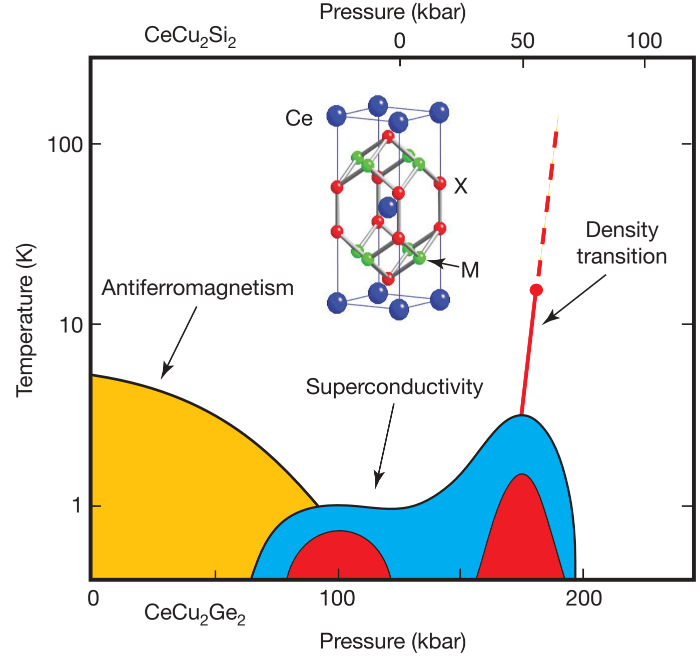
Spinon

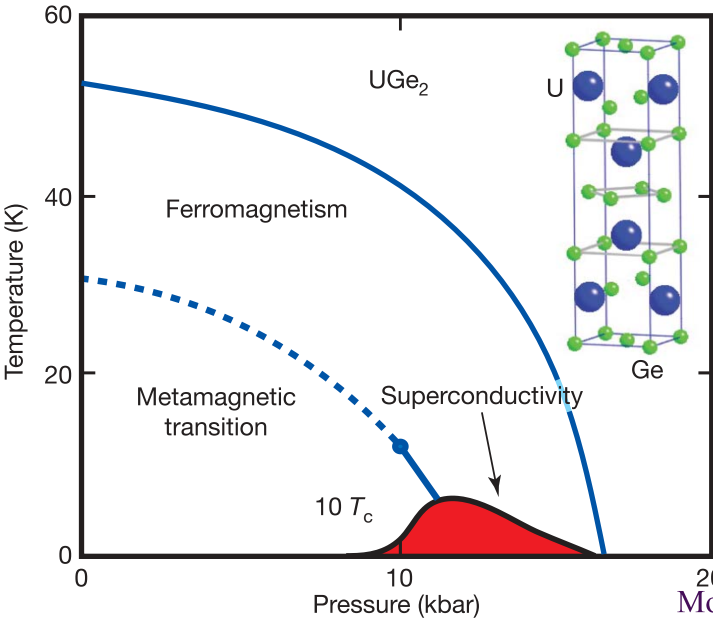
Holon

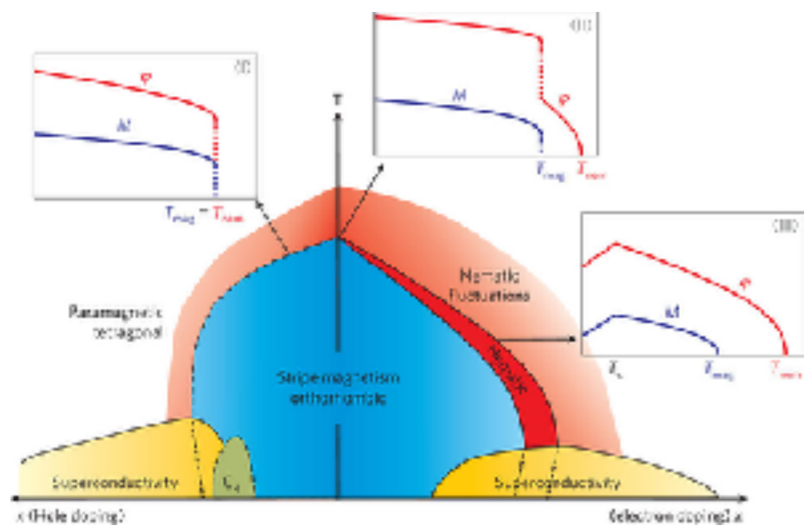
$$f_{i\uparrow}^\dagger f_{i\uparrow} + f_{i\downarrow}^\dagger f_{i\downarrow} + b_i^\dagger b_i = 1 .$$

2. QCP under the SC dome



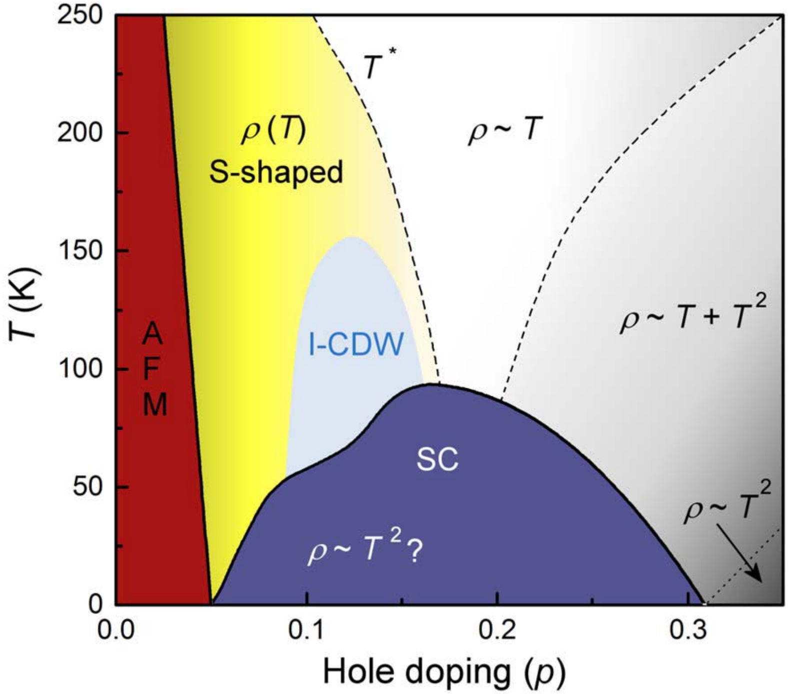


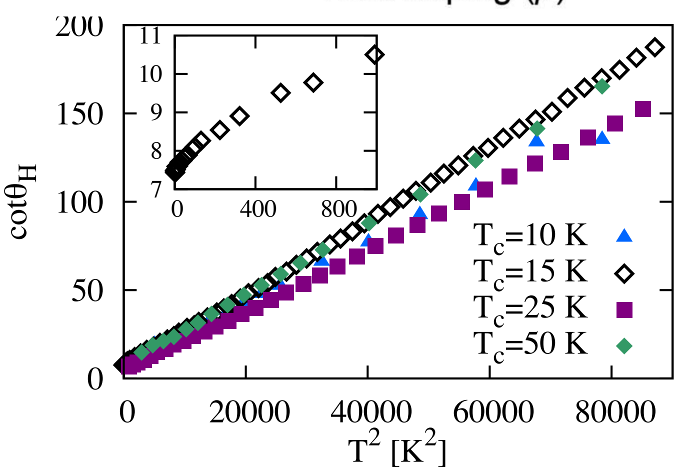


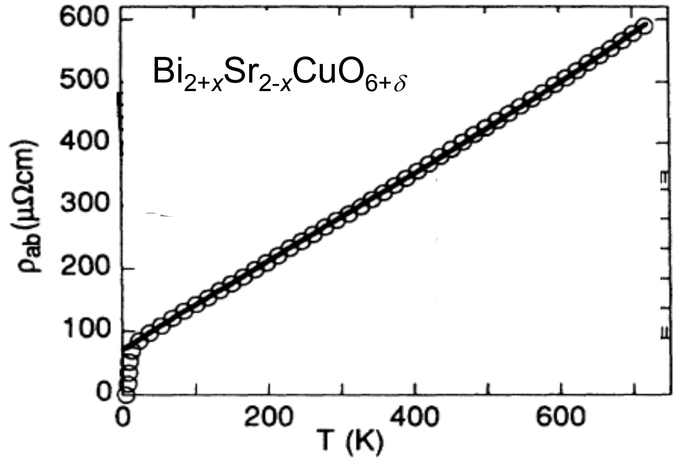


Monthoux, Pines, Lonzarich 07

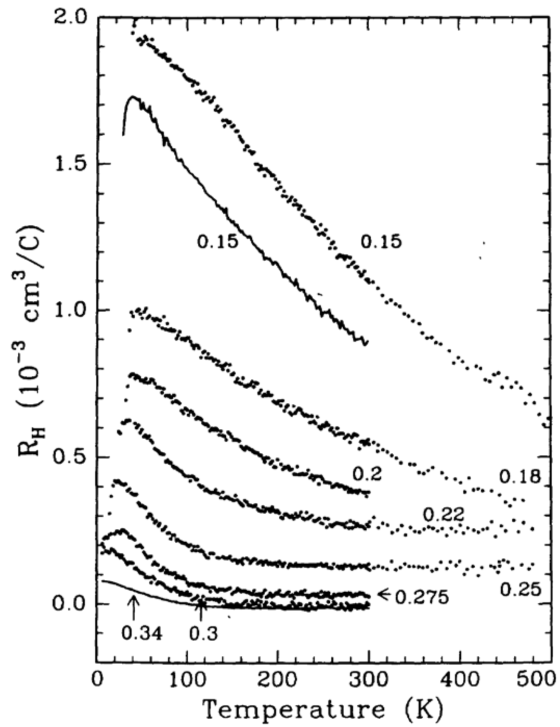
Most strongly Correlated QCP ?





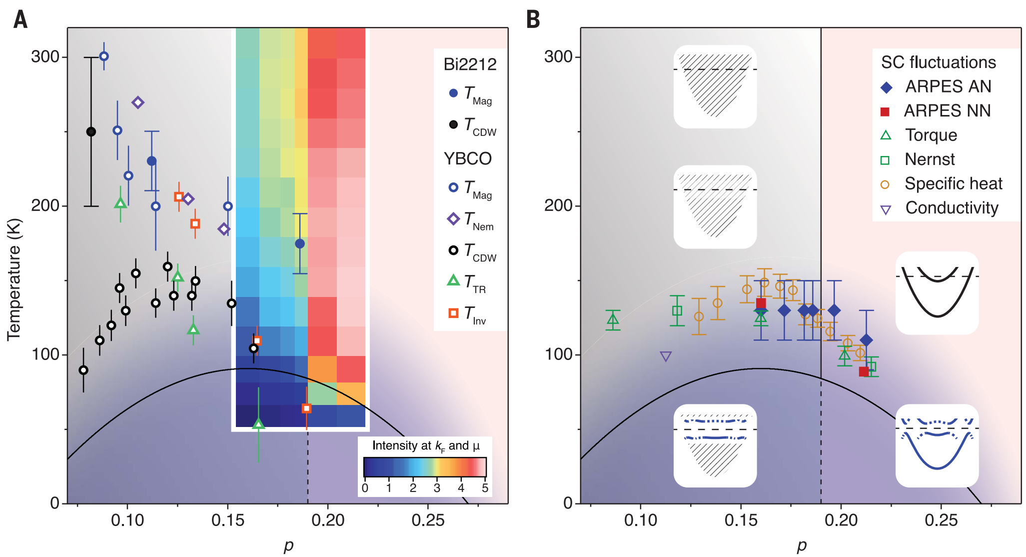


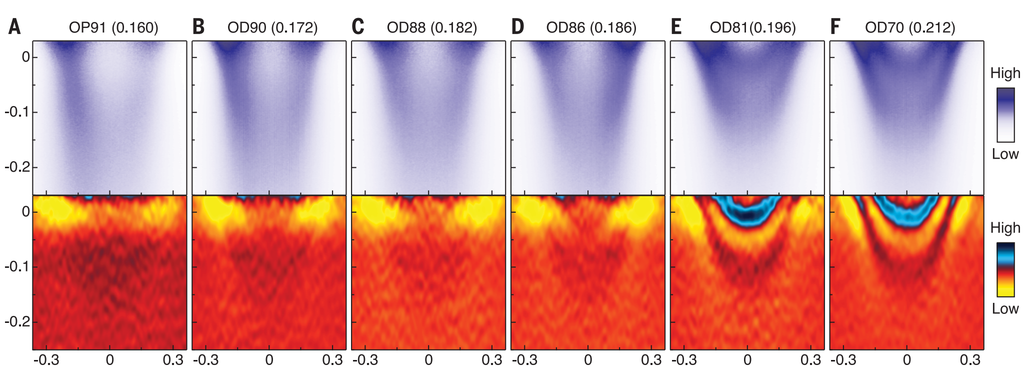
Martin *et al.*, *Phys. Rev. B* (1990)



