Pseudo-spin skyrmions in the under-doped cuprates

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H. Meier
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X. Montiel

C. Morice & D.Chakraborty

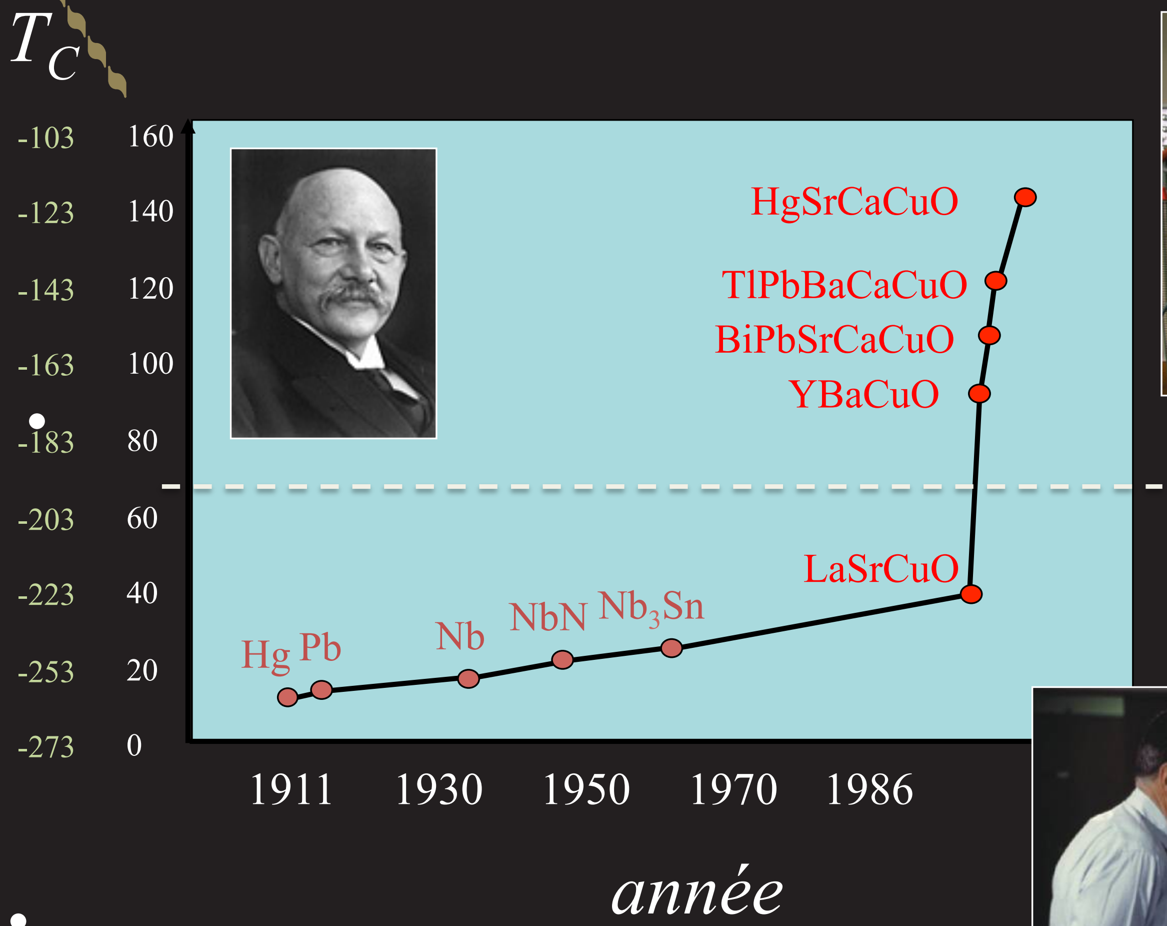
Catherine Pépin

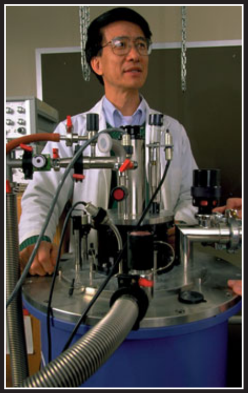
(IPhT, CEA-Saclay)

Intertwined 17,
Santa Barbara, Sept. 12th, 2017

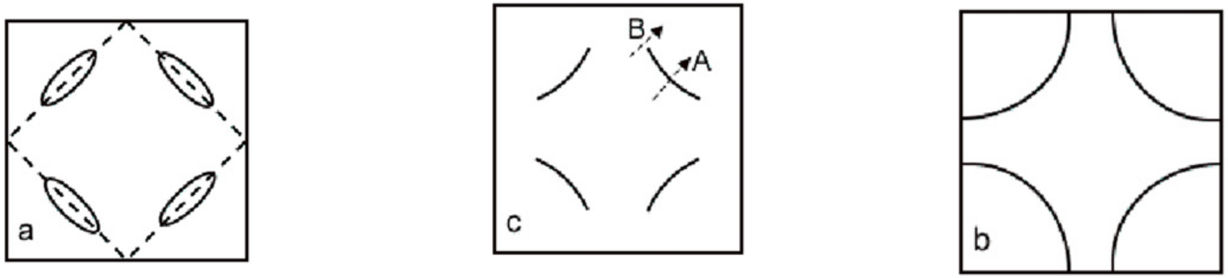
X.Montiel, T. Kloss and CP, PRB 2017

C.Morice, D. Chakraborty, X.Montiel and CP, preprint

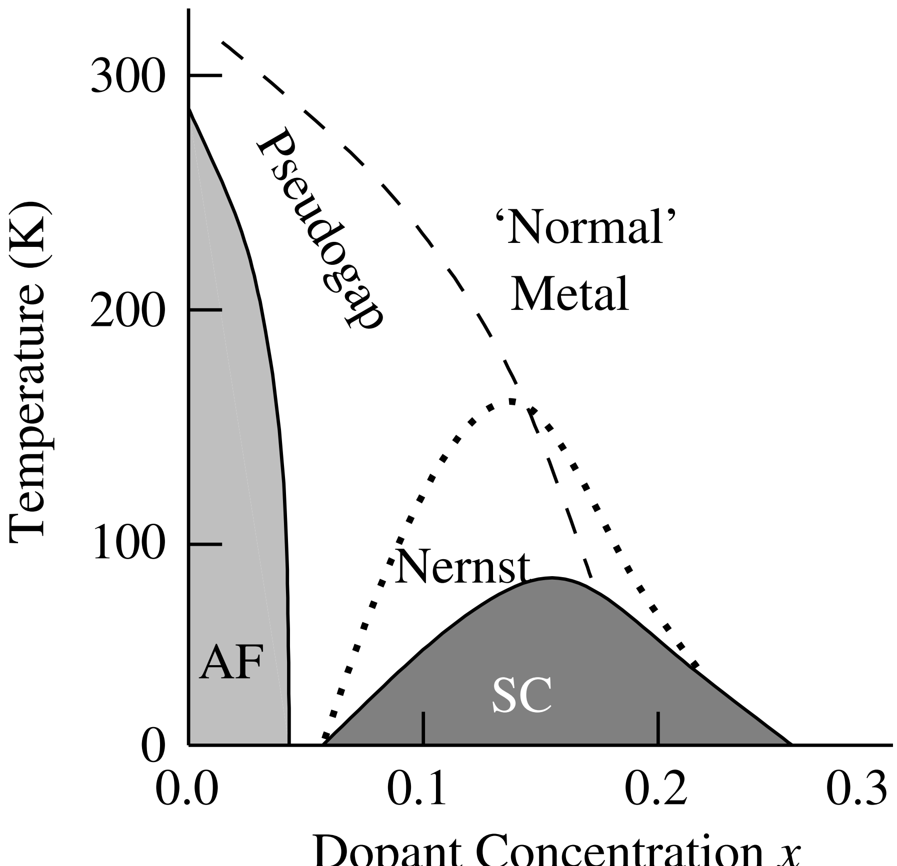

T_C
-103 160
-123 140
-143 120
-163 100
-183 80
-203 60
-223 40
-253 20
-273 0
HgSrCaCuO
TlPbBaCaCuO
BiPbSrCaCuO
YBaCuO
LaSrCuO
Hg Pb
Nb
NbN
Nb_3Sn
1911 1930 1950 1970 1986
année



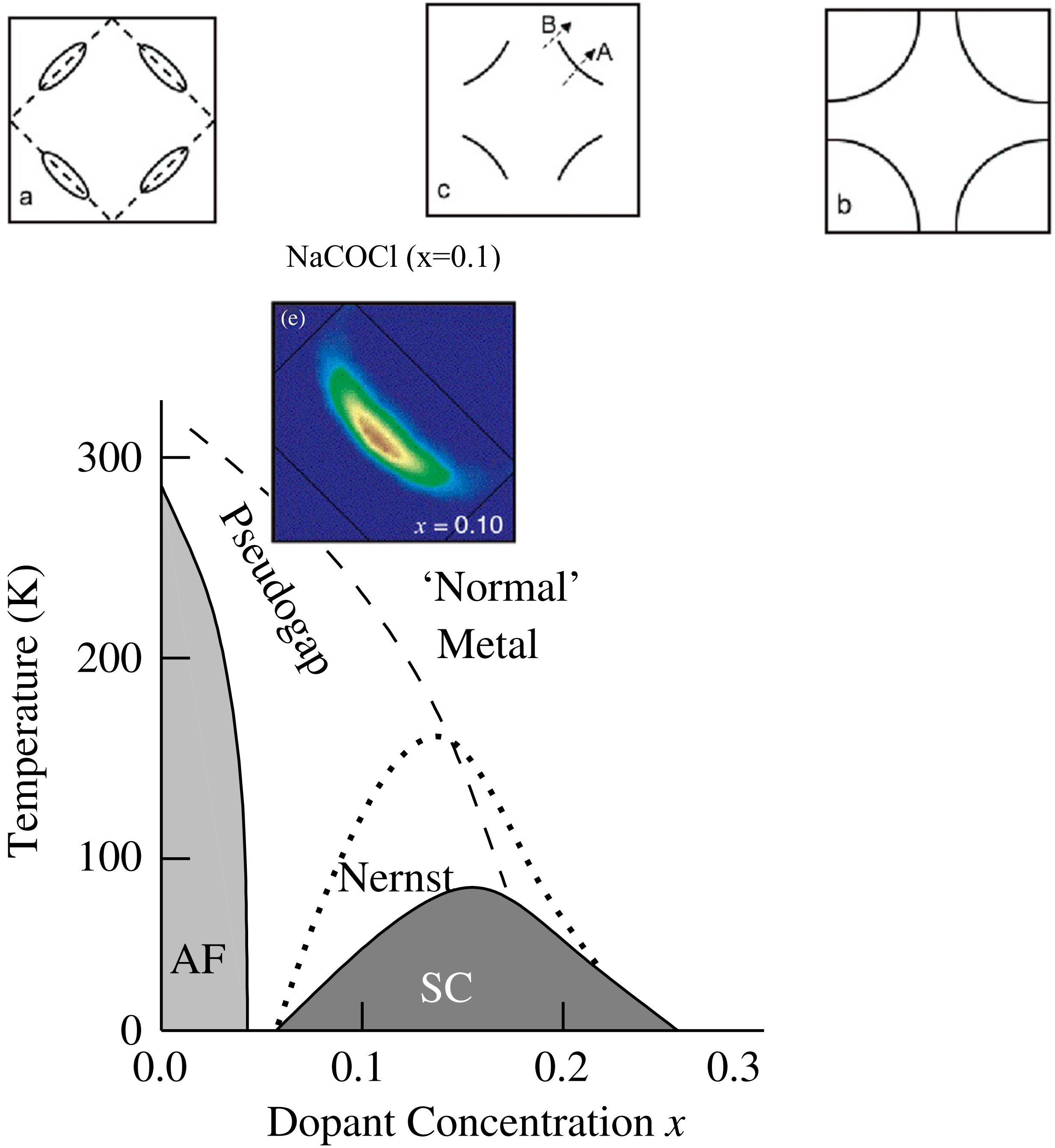
1987…



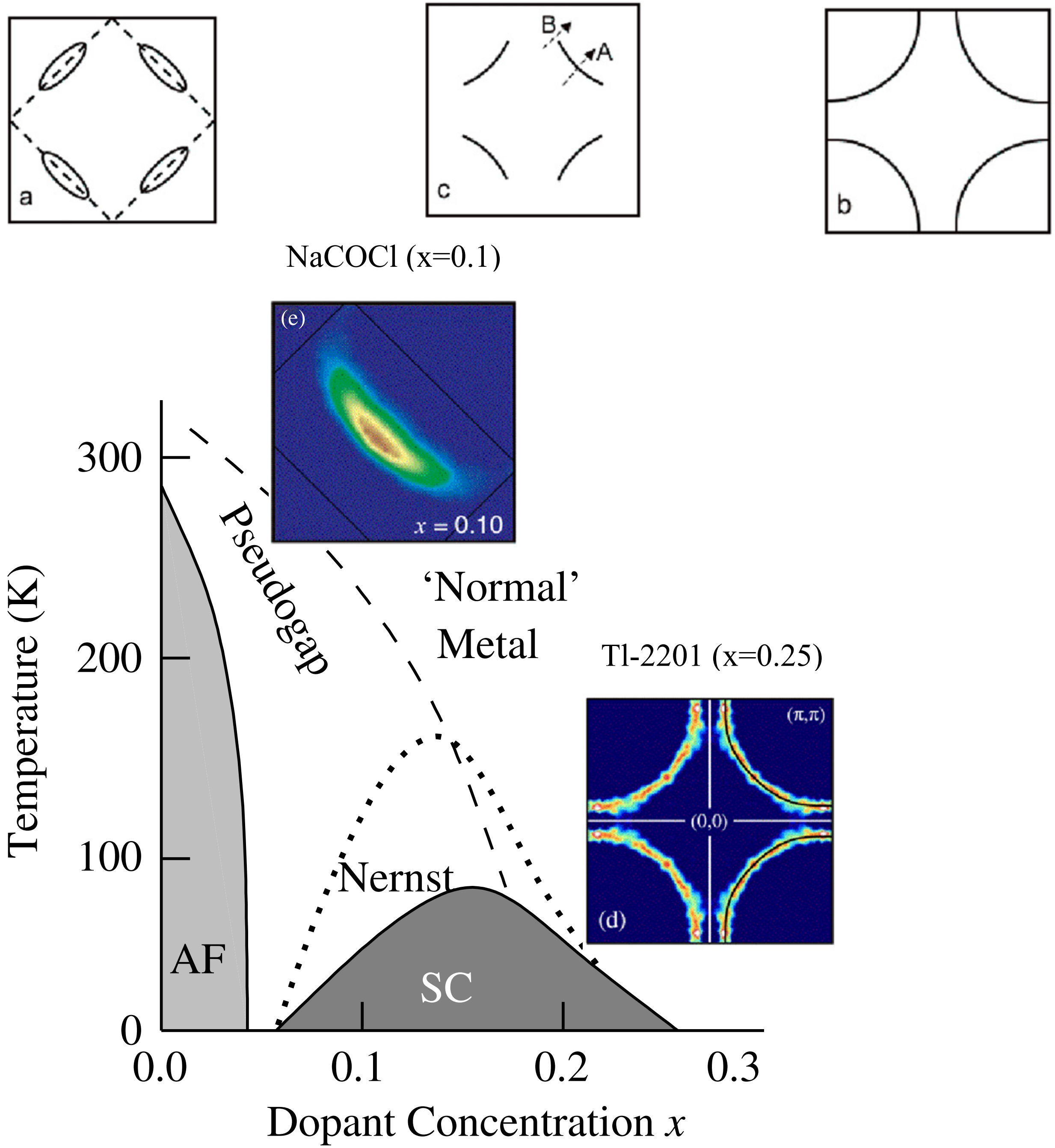
a
B
A
c
b



Temperature (K)
300
200
100
0
Pseudogap
'Normal'
Metal
Nernst
AF
SC
0.0
0.1
0.2
0.3
Dopant Concentration x