Hwang *et al.*, *PRL* **72** 2636 (94)

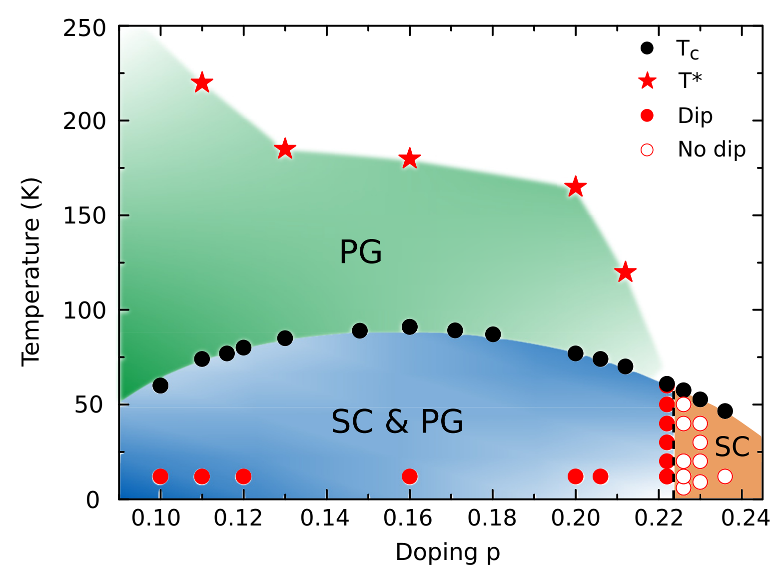
QCP questionned : an abrupt change at p ?*





ARPES Bi2212, Chen et al. 2019

Raman Bi2212, Loret et al. 2019



3. Fluctuations

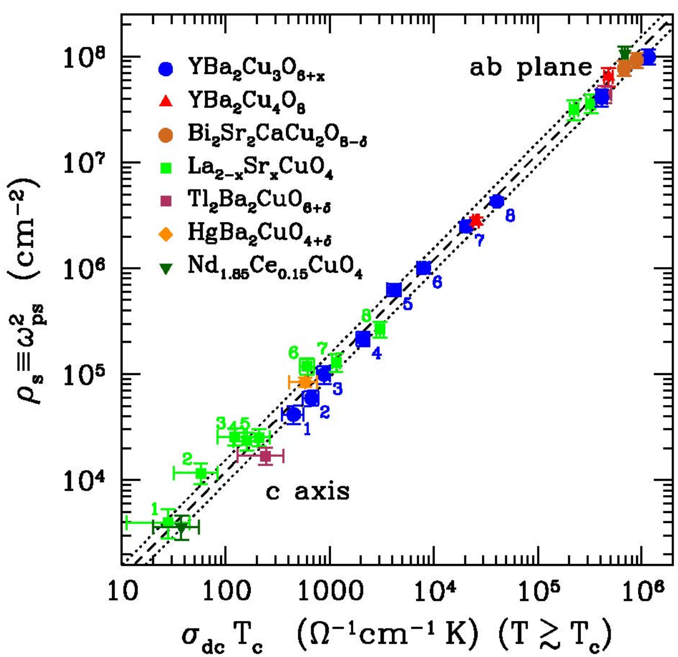
TABLE 1 Phase stiffness and T_θ^{max} for various superconductors

Material	l (Å)	λ (Å)	T_c (K)	V_0 (K)	T_θ^{max}/T_c	Ref.
Pb	830	390	7	6×10^5	2×10^5	17
Nb_3Sn	60	640	18	2×10^4	2×10^3	18
UBe_{13}	140	11,000	0.9	10^2	3×10^2	19, 20
$LaMO_6S_8$	200	7,000	5	4×10^2	2×10^2	12, 21
$B_{0.6}K_{0.4}BiO_3$	40	3,000	20	5×10^2	50	12
K_3C_{60}	30	4,800	19	10^2	17	22, 23
$(BEDT)_2Cu(NCS)_2$	15.2	8,000	8	15	1.7	24
$Nd_{2-x}Ce_xCu_2O_{4+\delta}$	6.0	1,000	21	4×10^2	16	25
$Tl_2Ba_2CuO_{6+\delta}$	11.6	2,000	80	2×10^2	2	26, 27
	11.6	1,800	55	2×10^2	3.6	26, 27
$Bi_2Sr_2CaCu_2O_8$	7.5	1,850	84	140	1.5	28, 29
$Bi_2Pb_xSr_2Ca_2Cu_3O_{10}$	5.9	1,850	105	110	0.9	28
	8.9	1,850	105	160	1.4	28
$La_{2-x}Sr_xCuO_{4+\delta}$	6.6	3,700	28	30	1	30
	6.6	2,200	38	85	2	30
$YBa_2Cu_3O_{7-\delta}$	5.9	1,600	92	145	1.4	31
$YBa_2Cu_4O_8$	6.8	2,600	80	65	0.7	31

$$V_0 = \frac{(\hbar c)^2 a}{16\pi e^2 \lambda^2(0)}$$

$$T_\theta^{max} \simeq V_0$$

Emery Kivelson 95



Uemura's plot

C. Holmes et al, 2004

Amplitude Fluctuations ····➤

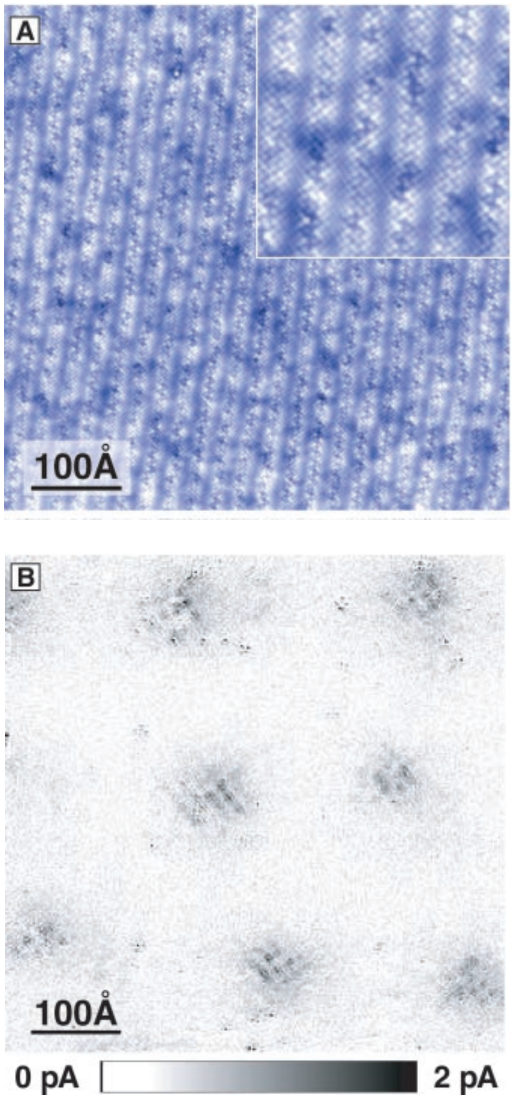
Phase fluctuations ····➤

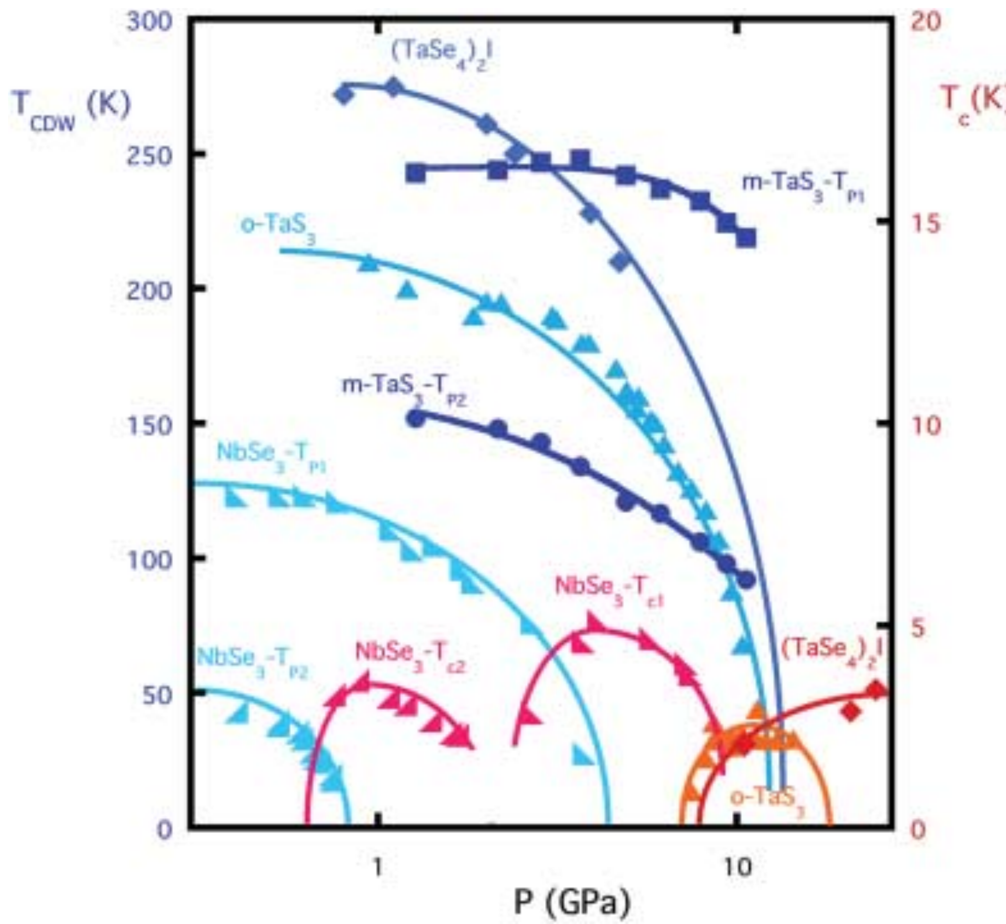
Condensate ····➤

Presence of competing orders

Charge modulations in strong competition with SC state

Hoffman, 2002 Kapitulnik, 2002





Charge order Landscape

Nematicity

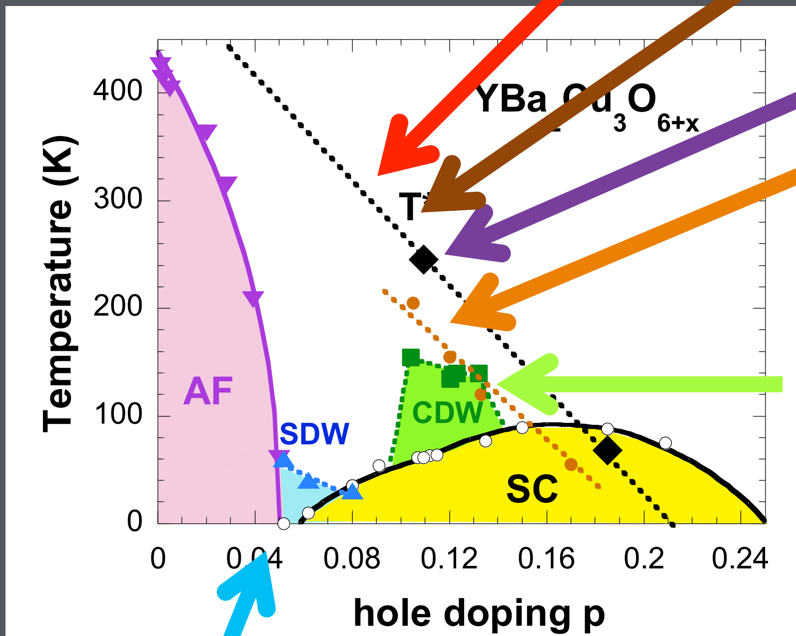
Inversion symmetry

loop currents

anomalous Kerr effect $T_k < T^*$

Xia, PRL 2008

$YBa_2Cu_3O_{6+x}$



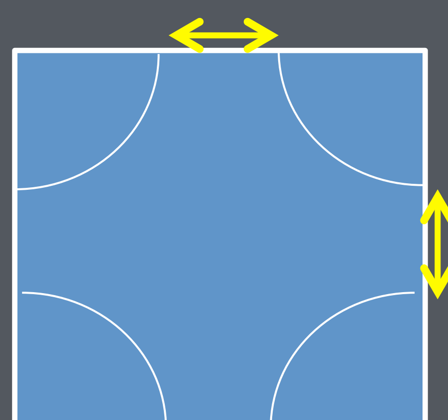
Incipient CDW – $T_m < T^*$

- *$Q^* = (\delta,0)$ 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



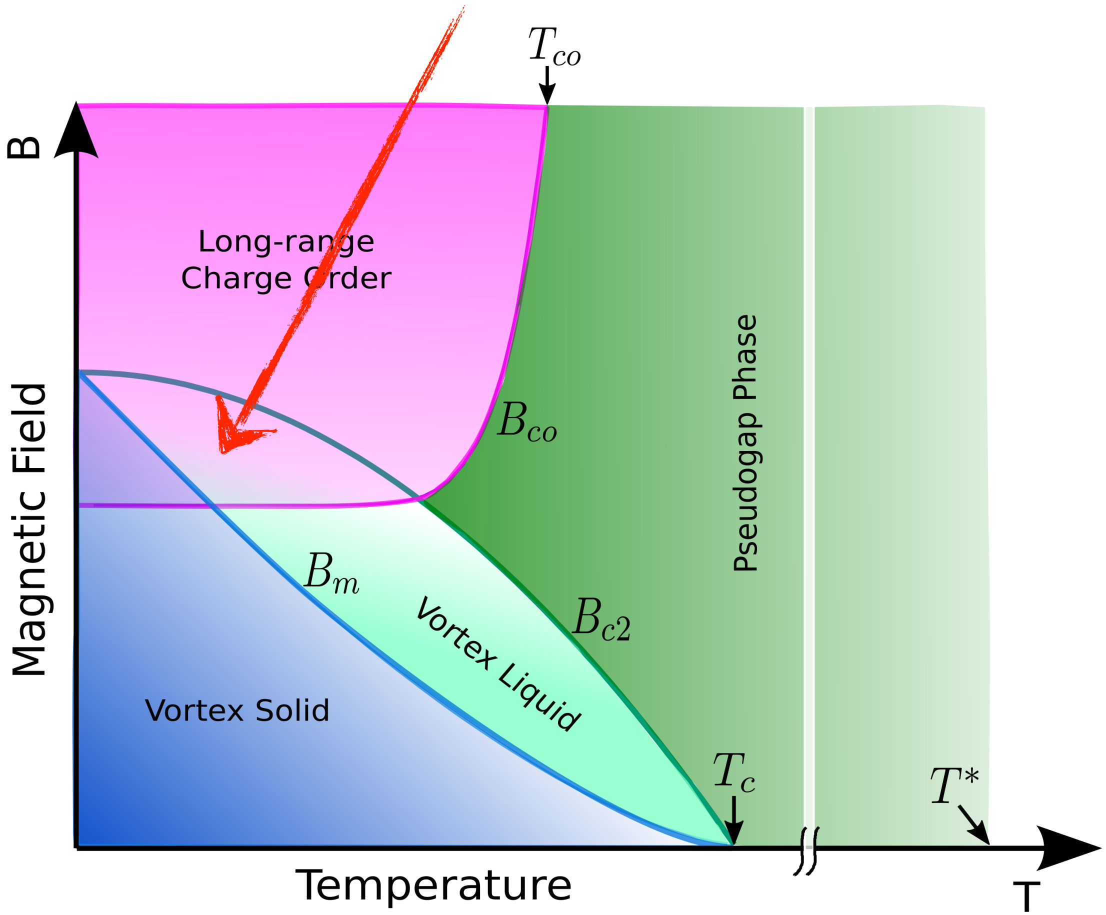
Stable CDW under magnetic field & Fermi surface reconstruction (NMR, quantum oscillation, ultrasound)

D. LeBoeuf, *Nature* 2007.
T. Wu et al., *Nature* 2011.
D. LeBoeuf et al., *Nature Physics* 2

Quest for PDW in the phase diagram : is it observed, or maybe not ?

s-wave PDW or supersolid phase modulations
at 4 lattice sites

Coherent with STM (Hamidian et al. 2016)

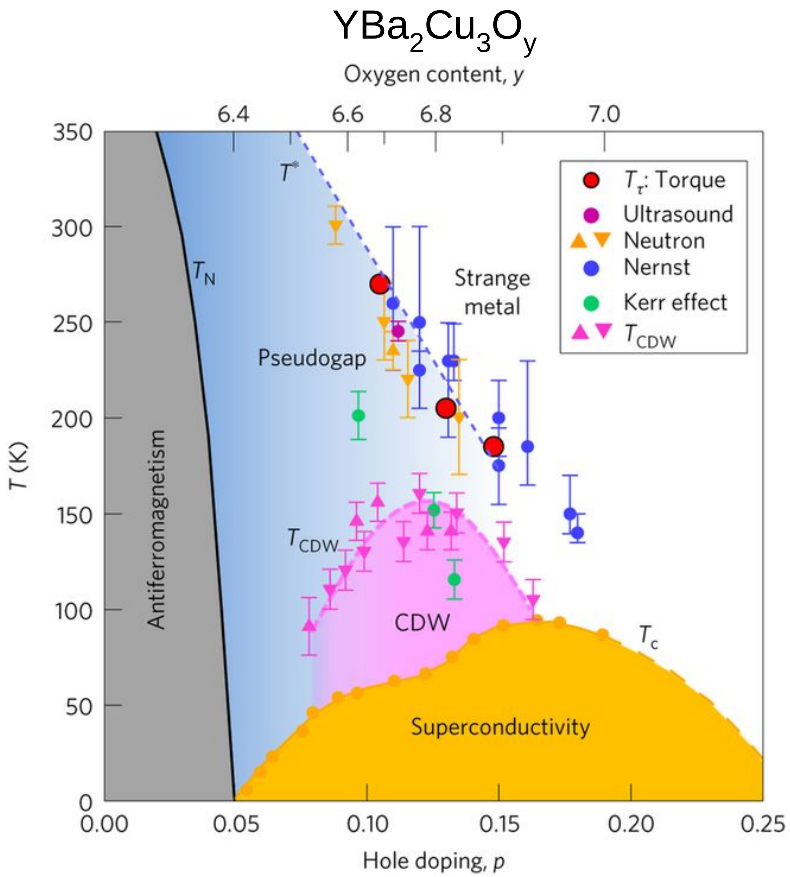


Field induced results
Show d-wave PDW
modulated
At 8 lattice spacings
Cf PA Lee's theory
(Edkins 2018)

So far X-ray didnt see
anything

Fractionalization of a PDW

The phase diagram



Slave-boson method :

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

Charge (holon) | Spin (spinon)

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

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

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 : $\begin{cases} \Delta_{ij} \to e^{i\theta}\Delta_{ij} \\ \chi_{ij} \to e^{i\theta}\chi_{ij} \end{cases}$

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

The phase diagram

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

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

$T = T^*$

θ gets to fluctuate

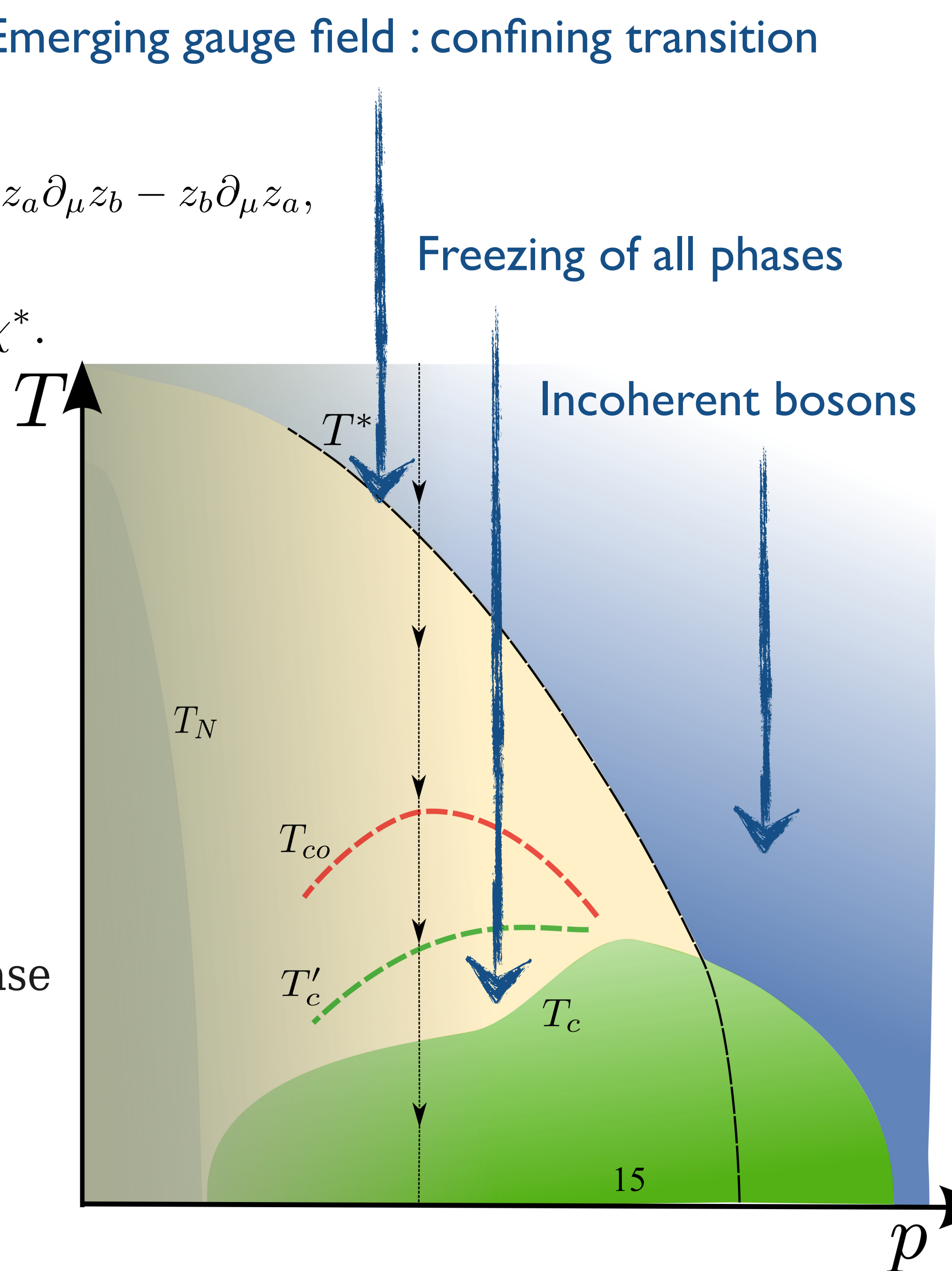
We obtain the constraint

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

$T = T_c$

ϕ gets frozen and we have global phase coherence.

Meissner effect.

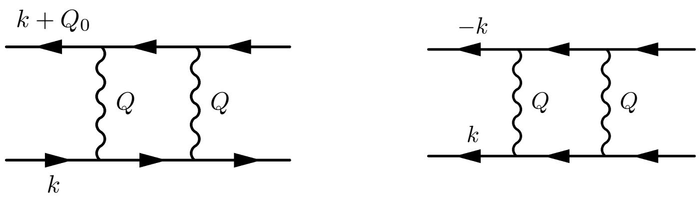


Why the system would want to do this ?