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

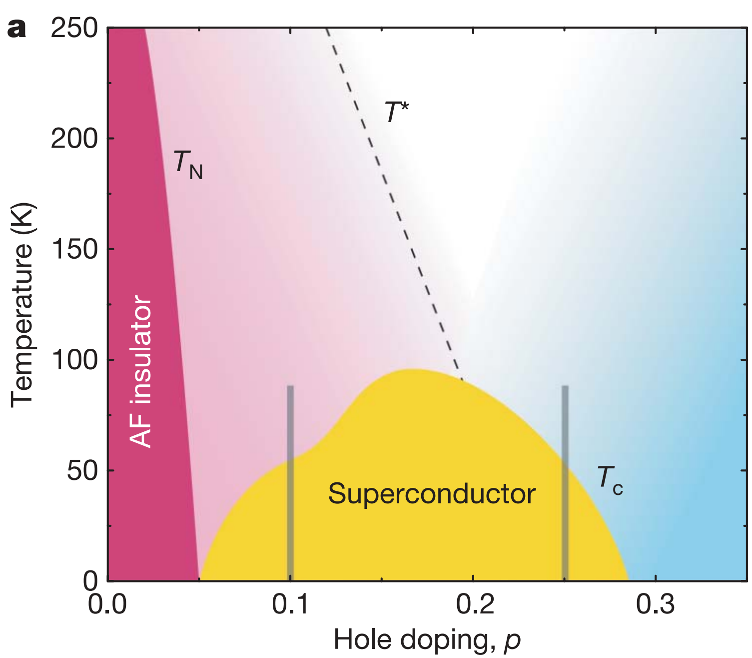

a
B
A
c
b
NaCOCl (x=0.1)
(e)
x = 0.10
300
200
100
0
Temperature (K)
Pseudogap
'Normal'
Metal
Tl-2201 (x=0.25)
(π,π)
(0,0)
(d)
Nernst
AF
SC
0.0
0.1
0.2
0.3
Dopant Concentration x

^{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



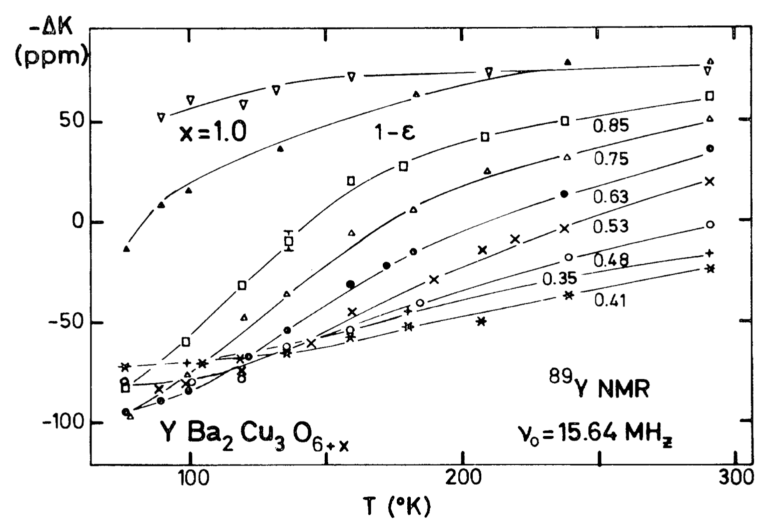


FIG. 1. The shift ΔK of the ^{89}Y line, referenced to YCl_3 plotted vs T, from 77 to 300 K. The lines are guides to the eye.

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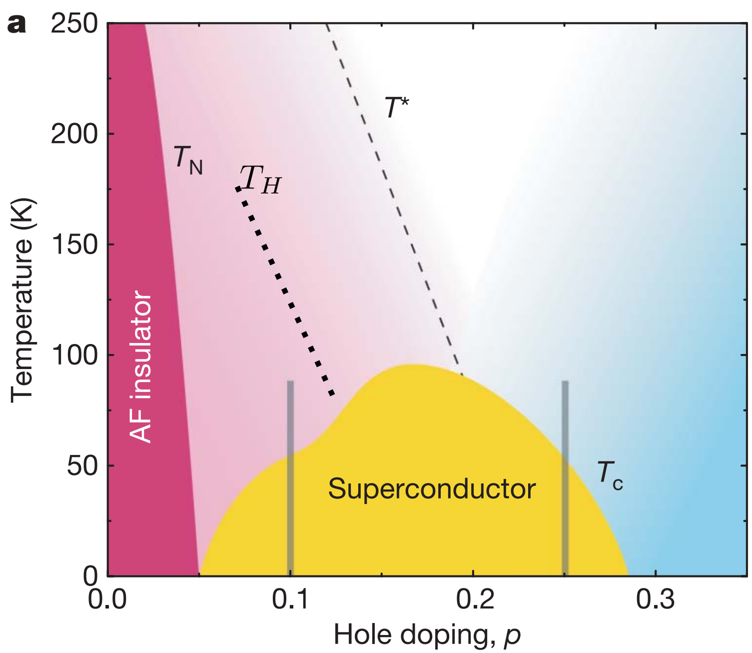

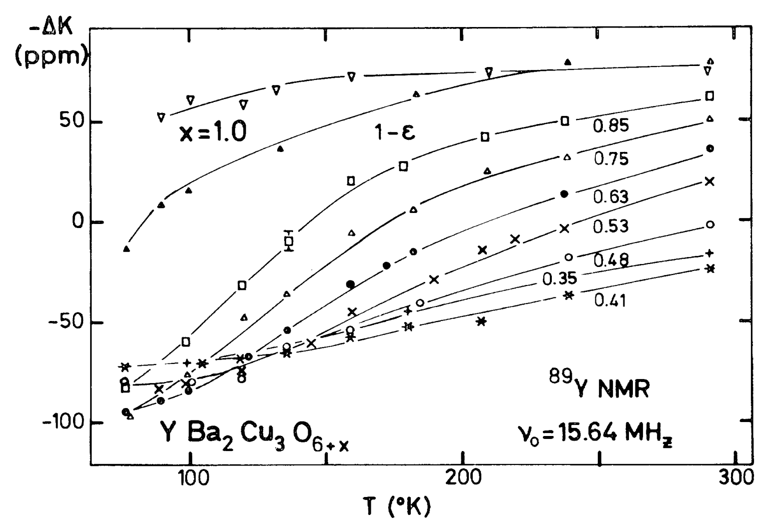

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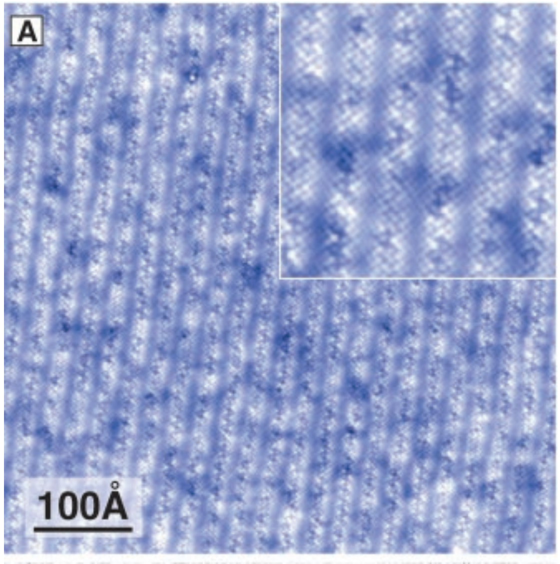
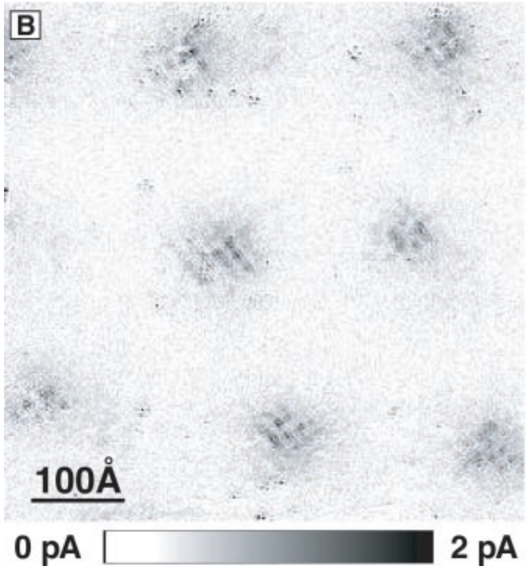
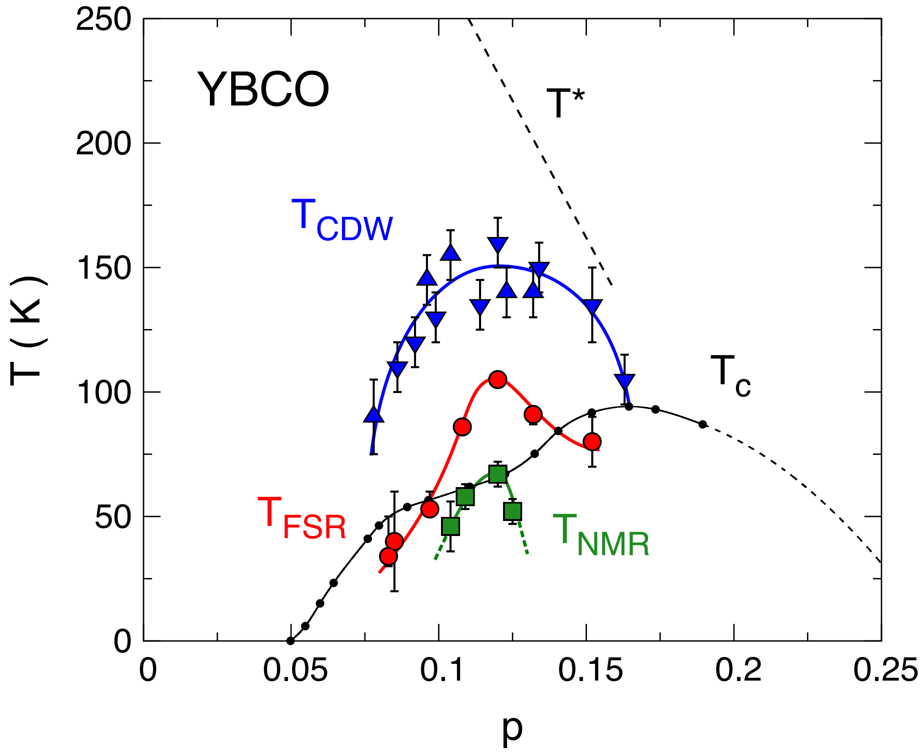
Charge modulations …



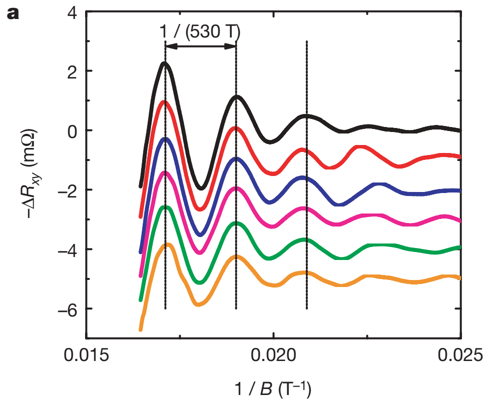


Hoffman, 2002

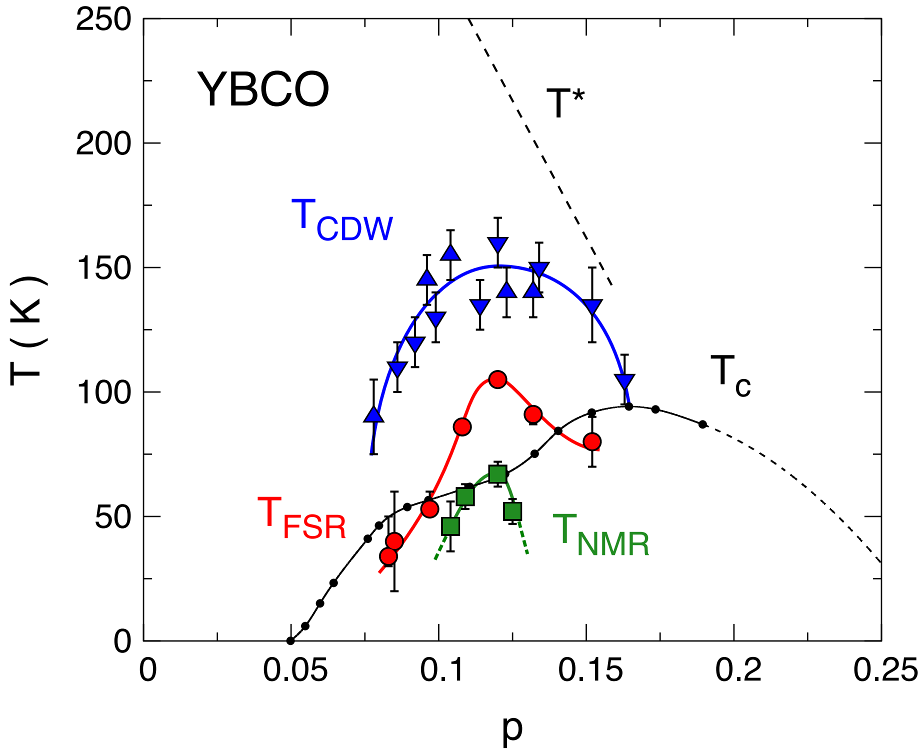
Cyr-Choignière, preprint 2015



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



Cyr-Choignière, preprint 2015



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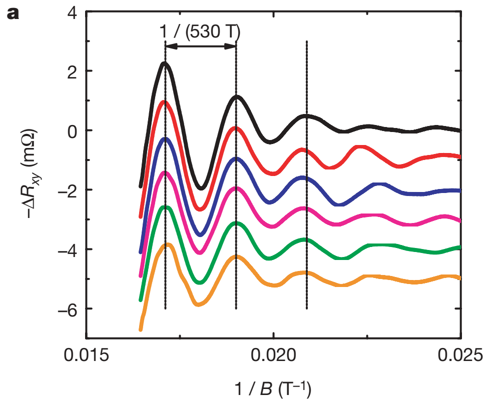
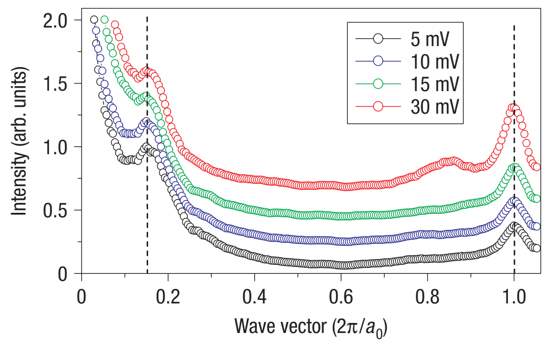
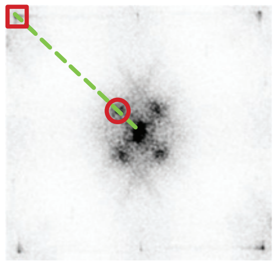


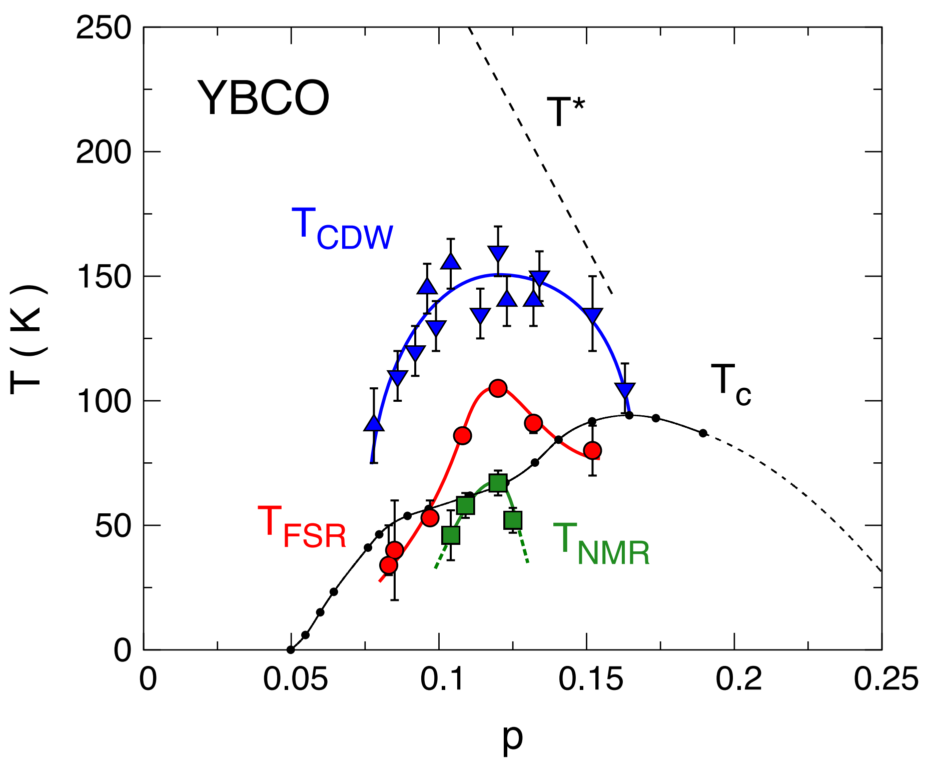
Wise et al, Nat. Phys. (2008)



BSCCO (opt. doped)



Cyr-Choignière, preprint 2015



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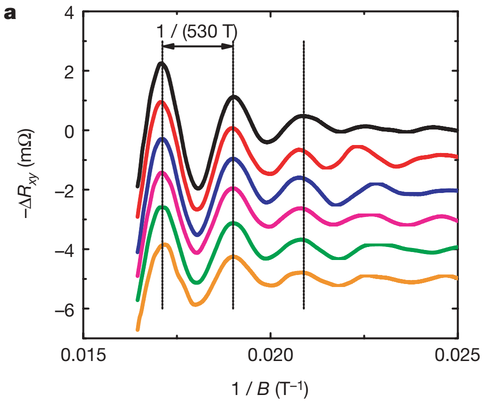

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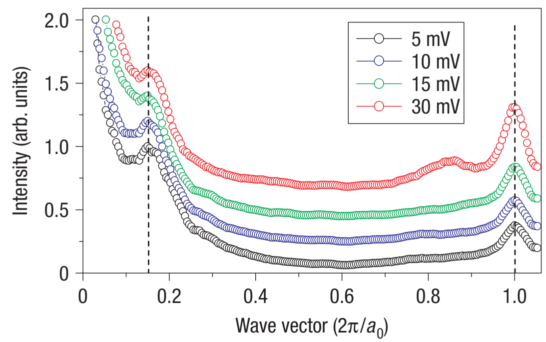

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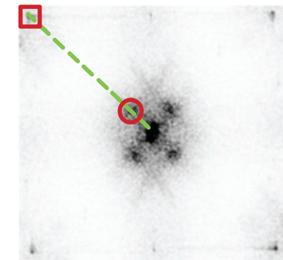
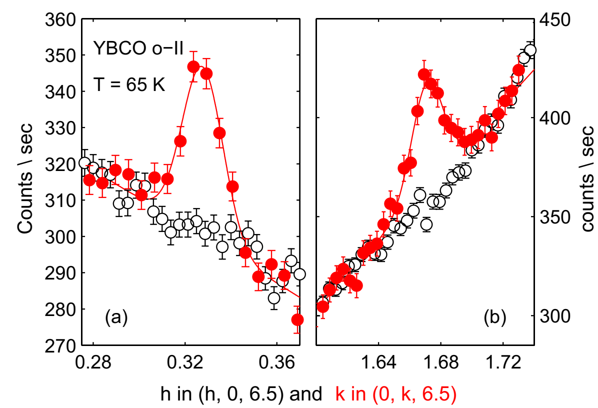
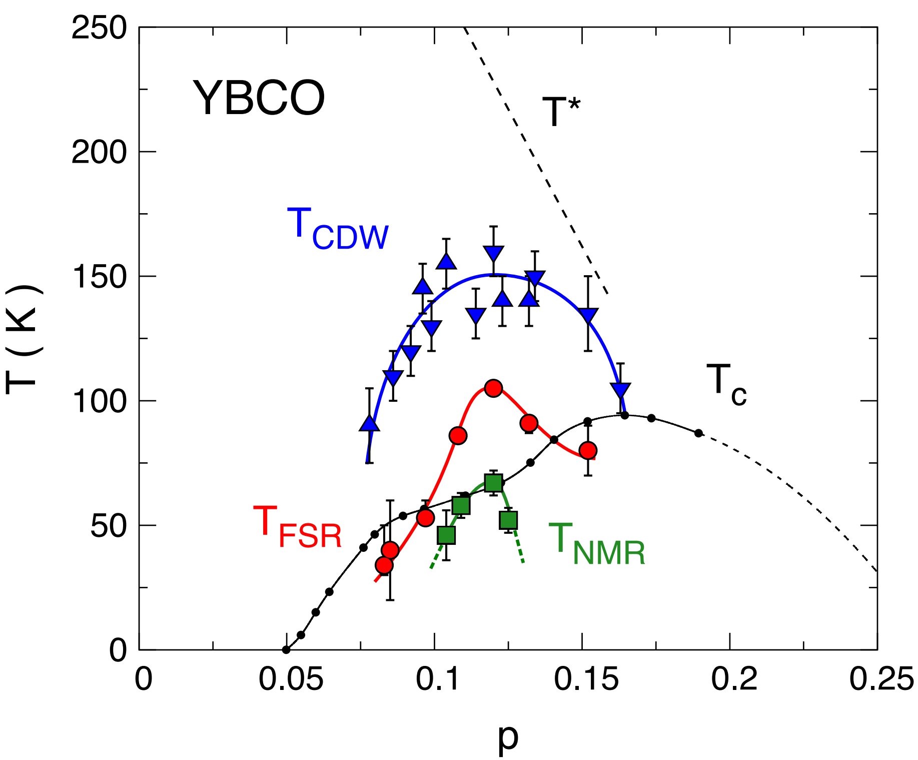


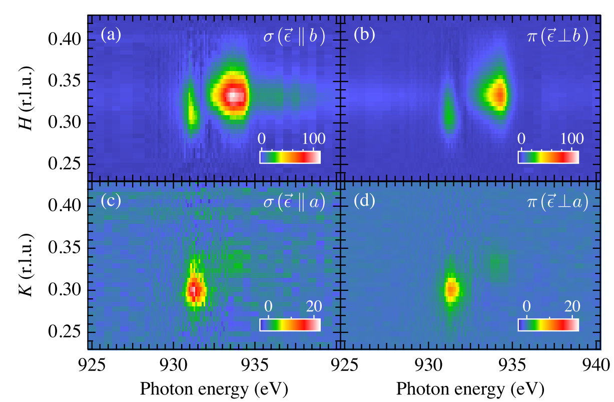
Blackburn et al, PRL (2013)



Cyr-Choignière, preprint 2015

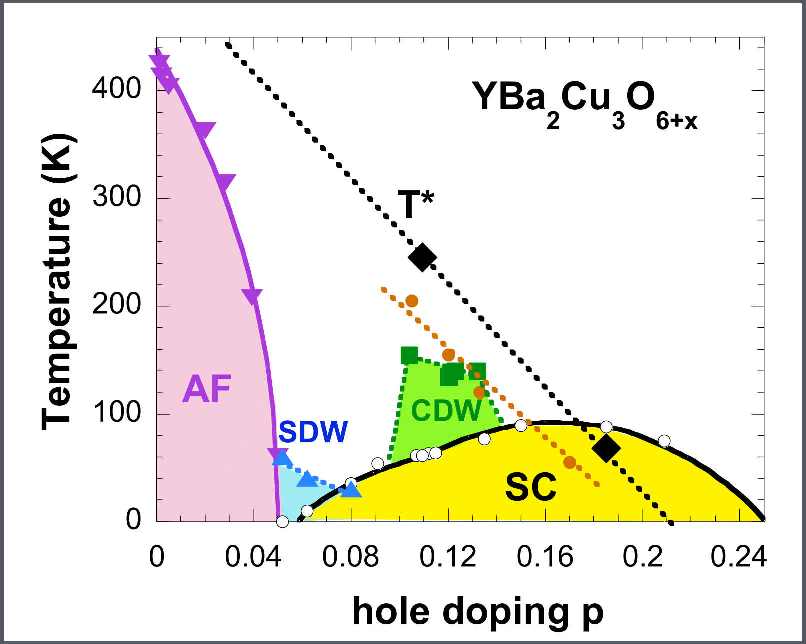


Achkar et al, PRL (2012)



Charge order Landscape

$YBa_2Cu_3O_{6+x}$



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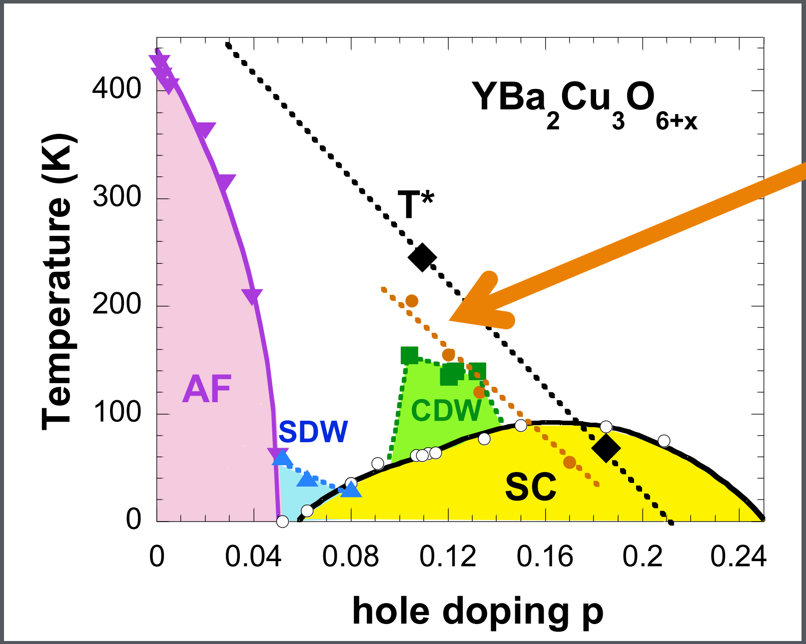
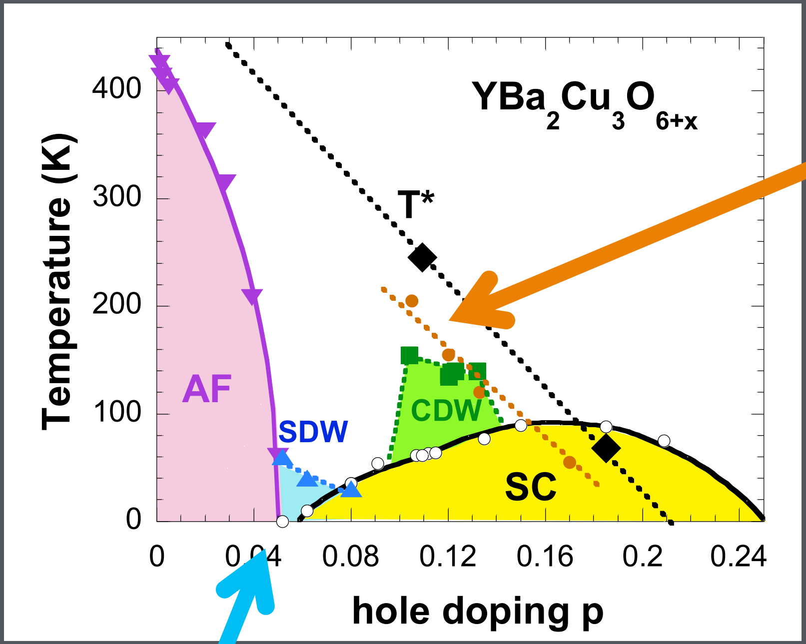


anomalous Kerr effect $T_k < T^*$

Xia, PRL 2008

Charge order Landscape

$YBa_2Cu_3O_{6+x}$



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

Haug, New J. Phys. 2010

T. Wu et al., PRB 2013

Charge order Landscape

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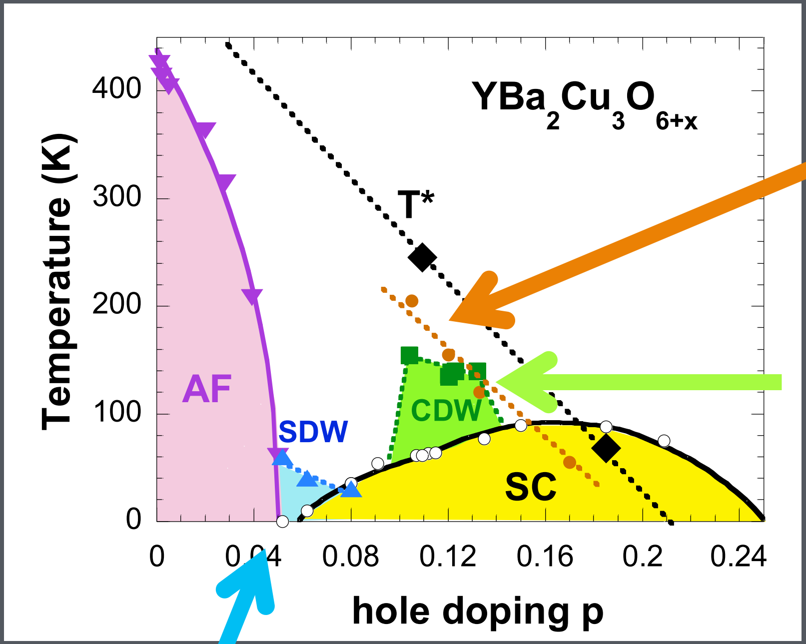

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Incipient CDW – $T_m < T^*$

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

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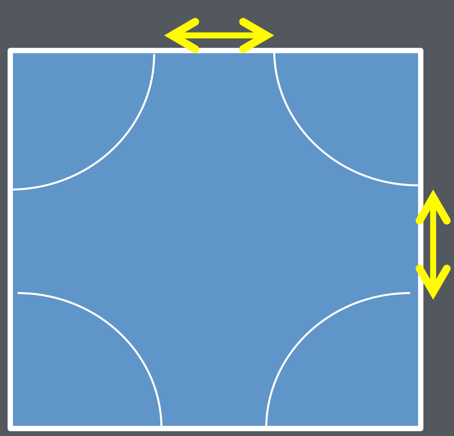

Charge order Landscape

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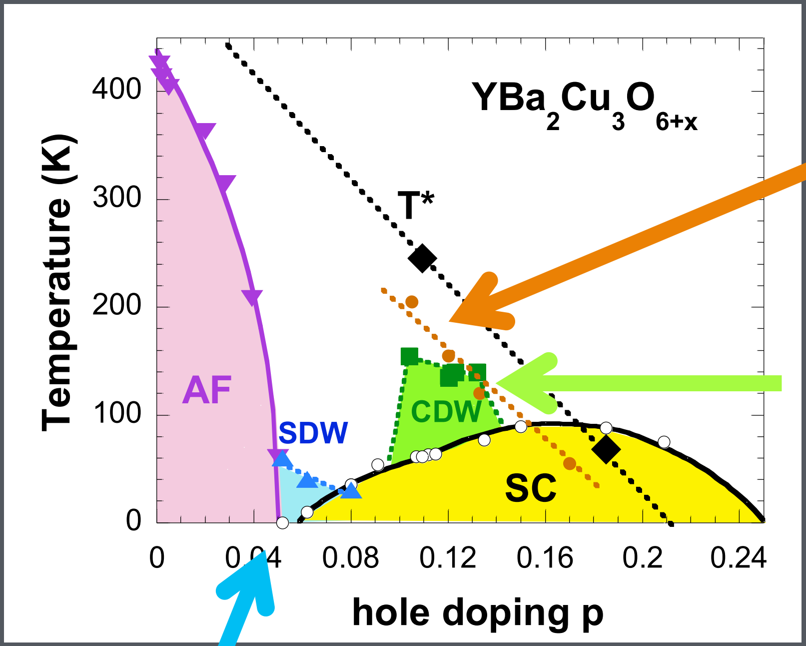