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

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

a) b)



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

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

<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

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

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

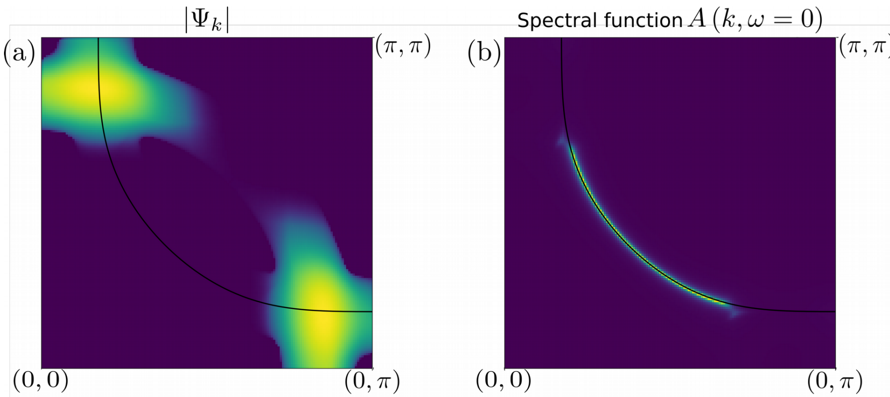
$$E_{CDW} = \frac{1}{2J_+} |\chi_{k=k_F}|^2 = 0.011\, eV.$$

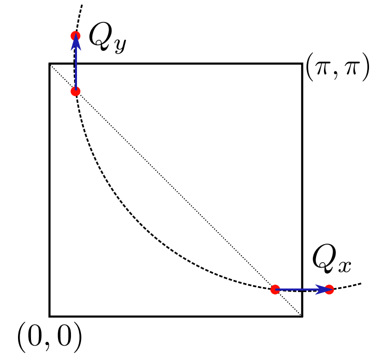
<u>Energy scales :</u>

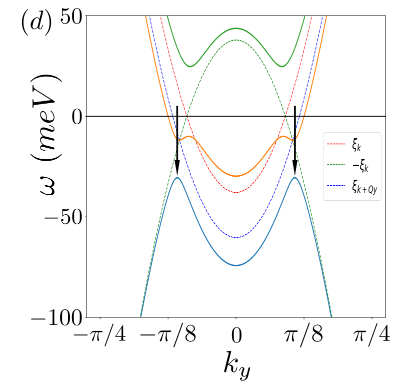
$$\Delta_k \sim 3J - V$$

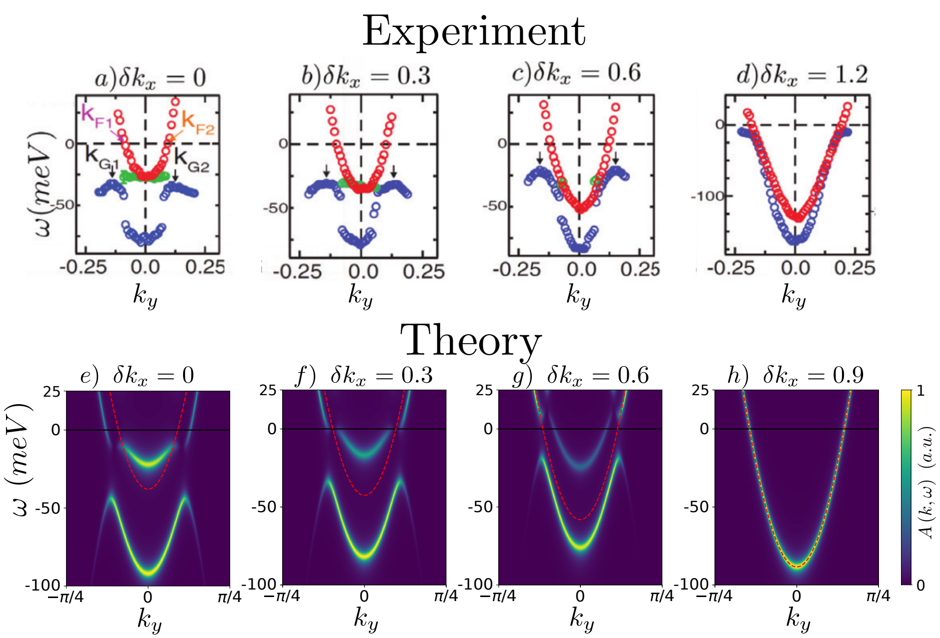
$$\chi^{Q}_{k} \sim 3J + V$$

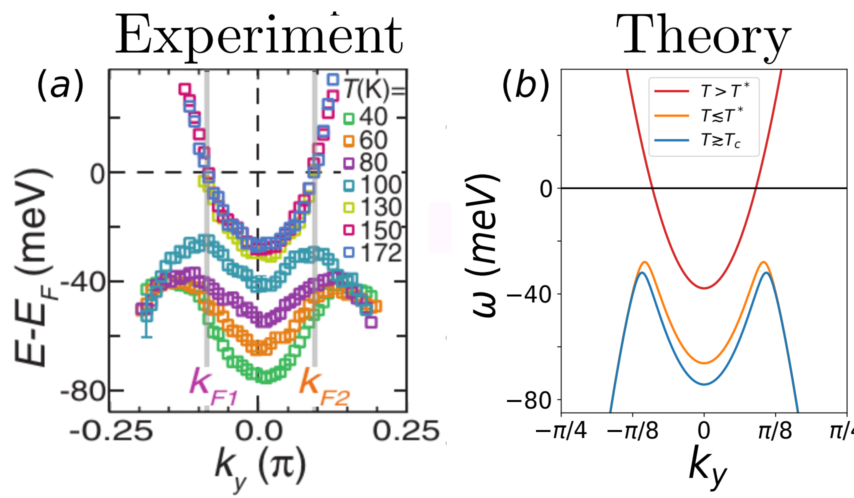
Opening a gap in the Fermi surface









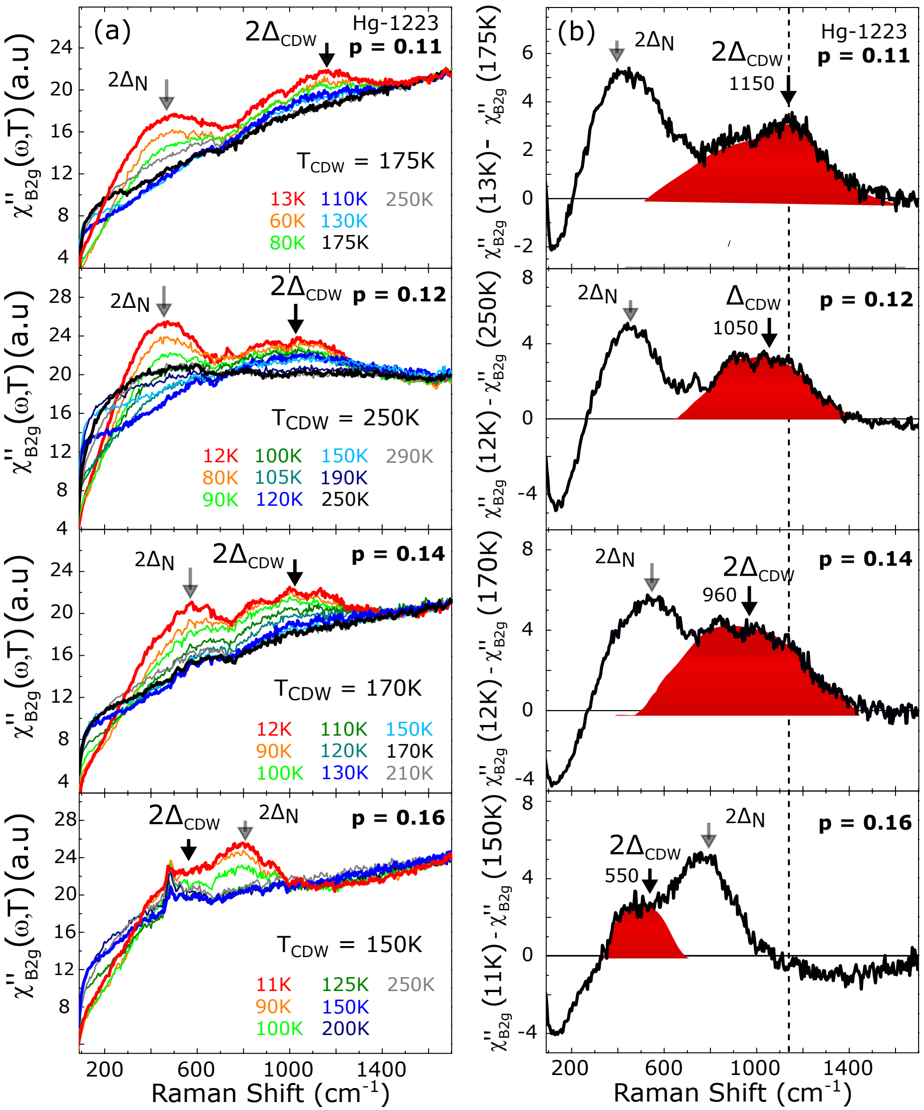


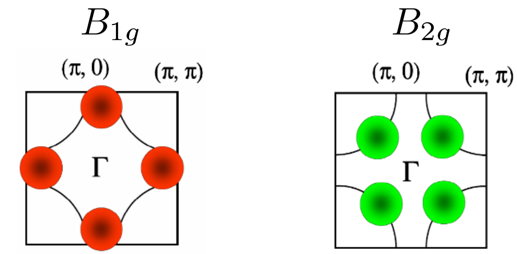
M. Grandadam et al. PRB (2020)

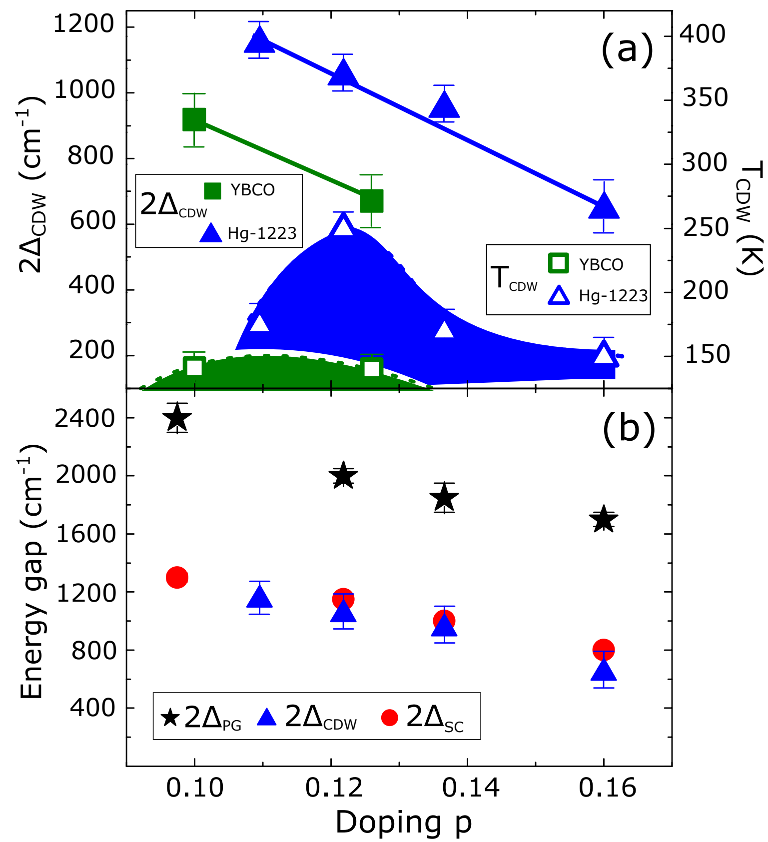
ARPES, Bi2201

Raman Scattering   B2g, T < Tco

Loret et al. Nat. Physics (2019)