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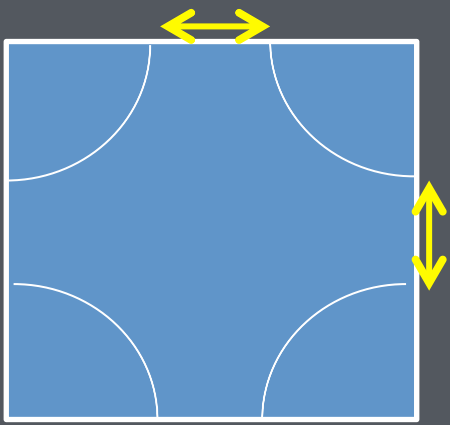


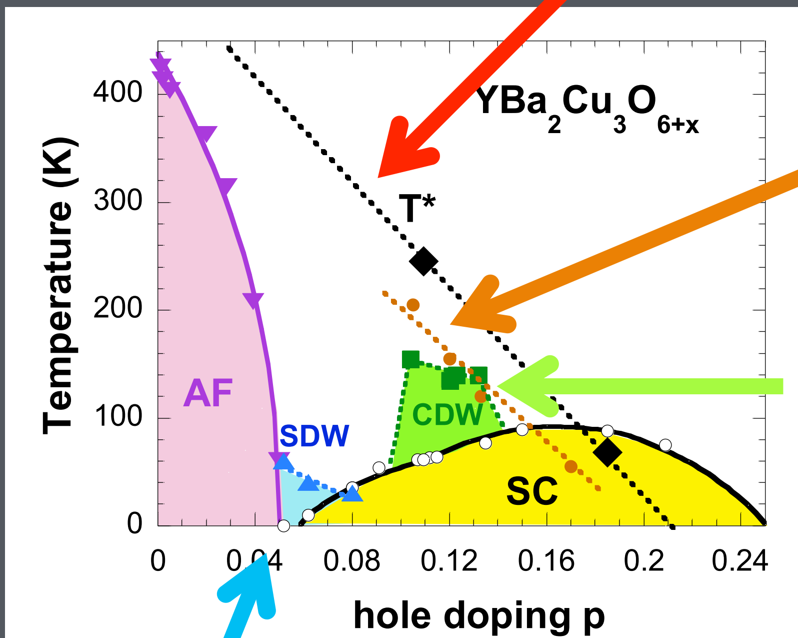
Stable CDW under magnetic field &
Fermi surface reconstruction
(NMR, quantum oscillation,
ultrasound)

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

Charge order Landscape

Nematicity

$YBa_2Cu_3O_{6+x}$



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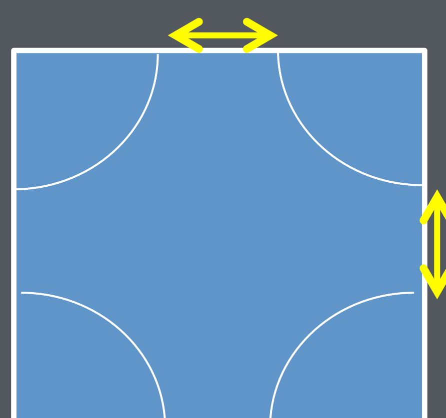

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Charge order Landscape

Nematicity

loop currents

anomalous Kerr effect $T_k < T^*$

Xia, PRL 2008

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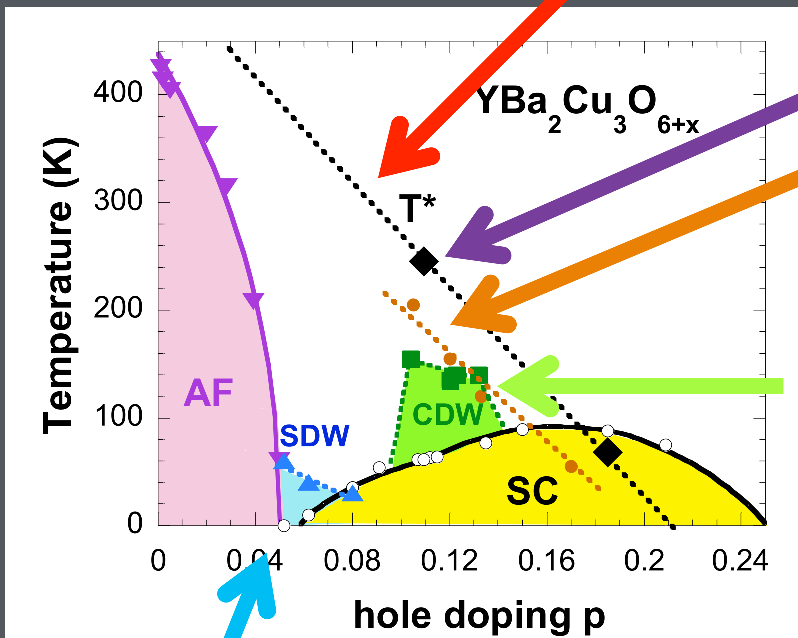

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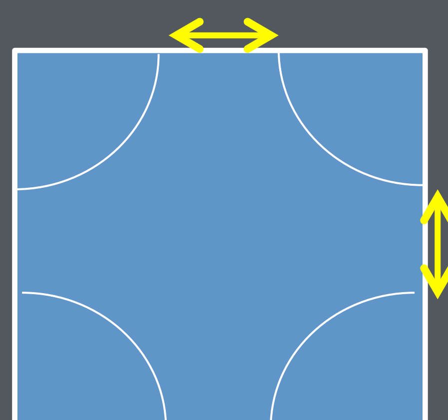

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T. Wu et al., *Nature* 2011.
D. LeBoeuf et al., *Nature Physics* 2

Charge order Landscape

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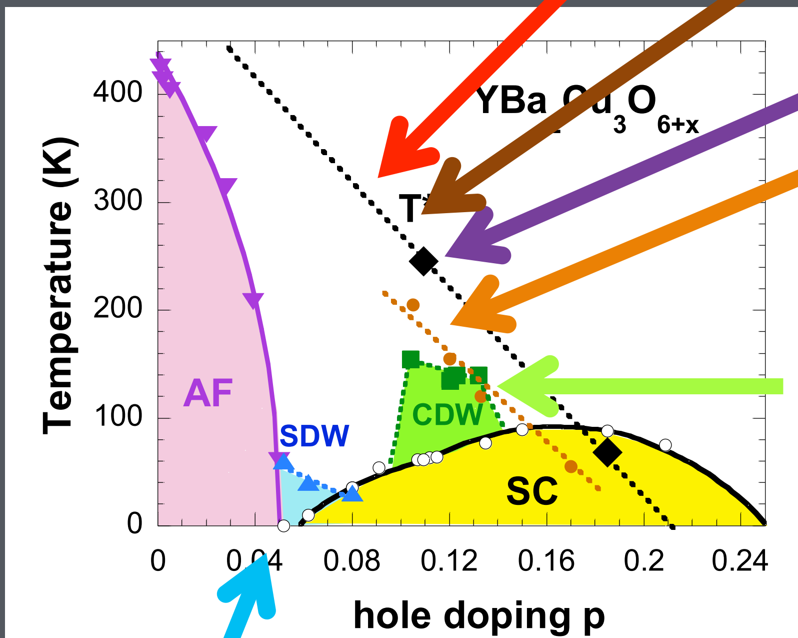

Nematicity

Inversion symmetry

loop currents

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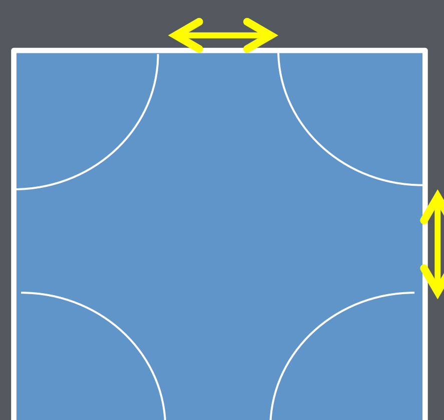

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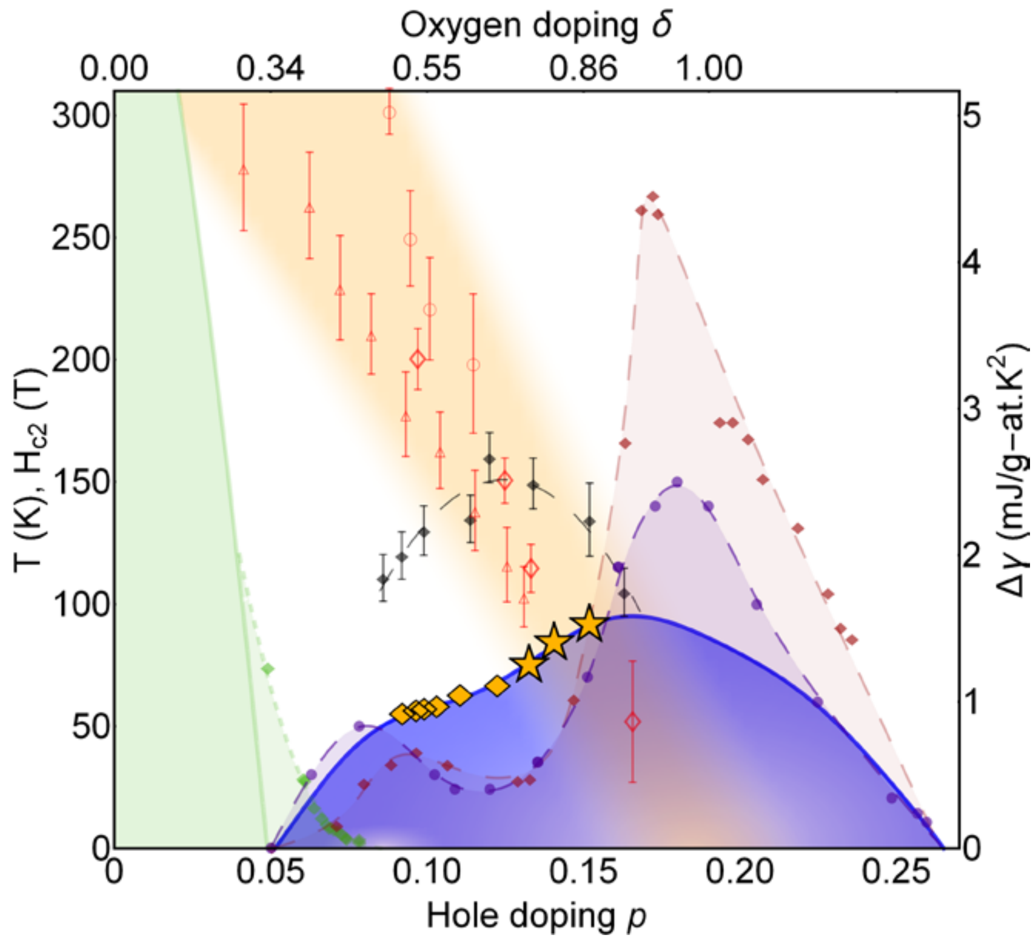
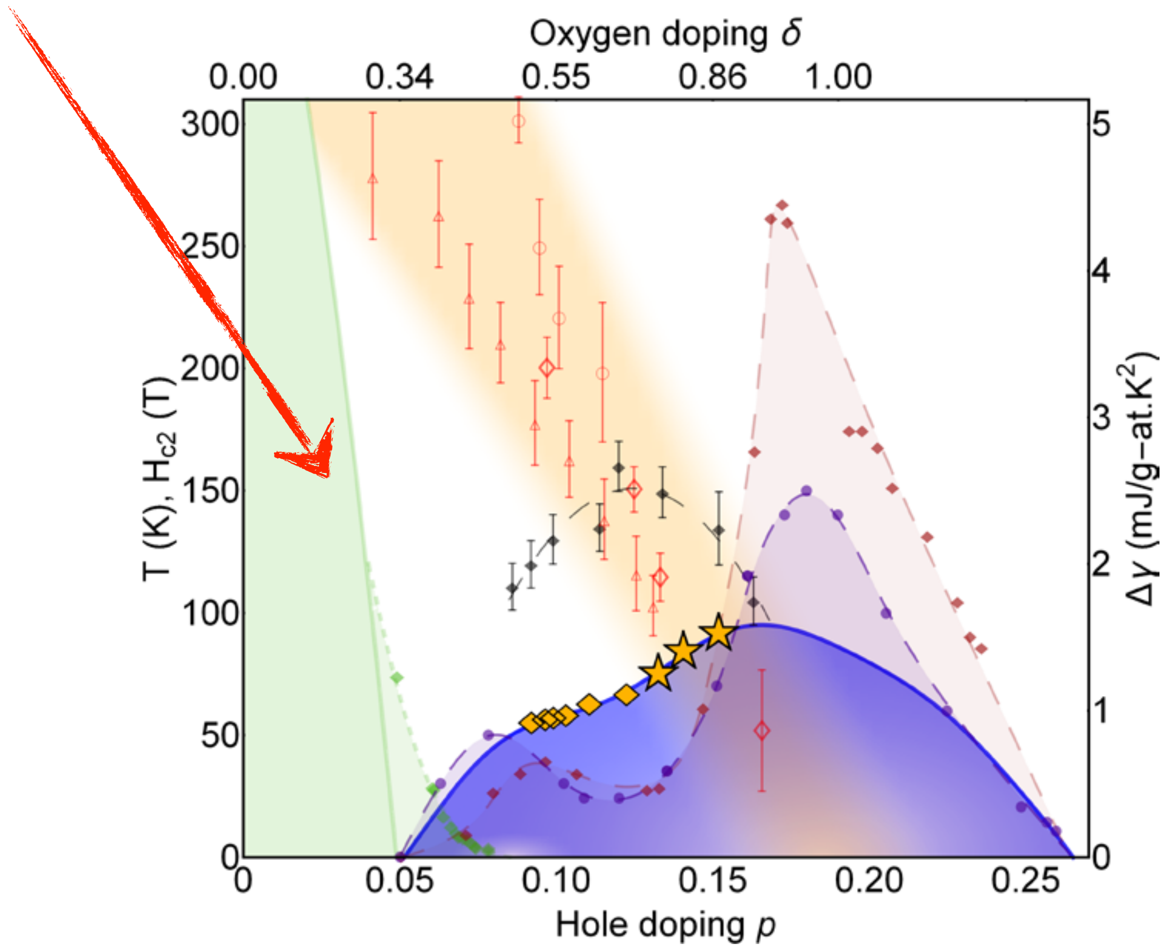
Is the Pseudo-Gap a phase transition or a cross over ?