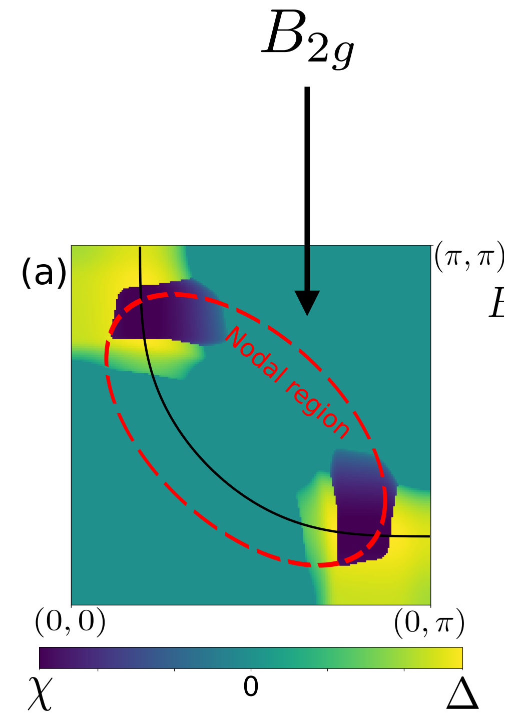


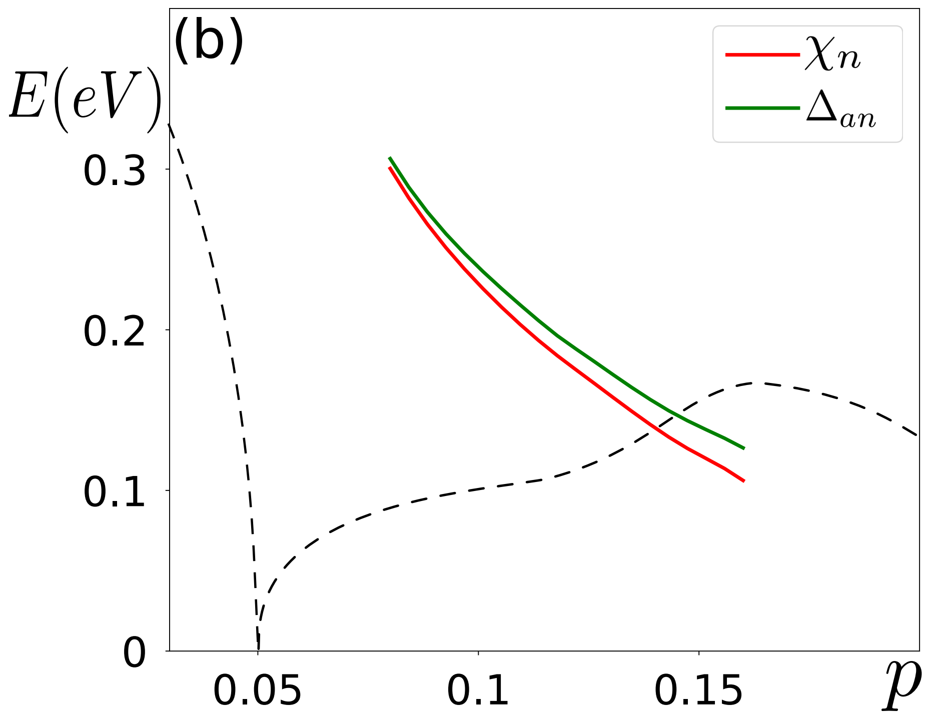


Solving gap equations

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

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





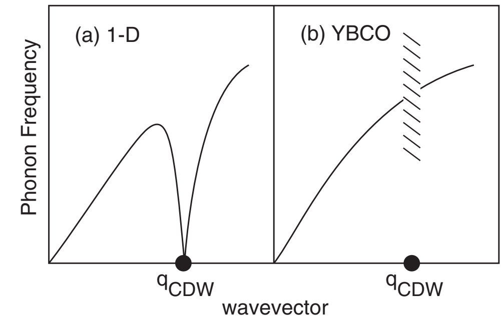
Same order of magnitude for

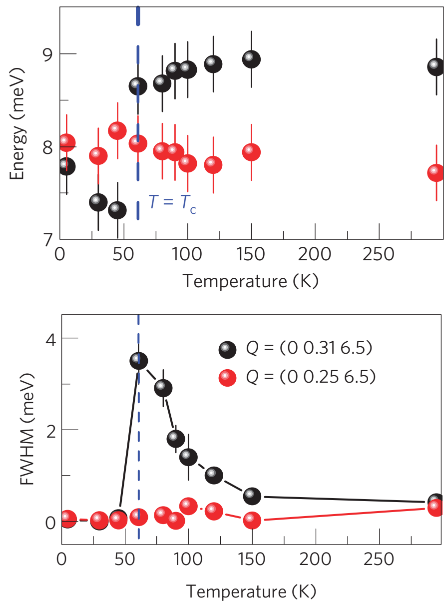
Δ and χ

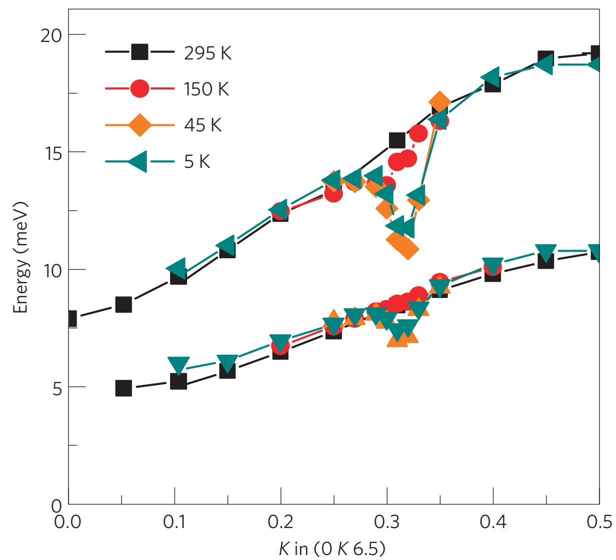
M. Grandadam et al. PRB (2019)

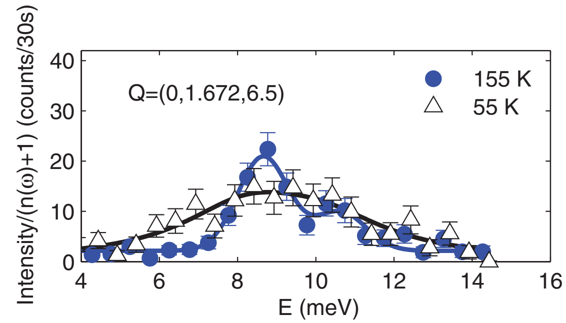
Anomalous softening of phonons

Blackburn, 2013

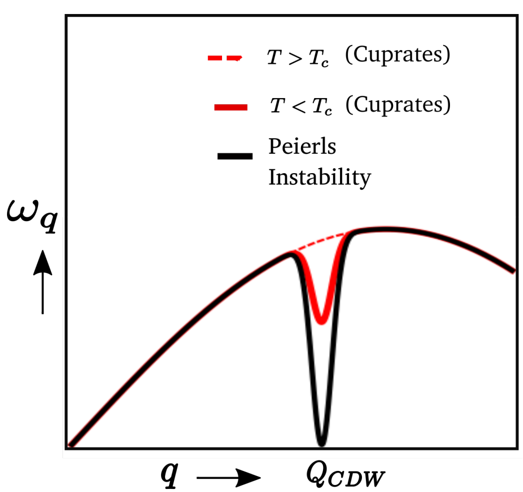






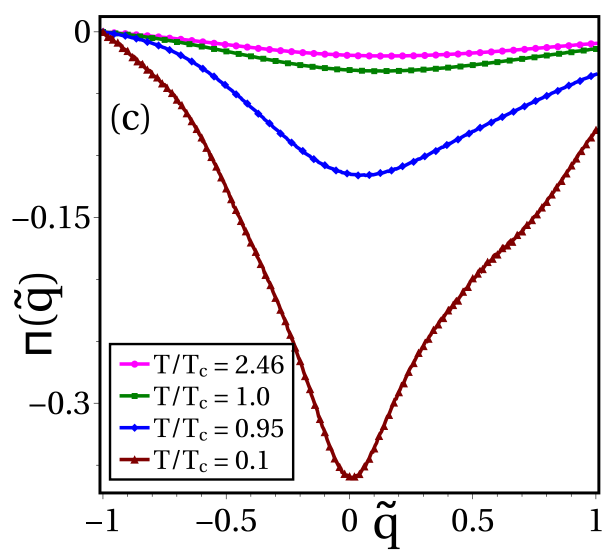


Le Tacon, 2013



S. Sarkar et al. (2020)

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

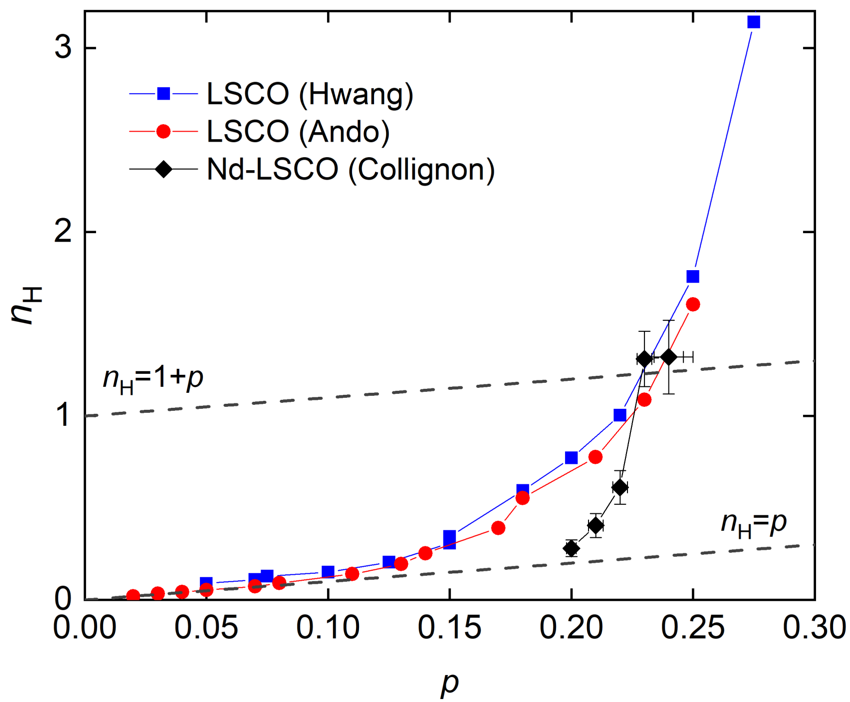


Transport in the Strange Metal

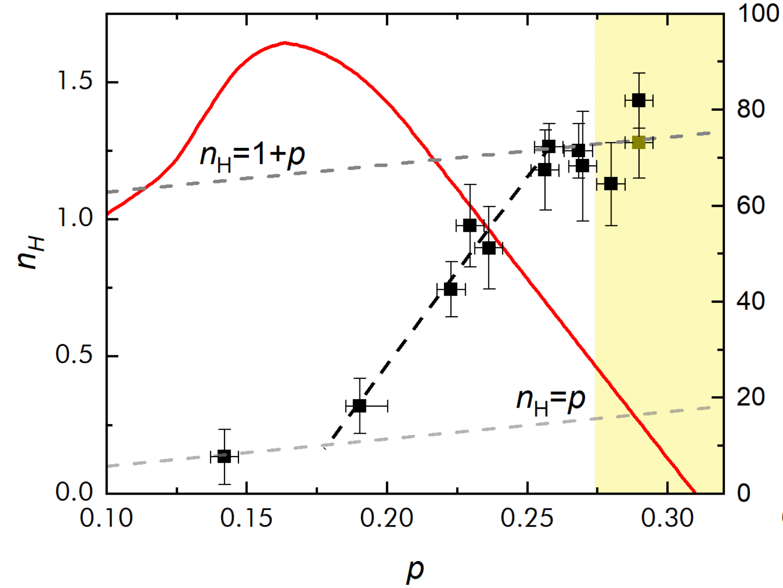
Recent controversy

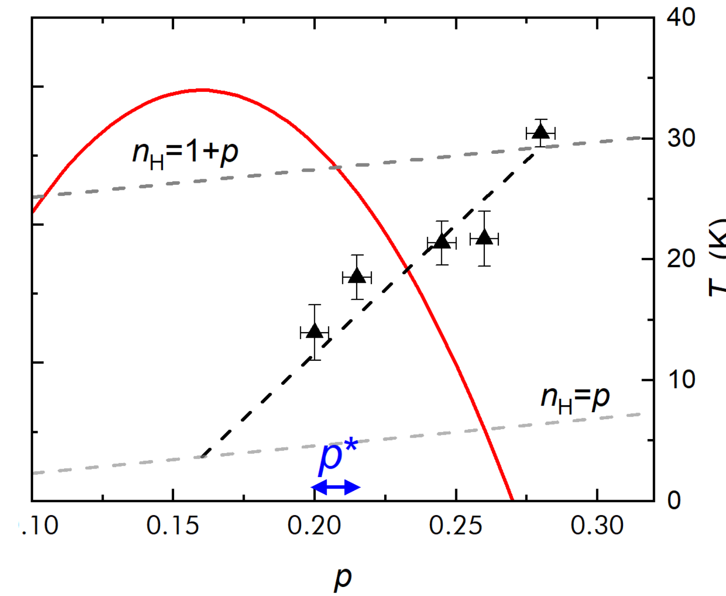
Spectral weight missing in the Strange Metal regime ?

Another type of carrier ?



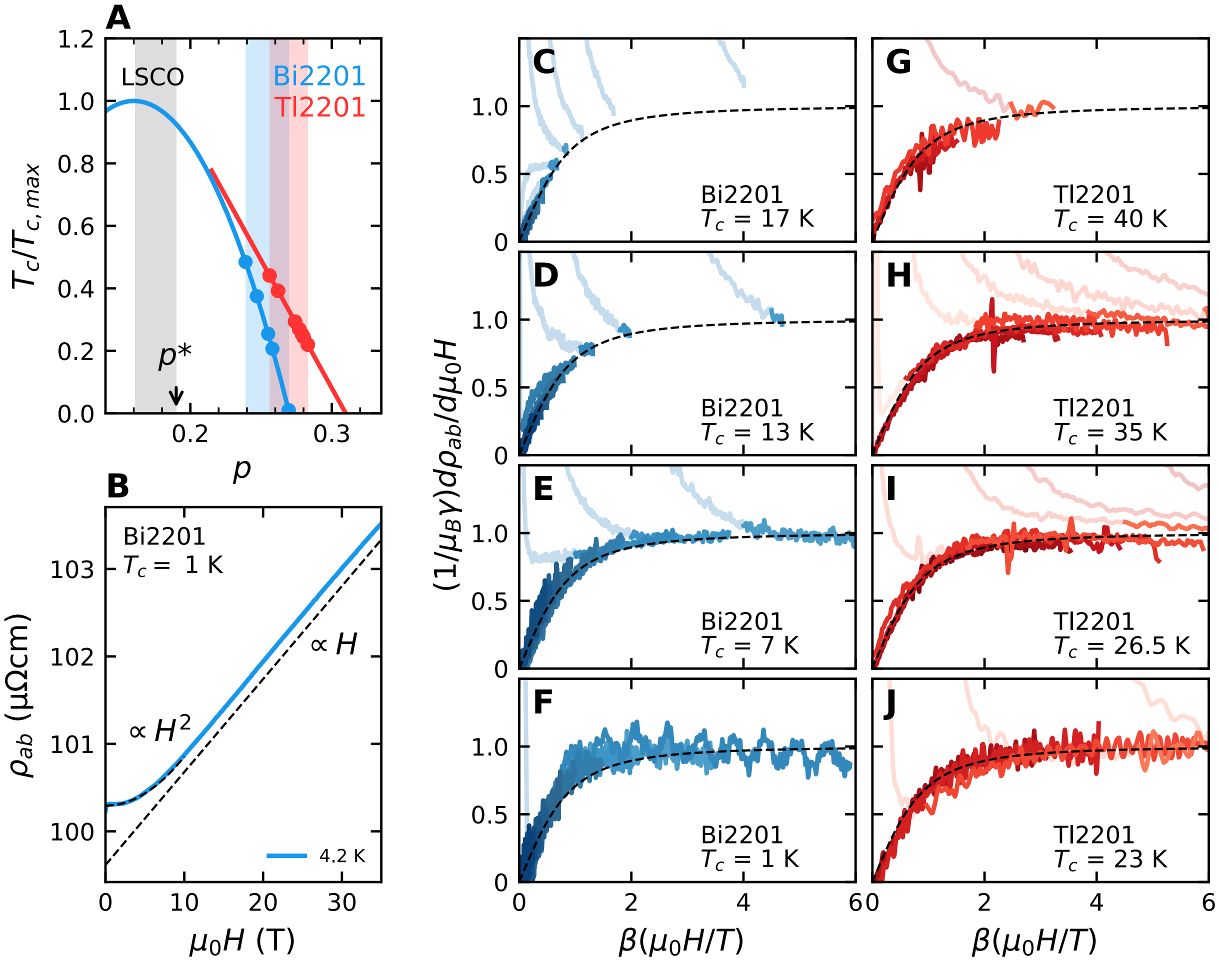
Prutzke et al. 2019





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*

$$\sigma_{xy} = 0$$

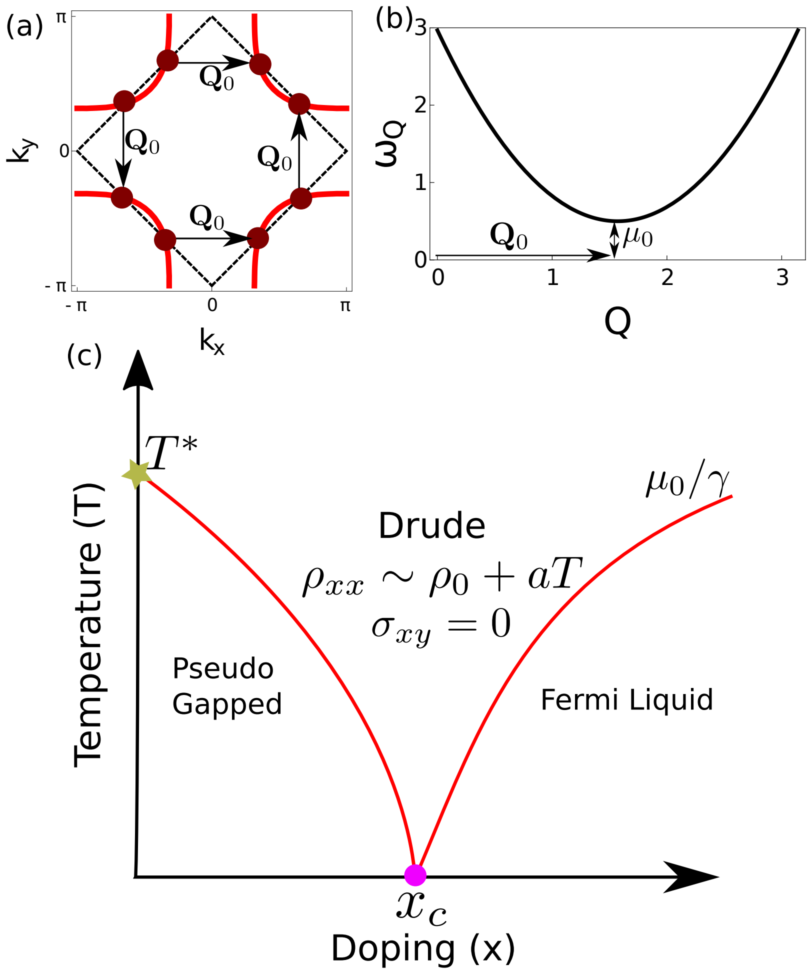
- *Planckian limit*

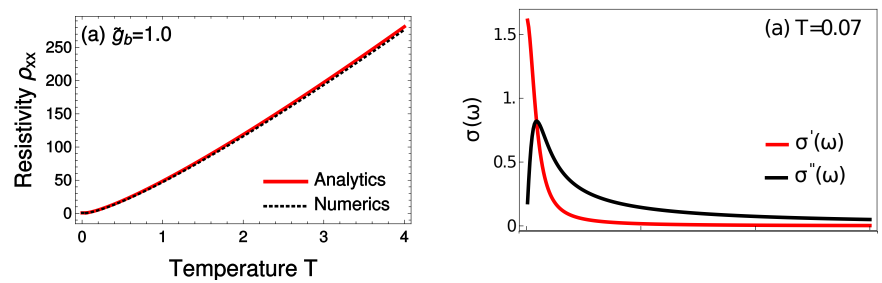
Ayres et al., preprint 2020, courtesy N.Hussey

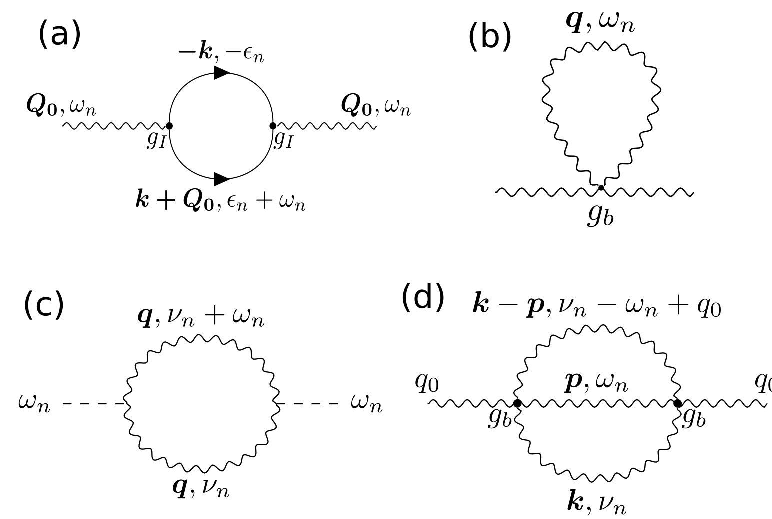
Our proposal : Charged bosons in the Strange Metal phase

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

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







A. Banerjee et al. (2020)

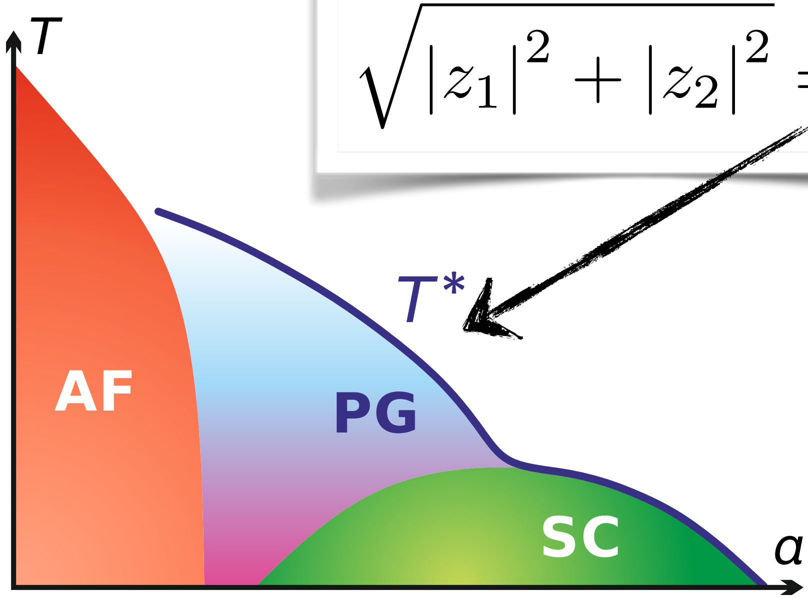
Analogy with SU(2) emergent symmetry

Eight hot spots, attractive Hubbard model at 1/2 filling… and beyond ?

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

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

$$\psi \to e^{i\theta} \psi,$$



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

SU(2) chiral model protected by a Pseudo Spin Higgs mechanism !