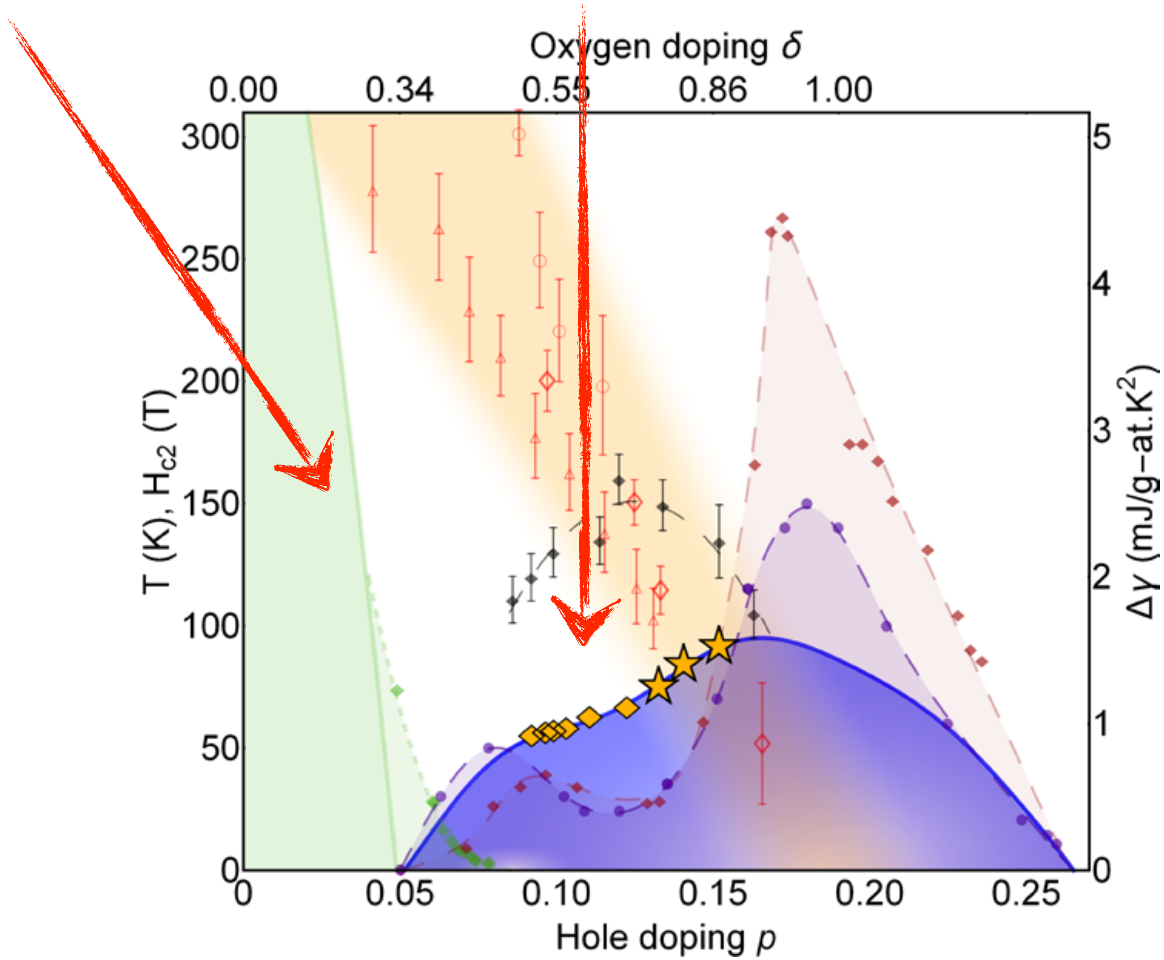
Ramshaw, 2015

Mott transition



Ramshaw, 2015

Mott transition Fluctuations

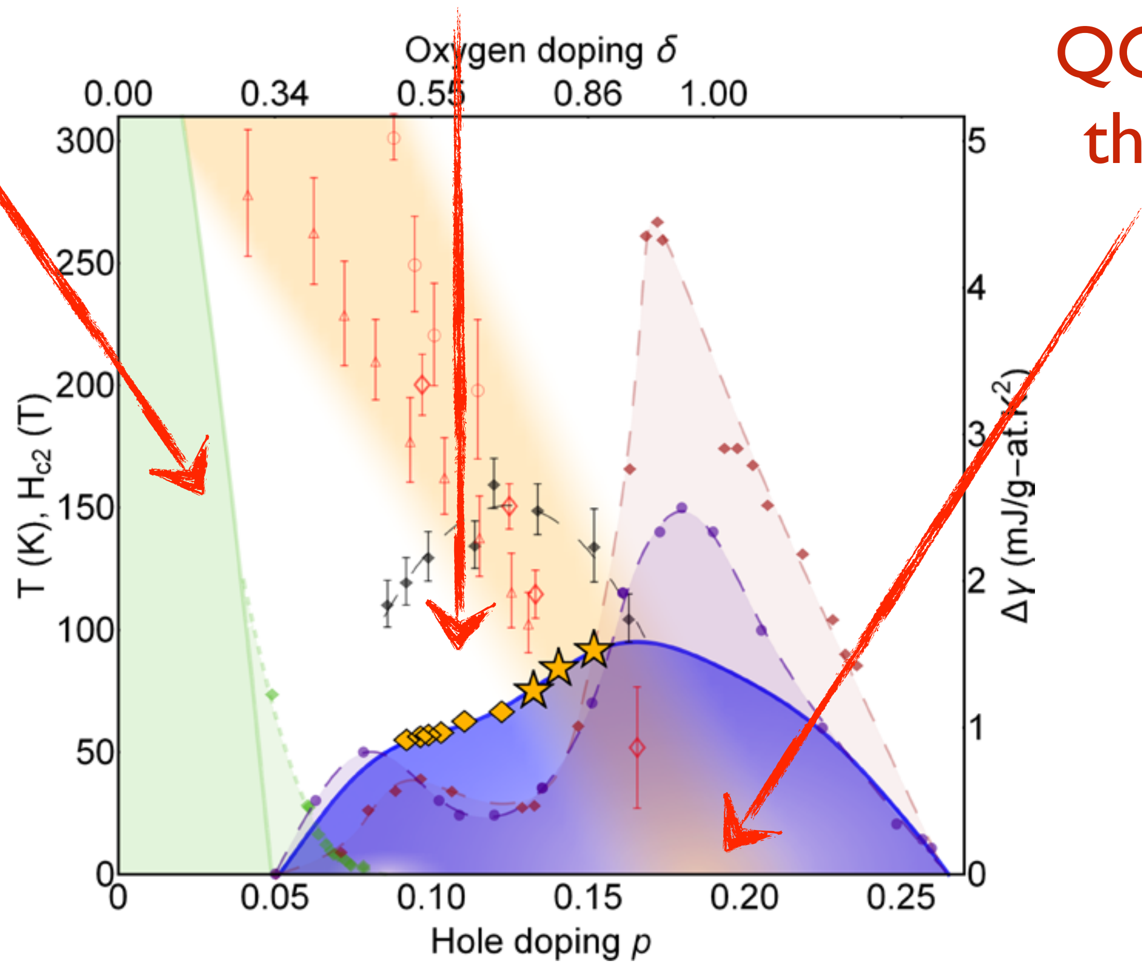


Ramshaw, 2015

Mott transition

Fluctuations

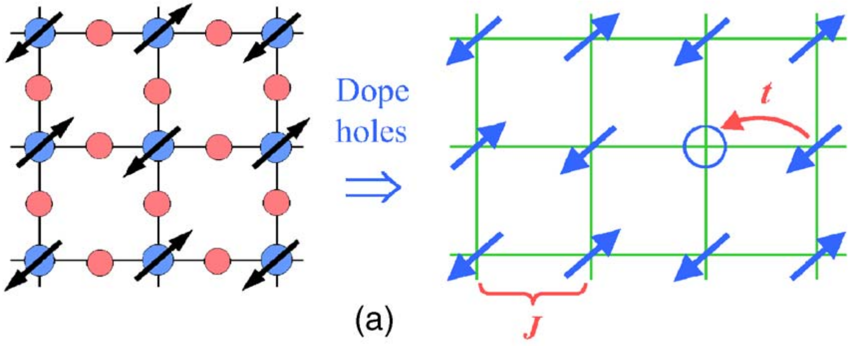
QCP under the dome



Ramshaw, 2015

The context : doping a Mott insulator

Resonating Valence Bond (RVB)



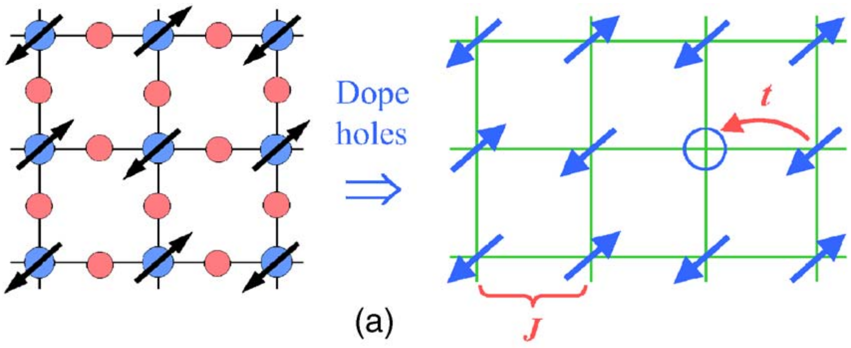
$$H = P\left[-\sum_{\langle ij\rangle,\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{i\sigma} + J \sum_{\langle ij\rangle} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \tfrac{1}{4} n_i n_j \right) \right] P$$

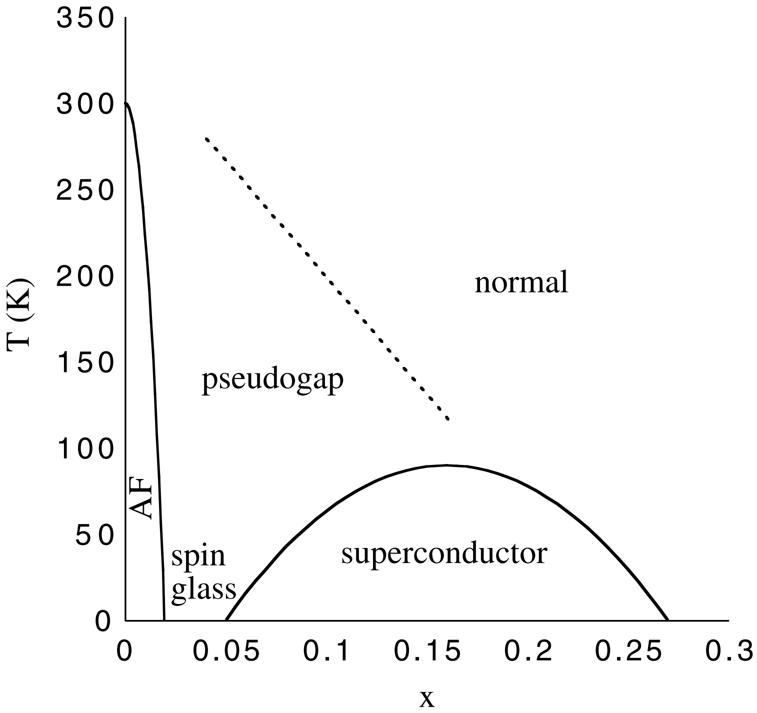
Anderson, Sachdev, Lee, Nagaosa, Rice …

P: projection on no double occupancy

The context : doping a Mott insulator

Resonating Valence Bond (RVB)





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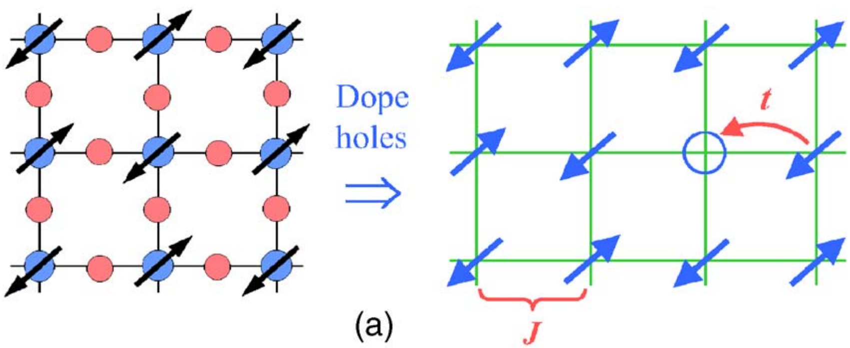

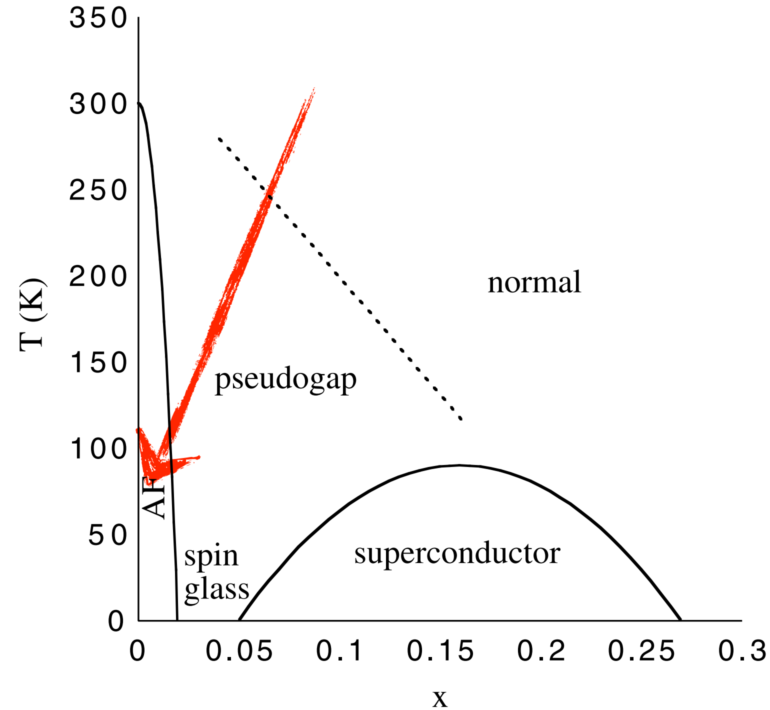

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Fluctuations

Emery Kivelson 95

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

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

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

Fluctuations

Emery Kivelson 95

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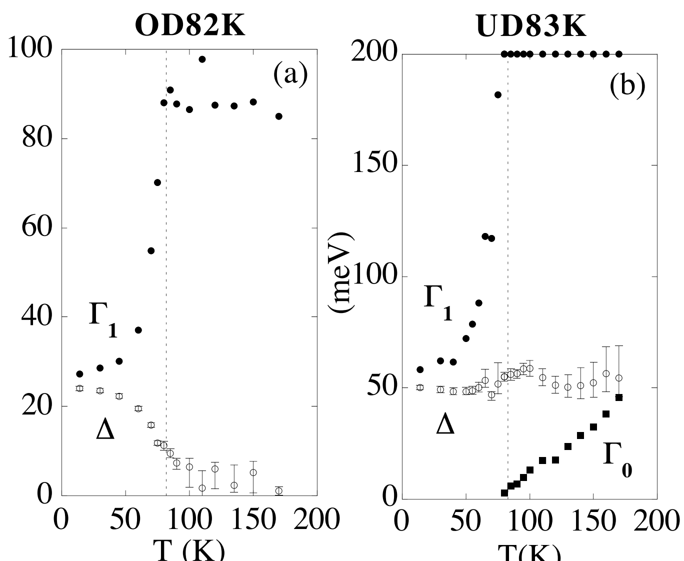
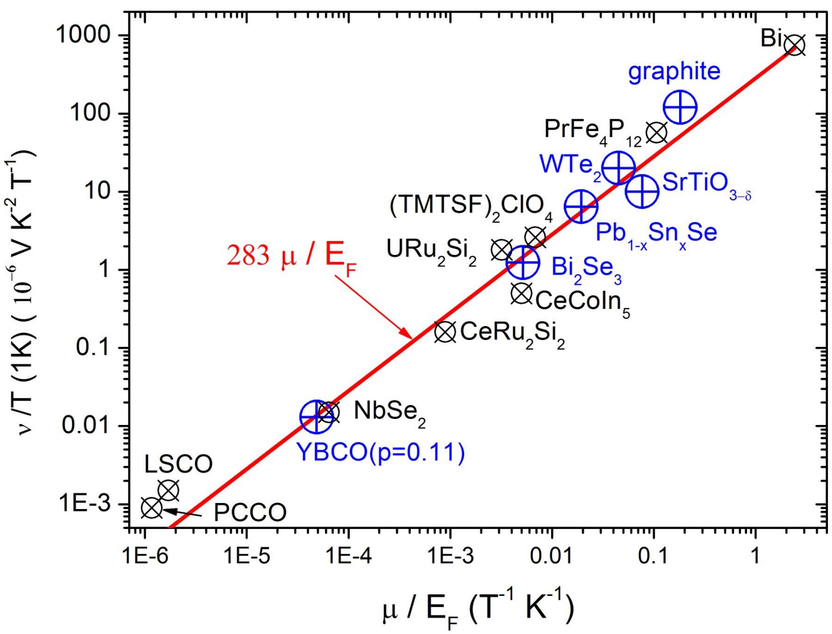