Conclusions

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

- For the first time observation of a precursor in the charge channel (as well as in the SC channel), which follow T*, not Tc or Tco

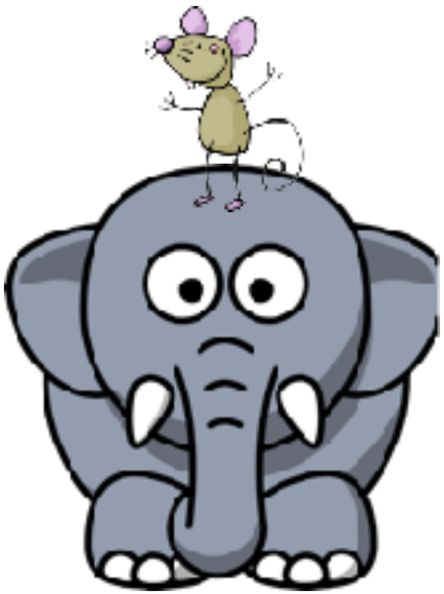
- New idea of fractionalizing a PDW or a more complex boson

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

- Explains recent Raman and phase coherence in STM

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

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



Discussions of the data and a few Refs

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

Alain Sacuto, Henri Alloul, Nigel Hussey

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

Saheli Sarkar, Maxence Grandadam, Catherine Pépin arXiv:2009.02975

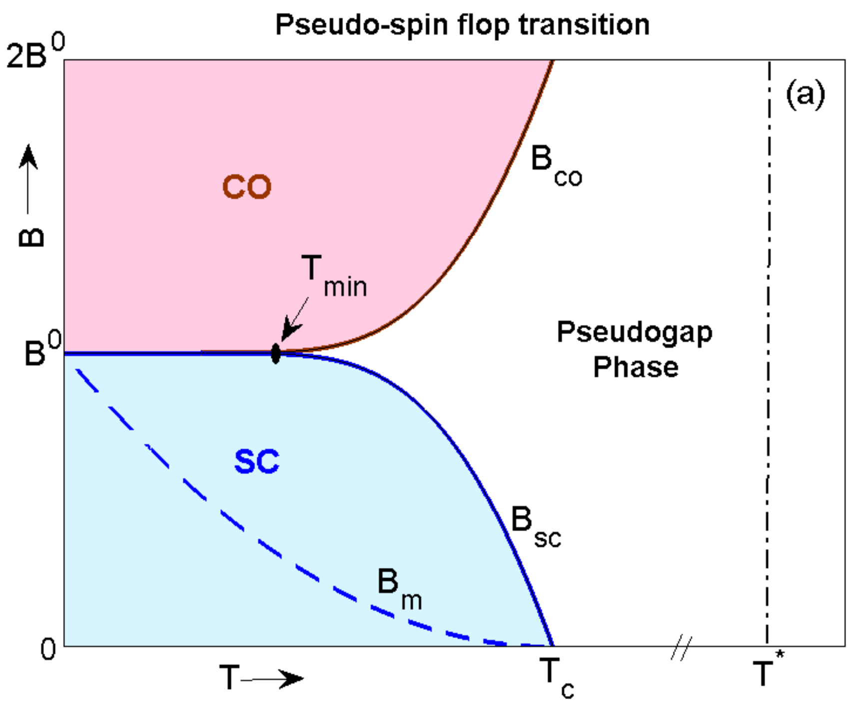
Maxence Grandadam, Debmalya Chakraborty, Xavier Montiel, Catherine Pépin arXiv:2002.12622

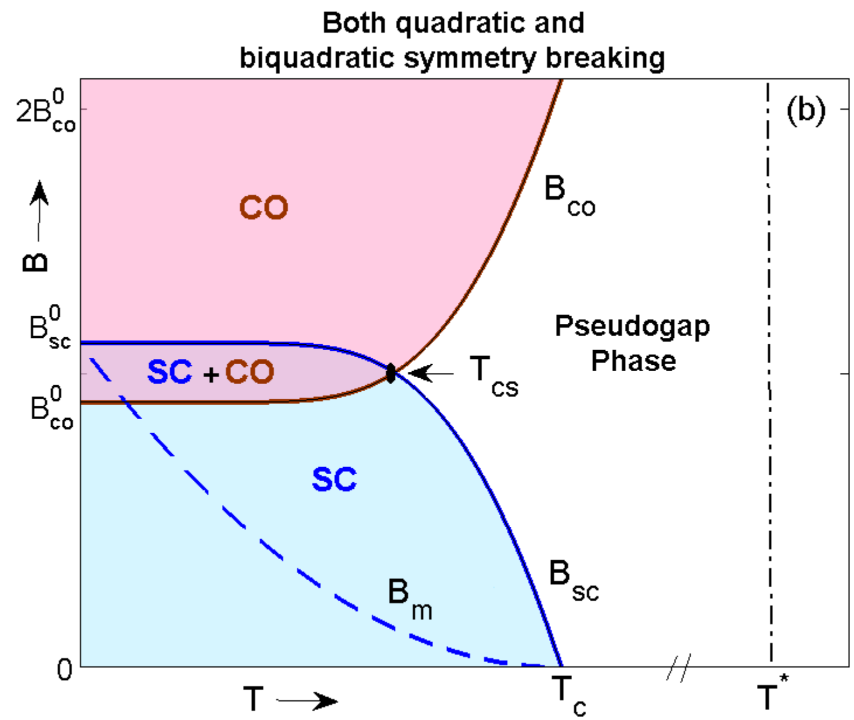
D. Chakraborty, M. Grandadam, M. H. Hamidian, J. C. S. Davis, Y. Sidis, C. Pépin arXiv:1906.01633

Saheli Sarkar, Debmalya Chakraborty, Catherine Pépin arXiv:1906.08280

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

O(3) Non linear Sigma Model



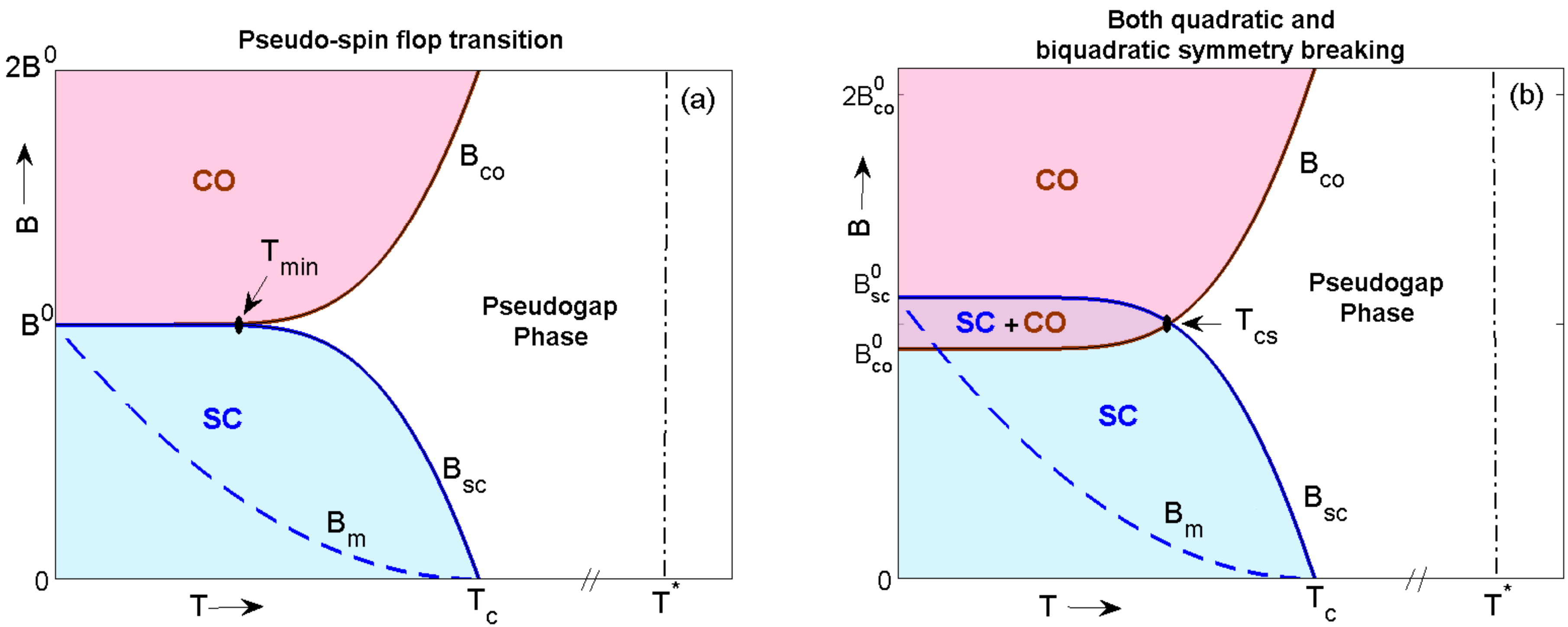


$$\frac{F}{T} = \frac{1}{t_0} \int tr[\nabla u^\dagger \nabla u + \kappa_0 \tau_3 u^\dagger \tau_3 u] dR$$

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

D. Chakraborty et al. PRB (2018)

O(3) Non linear Sigma Model



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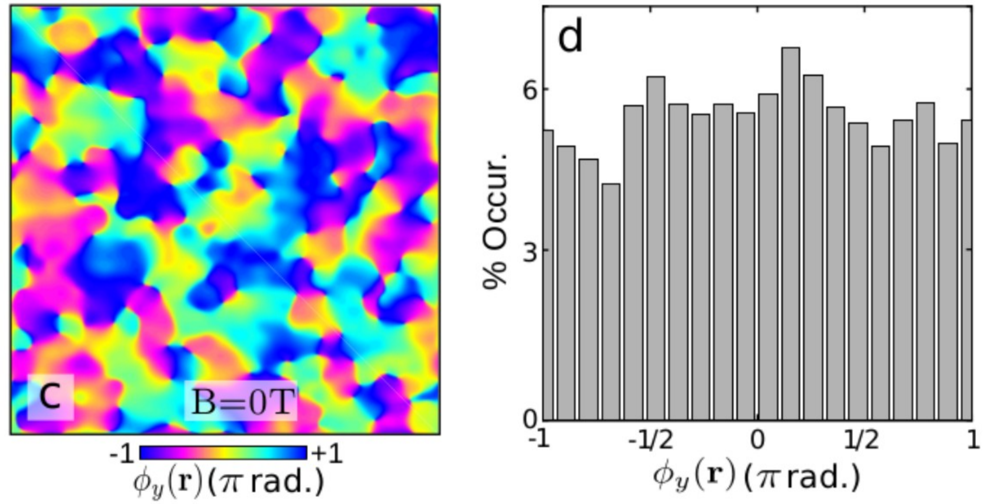
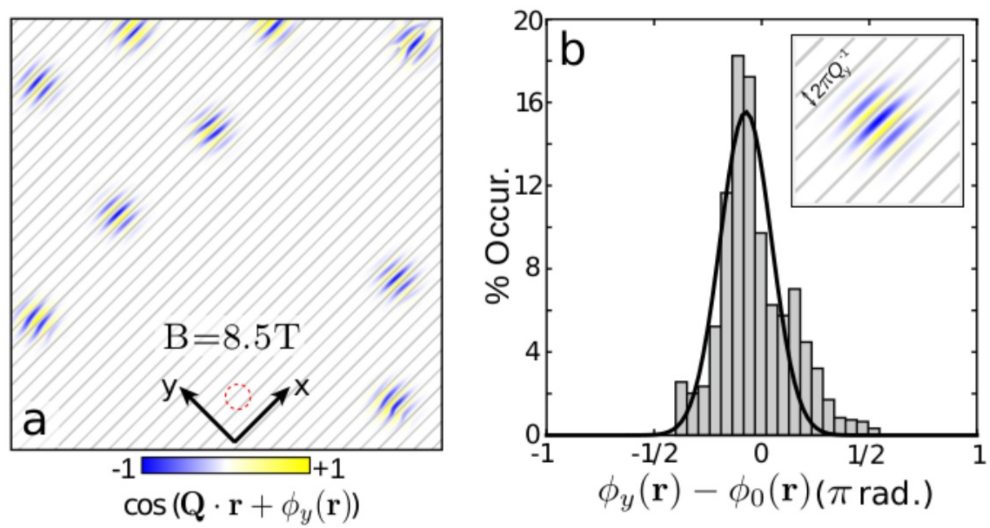
D. Chakraborty et al. PRB (2018)