Norman, Campuzano 98

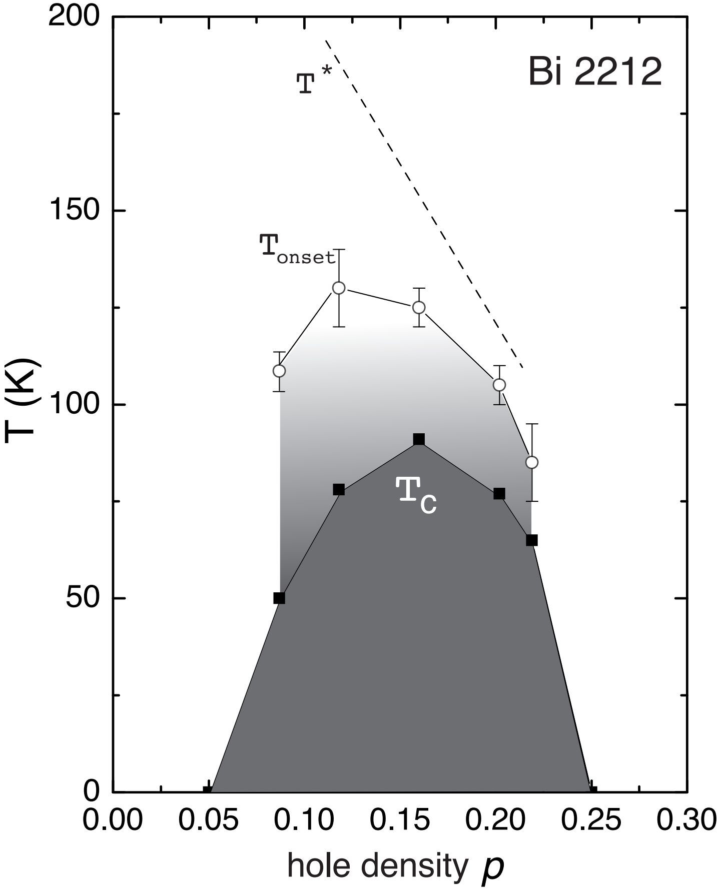
$$V_0 = \frac{(\hbar c)^2 a}{16\pi e^2 \lambda^2(0)}$$

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

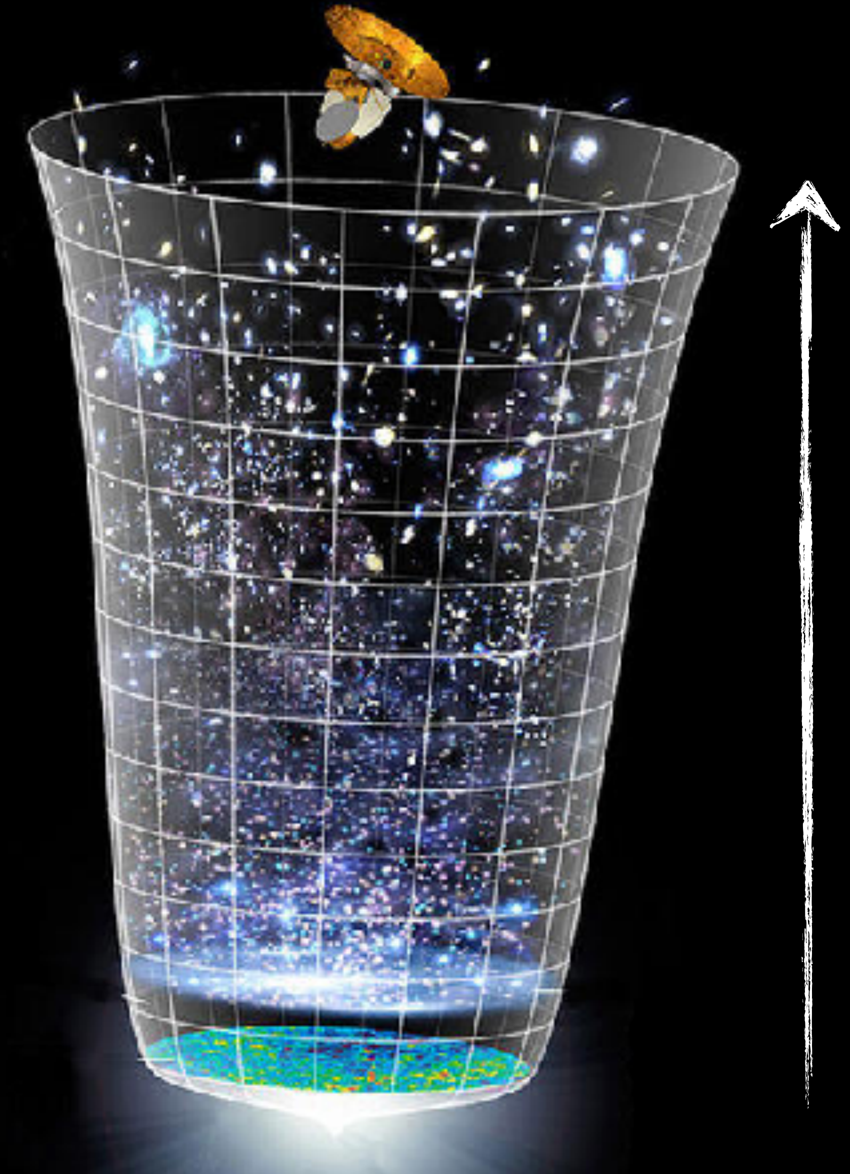
Benhia 2011



Ong 2005



Fluctuations of phase, amplitude, and others…



Condensate

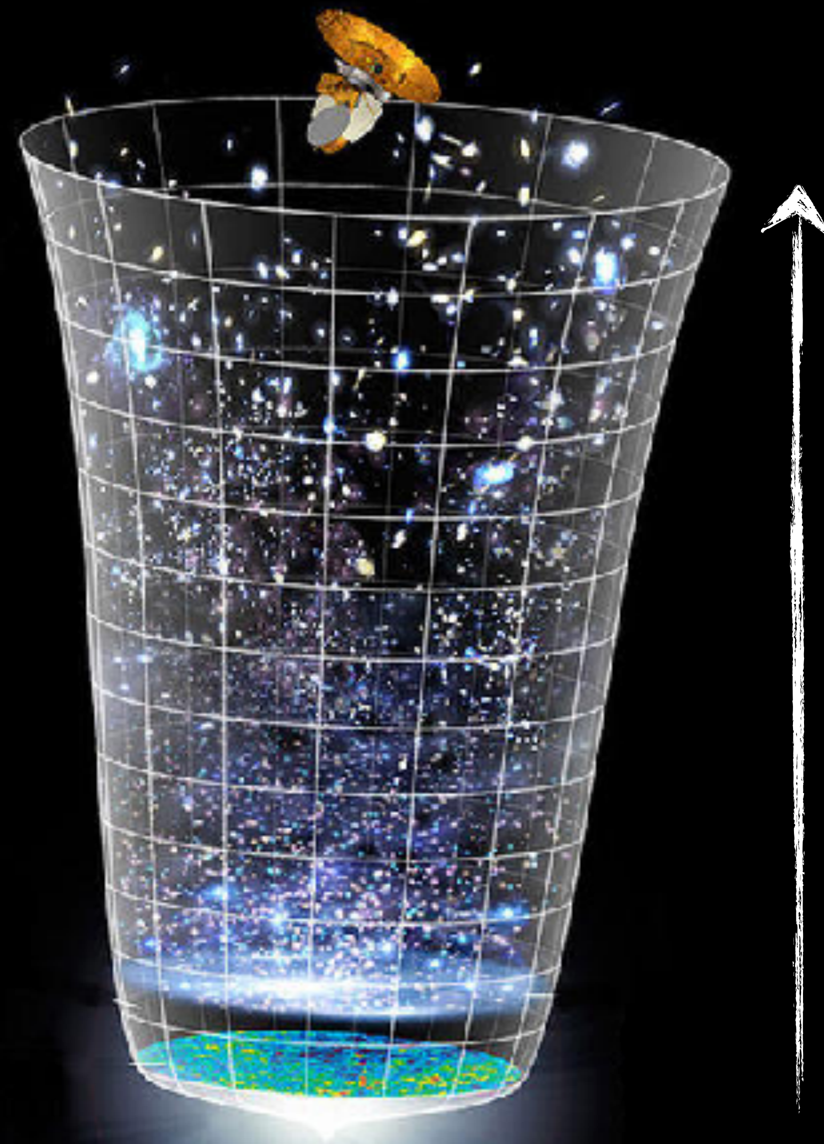
Phase fluctuations ····➤

Condensate ····➤

Amplitude Fluctuations →

Phase fluctuations →

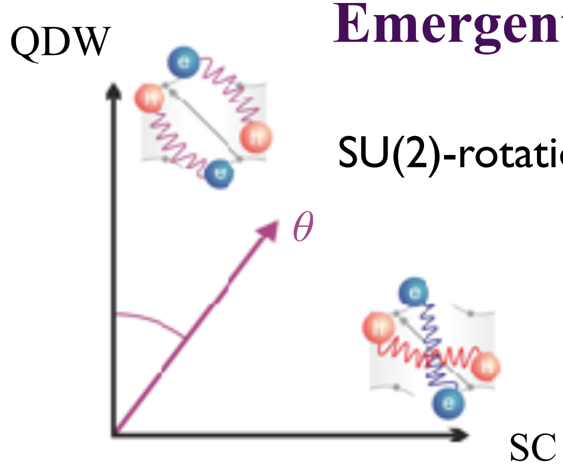
Condensate →



« Schyzofrenic » SU(2) flucutations

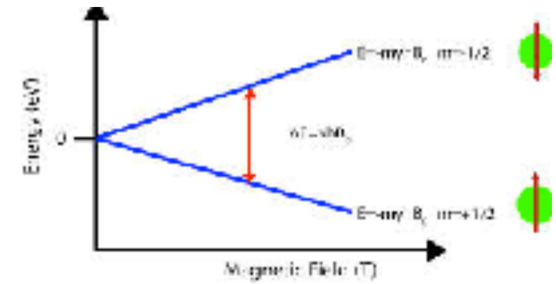
Emergent SU(2) flucutations

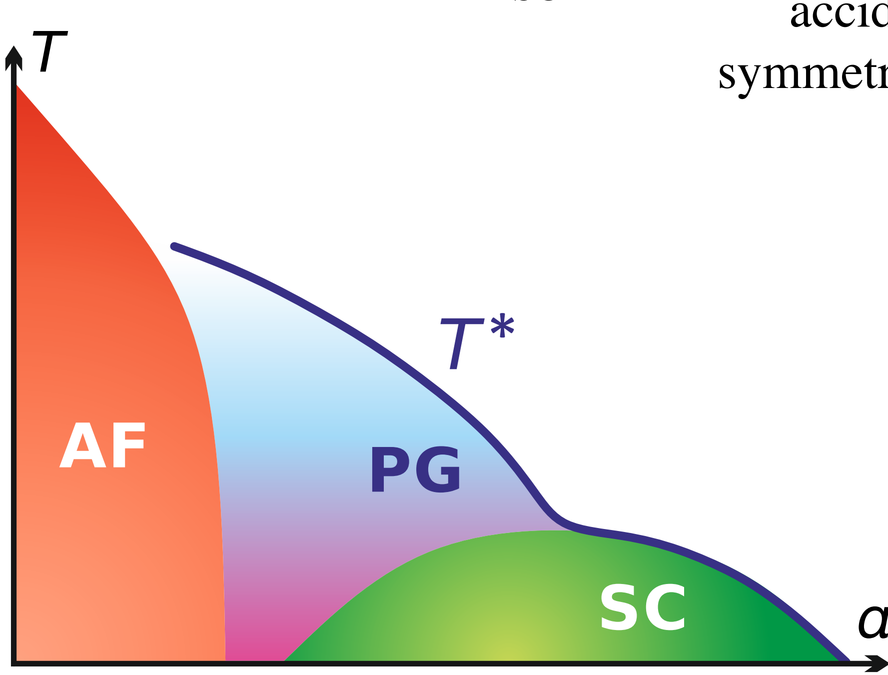
Emergent symmetries in the under-doped regime



SU(2)-rotations

Degenerescence of levels:
accidental ?
symmetry related ?

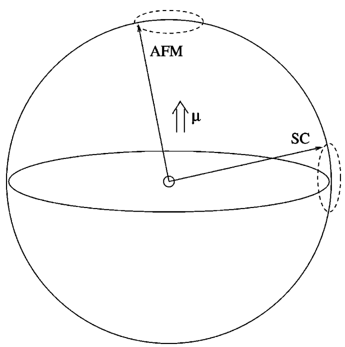


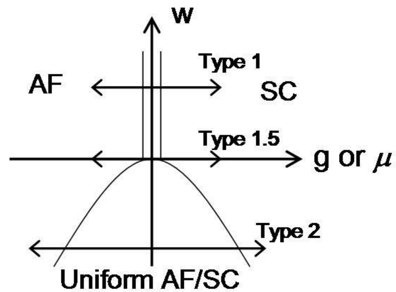


At some energy scale in the phase diagrams SC and Charge sectors are related by and SU(2) symmetry

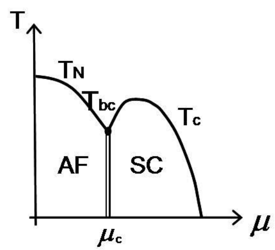
Sachdev et al (2013)
Efetov, Meier, CP (2013)

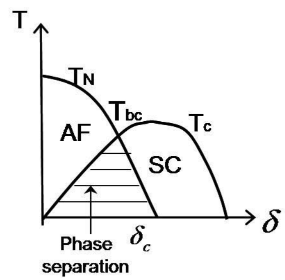
SO(5)-group

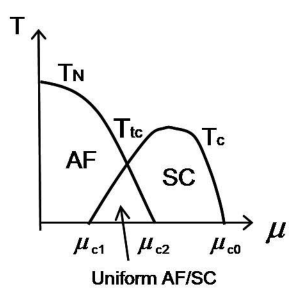




Fine-tuning condition ?







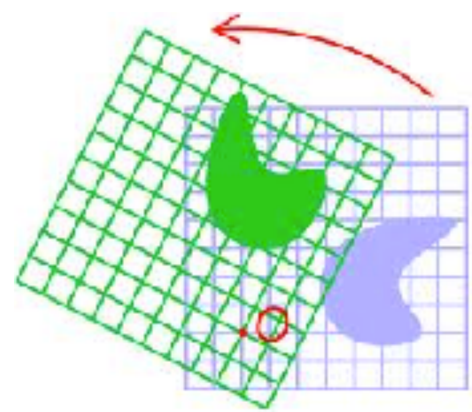
Demler, Zhang, Hanke (2005)

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

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

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

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

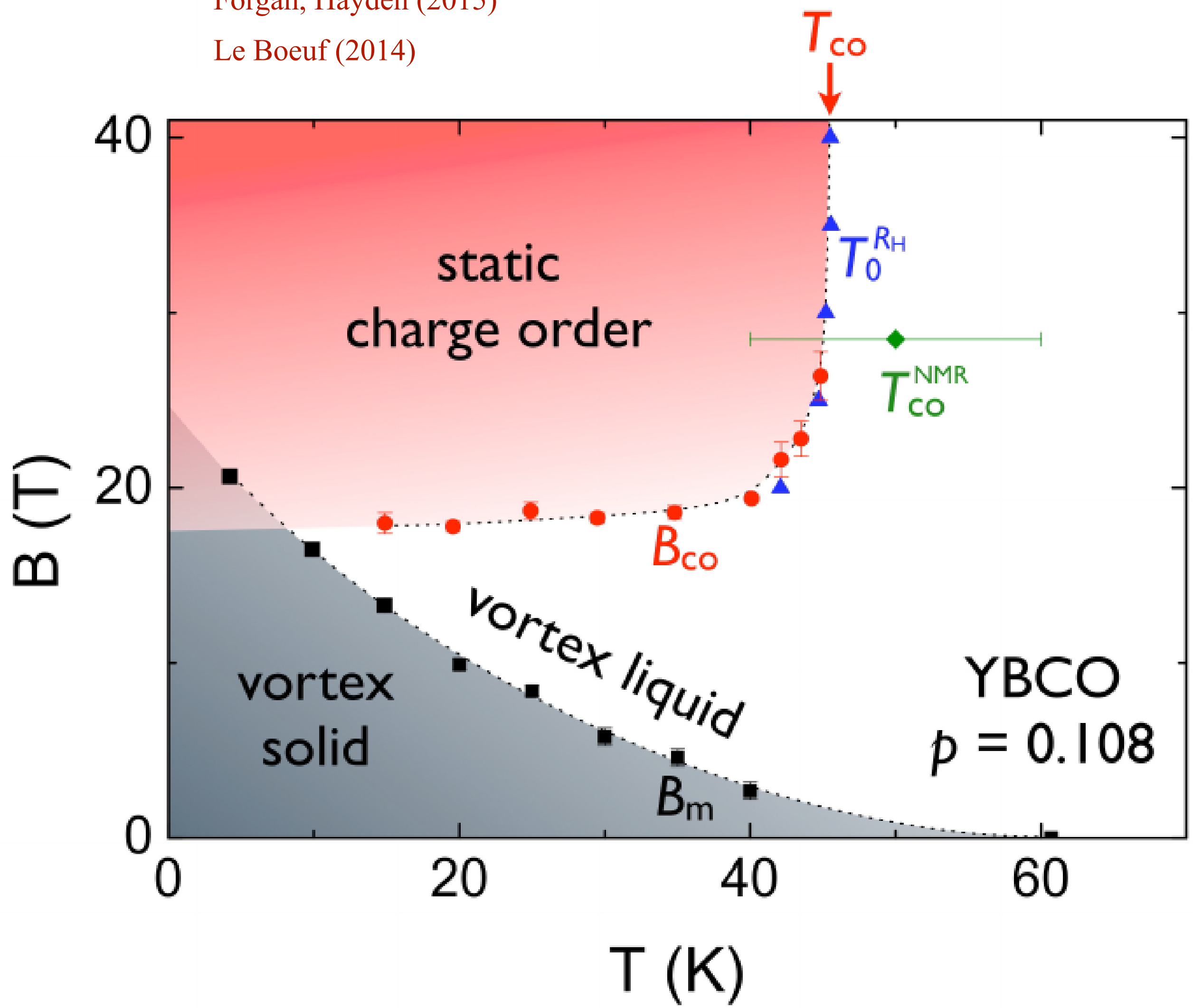


Sachdev et al (2013)
Kotliar and Liu (1988)
Lee, Wen, Nagaosa, RMP (2006)

Phase diagram under applied magnetic field

Forgan, Hayden (2015)

Le Boeuf (2014)



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

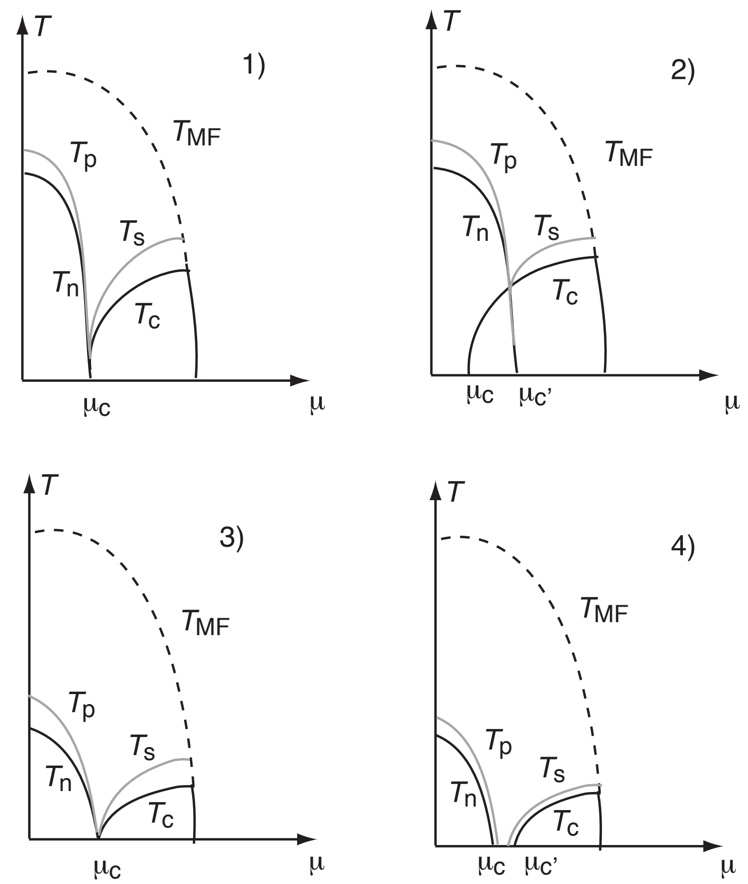
$$\Delta_1 = -\frac{1}{\sqrt{2}} \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\uparrow} c^\dagger_{-\mathbf{k}\downarrow},$$

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

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

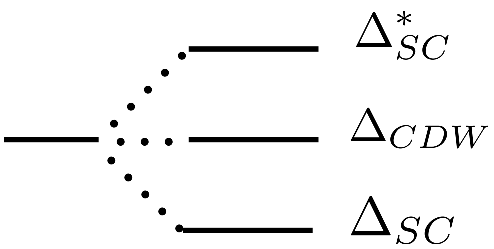
$$[\eta^\pm, \Delta_m] = \sqrt{l\,(l+1) - m\,(m \pm 1)}\Delta_{m\pm1},$$

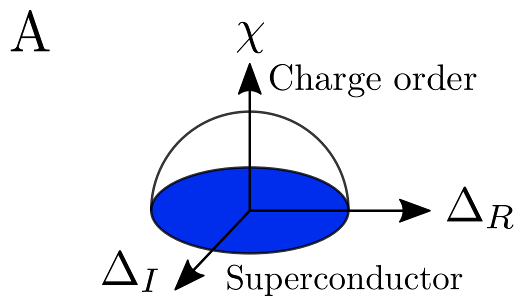
$$[\eta_z, \Delta_m] = m\Delta_m.$$



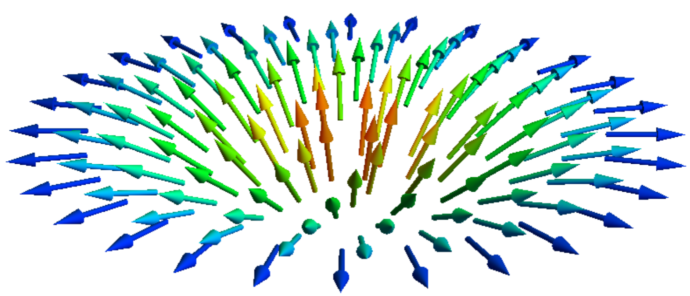
Topology and local structures

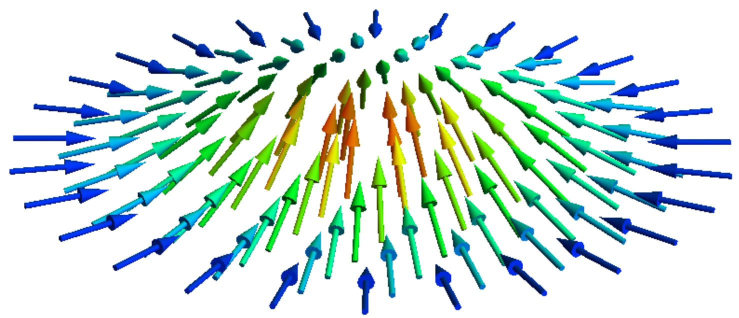
0(3) non linear σ-model





Topological structure:
Skyrmions in the pseudo spin space





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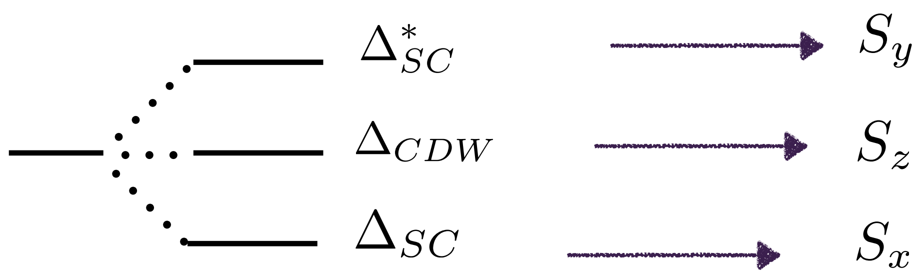
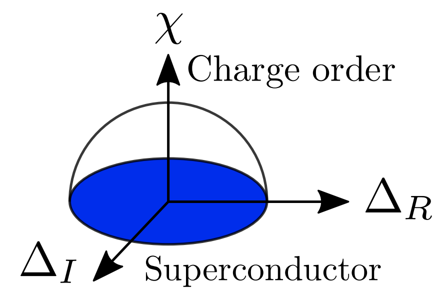


A



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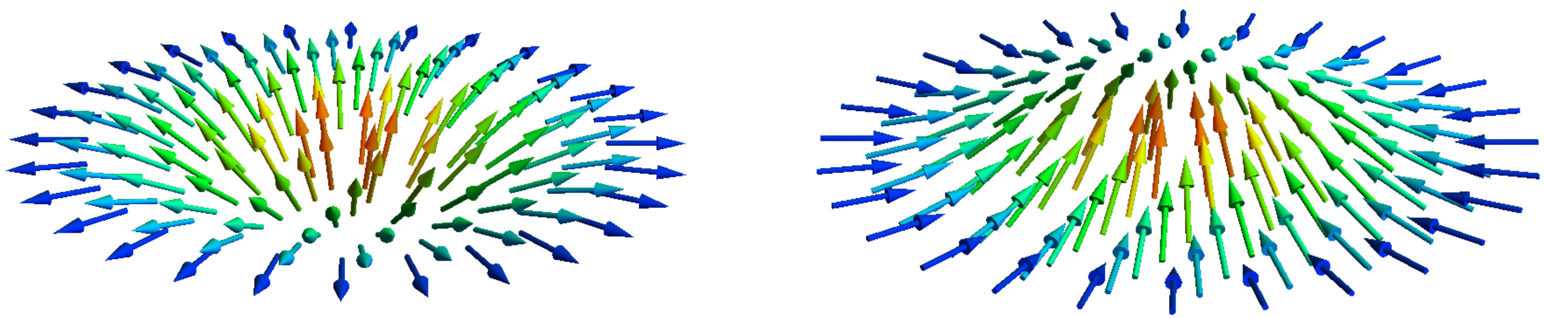
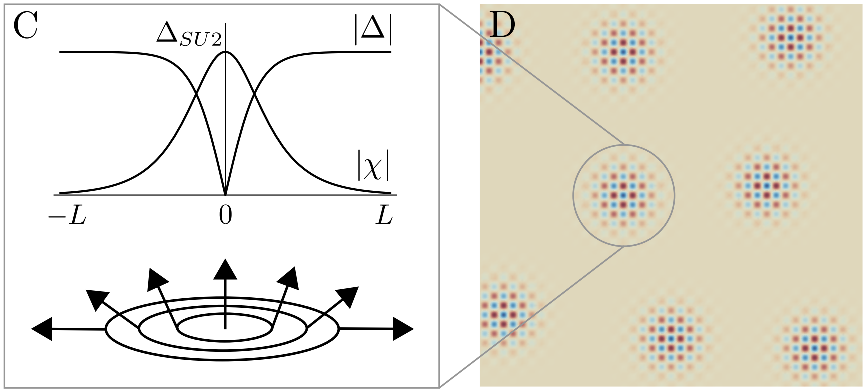


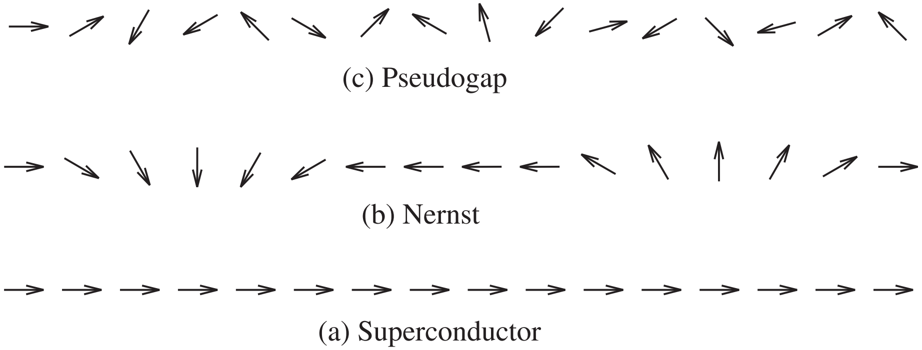
Homotopy classes

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

$$\pi_2(S_3) = 0$$



Vortex structure
Phase diagram



Homotopy classes

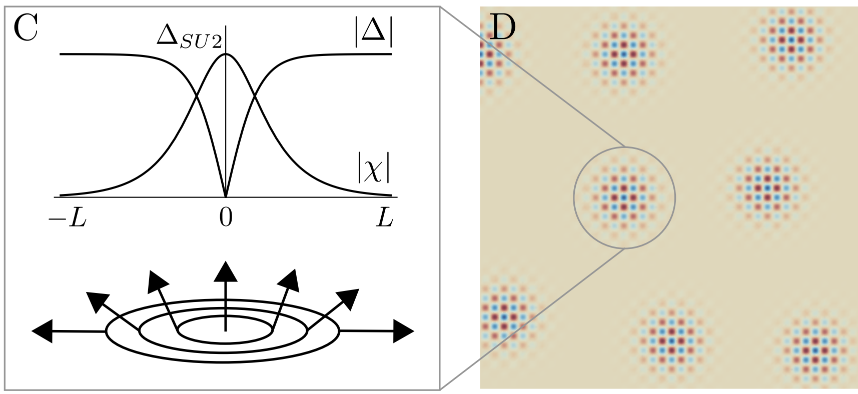
$$\Delta_{-,R}^2 + \Delta_{-,I}^2 + \Delta_{+,R}^2 + \Delta_{+,I}^2 = 1$$

$$\pi_2(S_3) = 0$$

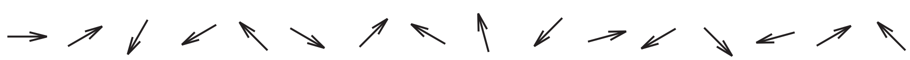
Phase of the CDW is frozen to an integer value