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 :



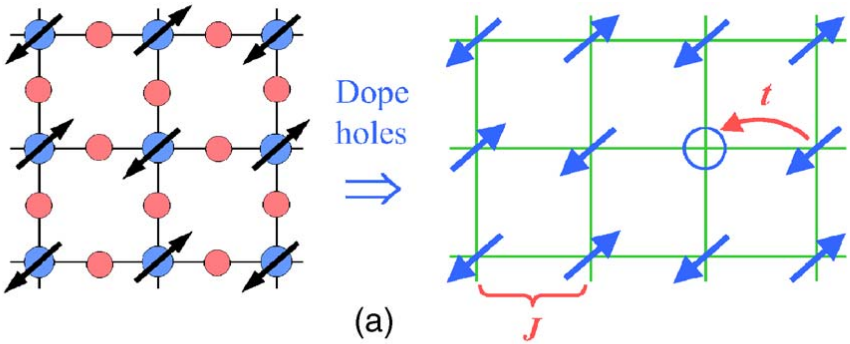
$B \neq 0\ T$ centered distribution :

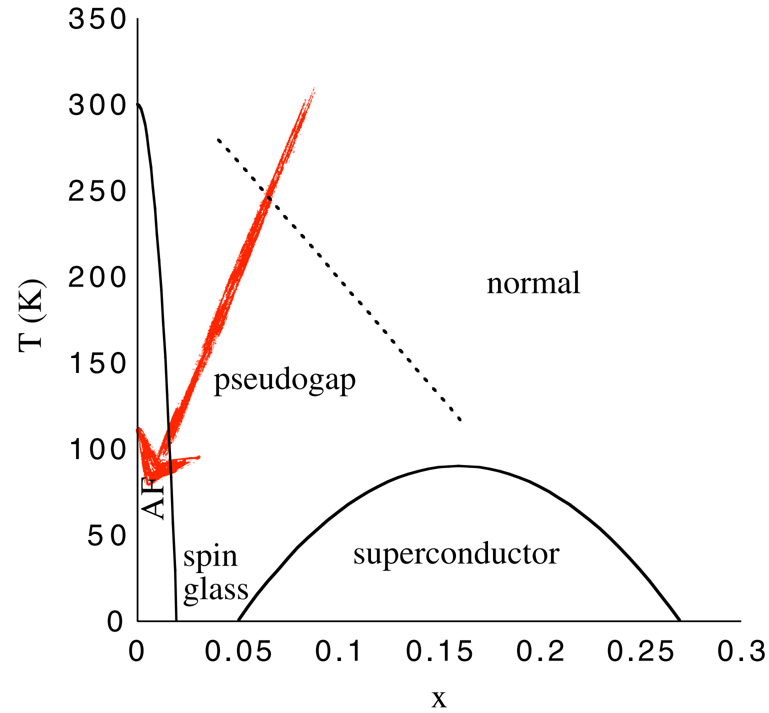


M.H. Hamidian et al., Nat. Phys. **12**, 150 (2015).
M.H. Hamidian et al., arXiv:1508.00620 (2015)

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…

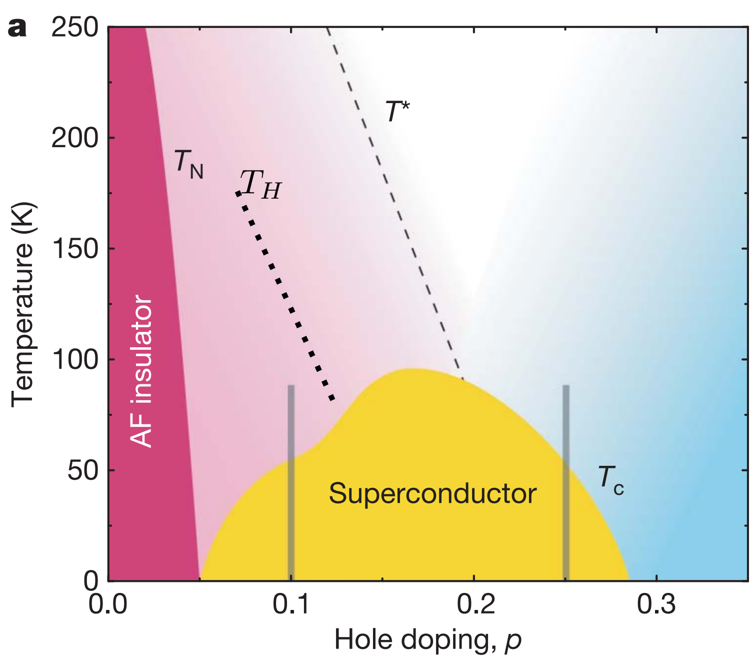
P: projection on no double occupancy

^{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



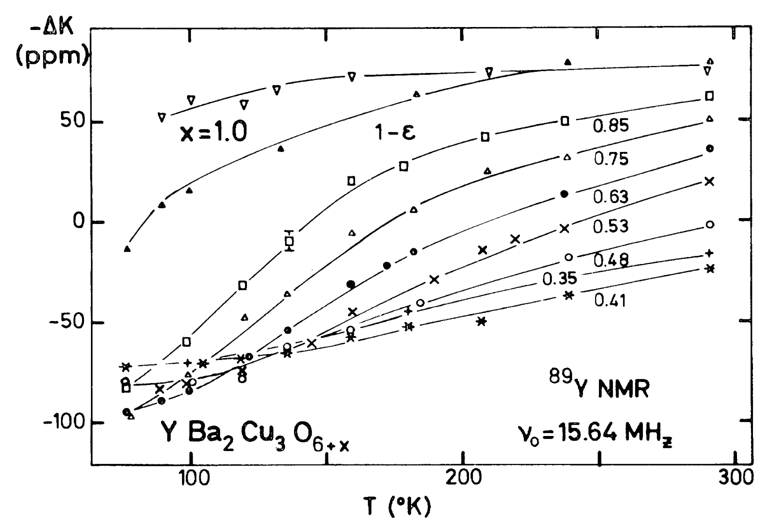
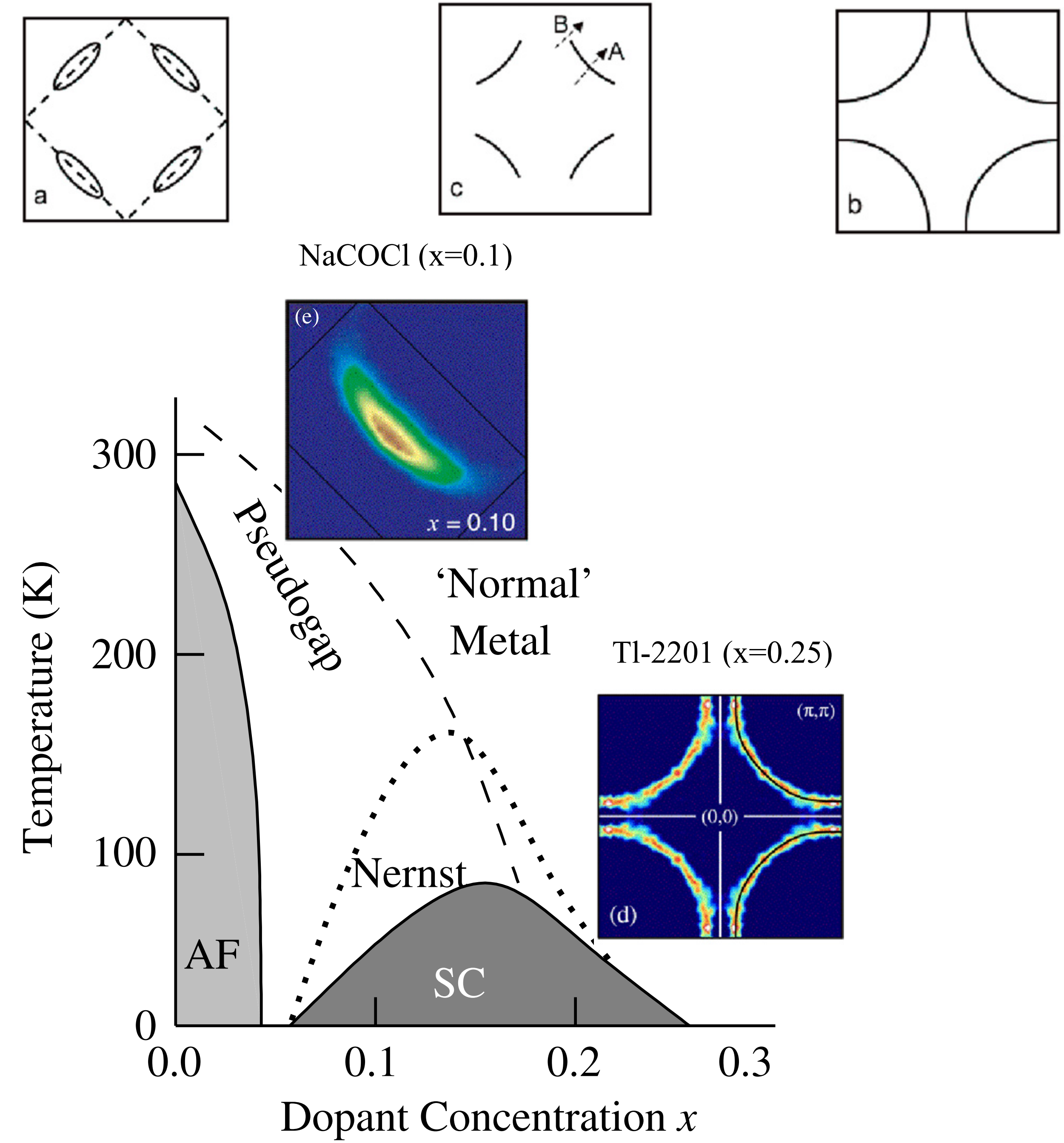


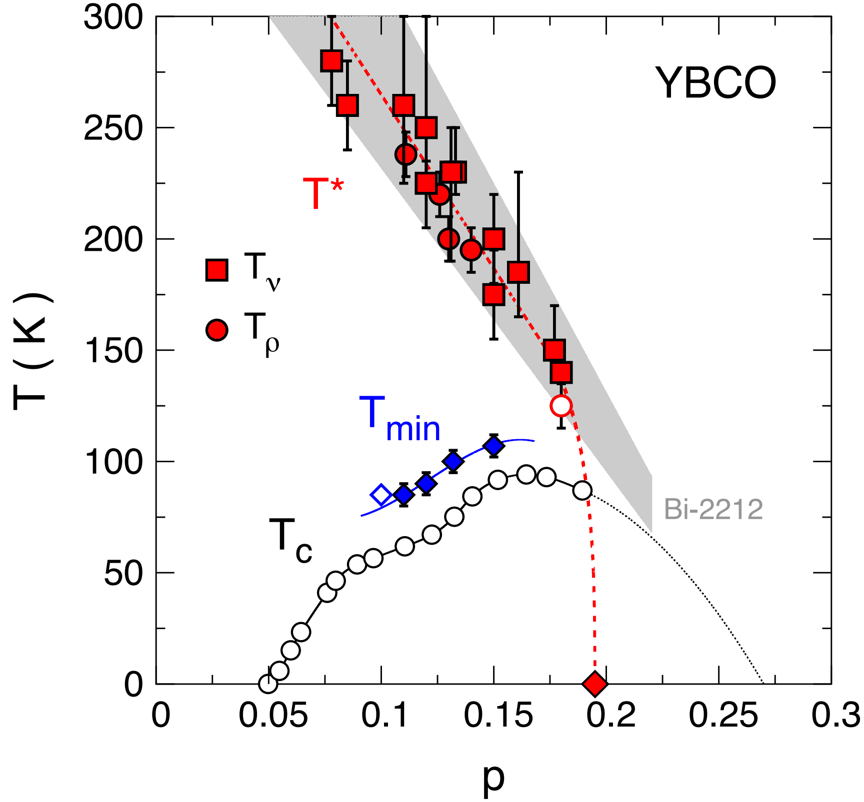
FIG. 1. The shift ΔK of the ^{89}Y line, referenced to YCl_3 plotted vs T, from 77 to 300 K. The lines are guides to the eye.


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

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)