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

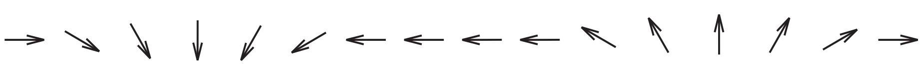
$$\pi_2(S_2) = Z$$



Vortex structure
Phase diagram

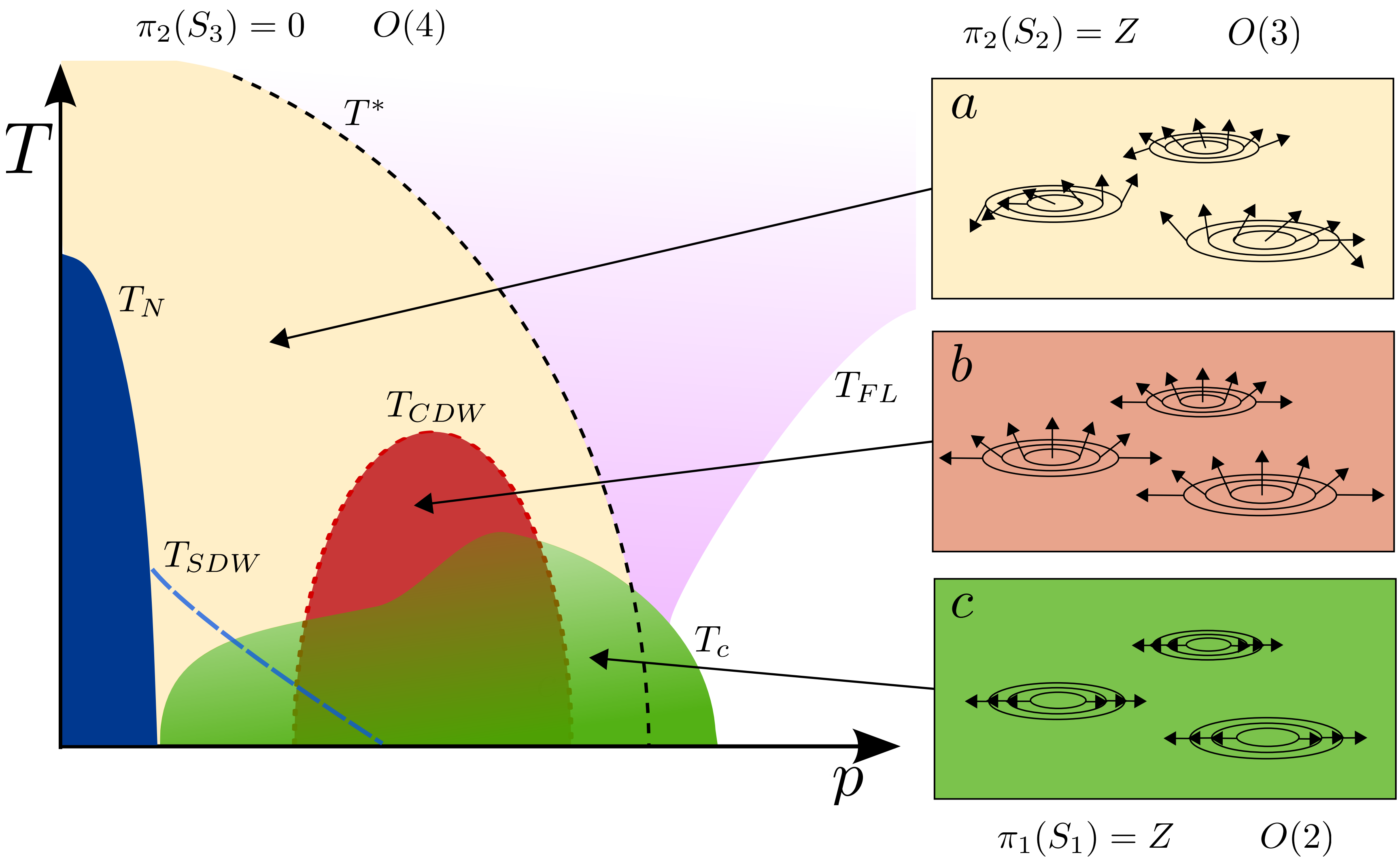


(c) Pseudogap



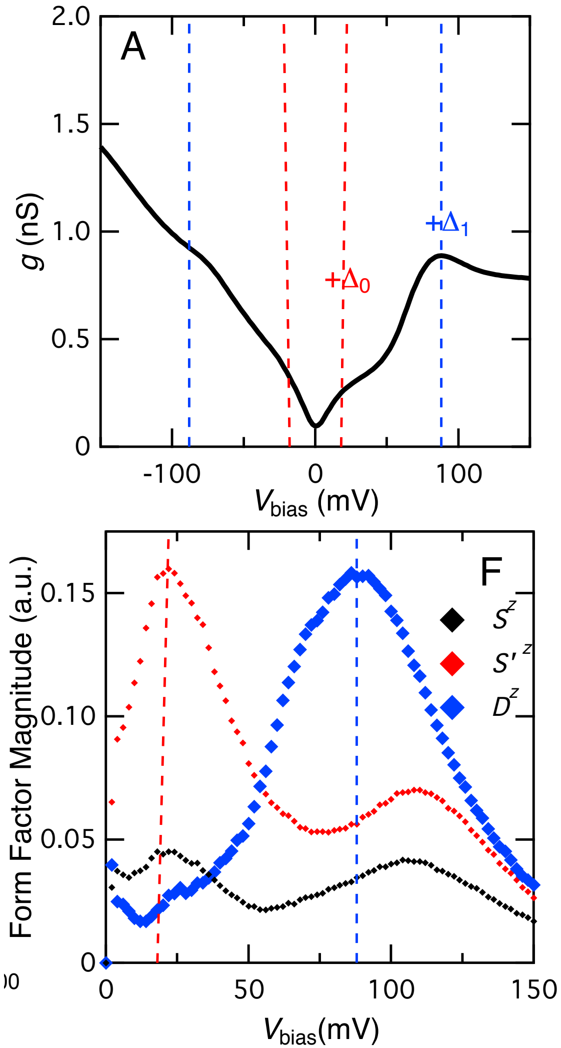
(b) Nernst

(a) Superconductor

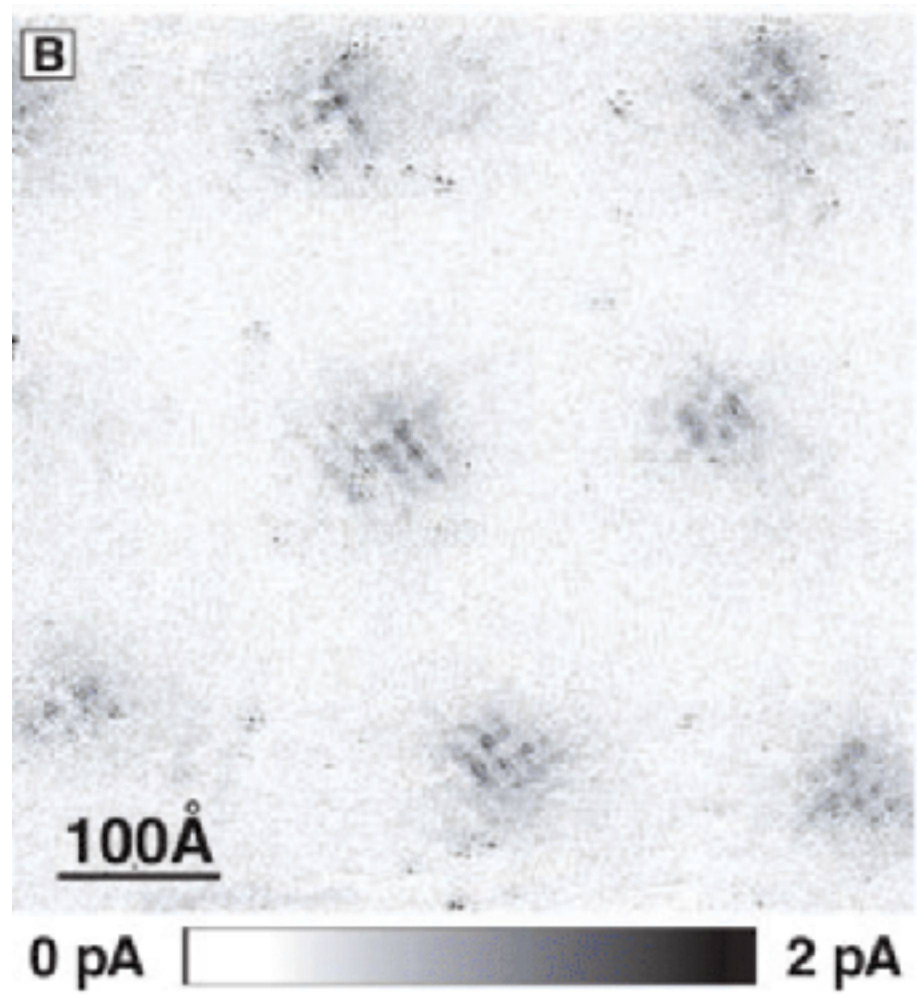


$\pi_2(S_3) = 0$ $O(4)$
$\pi_2(S_2) = Z$ $O(3)$
T
T^*
T_N
T_{CDW}
T_{FL}
T_{SDW}
T_c
p
a
b
c
$\pi_1(S_1) = Z$ $O(2)$

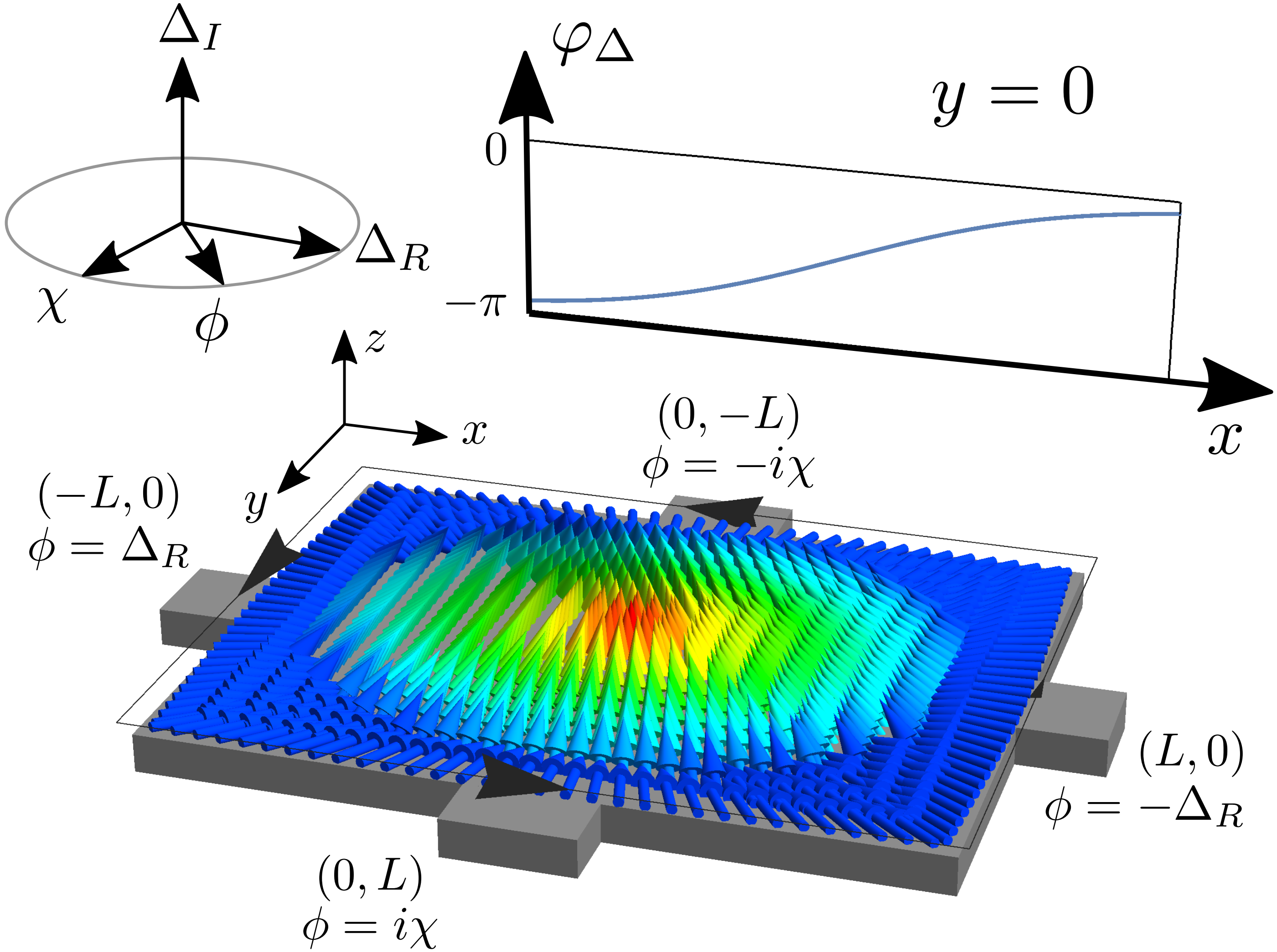
STM



Hamidian et al. (2015)



Hoffmann (2002)

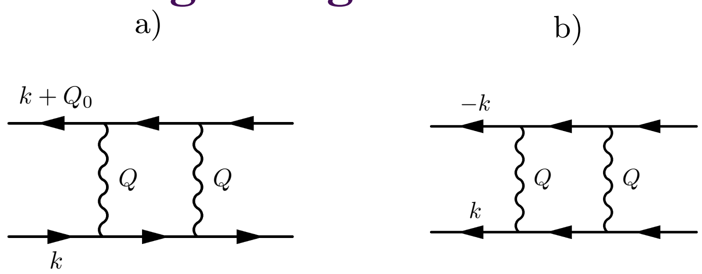

Δ_I
Δ_R
χ
ϕ
φ_Δ
$y = 0$
0
$-\pi$
x
z
x
y
$(0, -L)$
$\phi = -i\chi$
$(-L, 0)$
$\phi = \Delta_R$
$(L, 0)$
$\phi = -\Delta_R$
$(0, L)$
$\phi = i\chi$

Key ingredient

Short range AF correlations : J strong enough

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

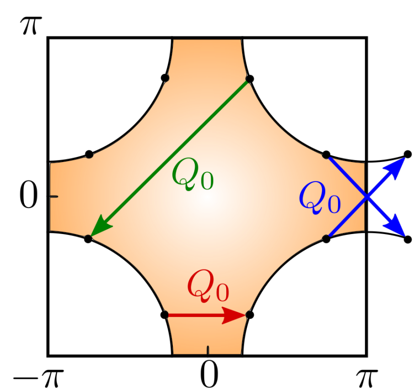
$$\mathbf{S}_i=\sum_{\alpha,\beta}c^{\dagger}_{i,\alpha}\sigma_{\alpha\beta}c_{i\beta}$$

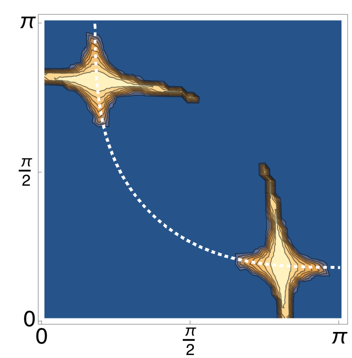


Generalizes the 8 hot spots model close to AF QCP

Metlitski, Sachdev et al (2011)
Efetov, Meier, CP (2013)

Degeneracy of wave vectors
0, (q,q), (q,0), (0,q) and SC at the hot spots

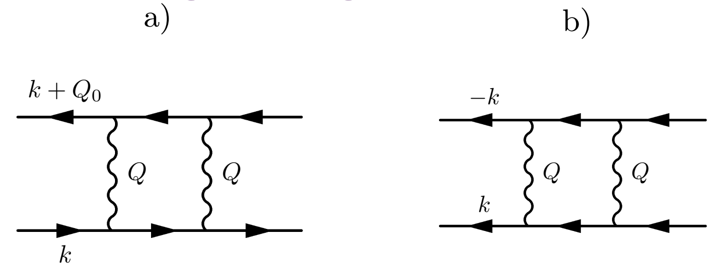




Short range AF correlations : J strong enough

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

$$\mathbf{S}_i = \sum_{\alpha,\beta} c^{\dagger}_{i,\alpha} \sigma_{\alpha\beta} c_{i\beta}$$



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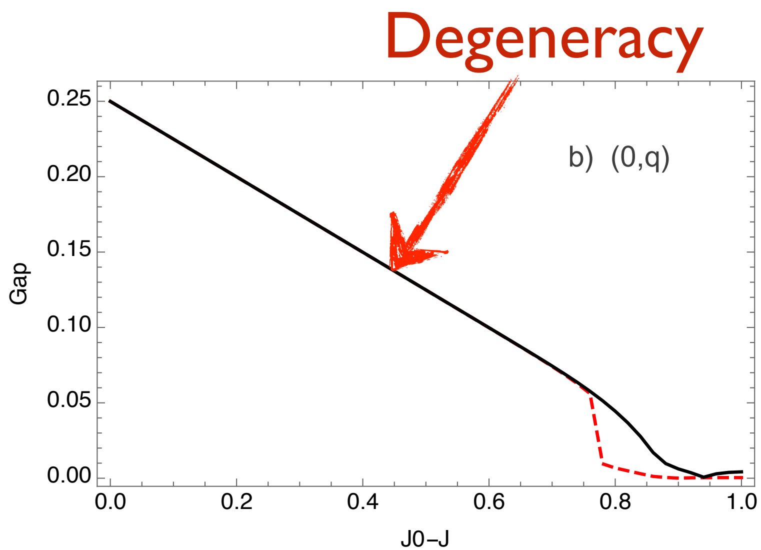
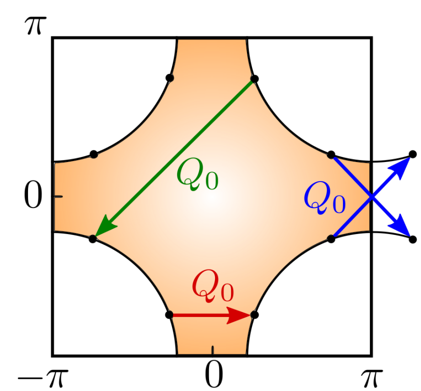
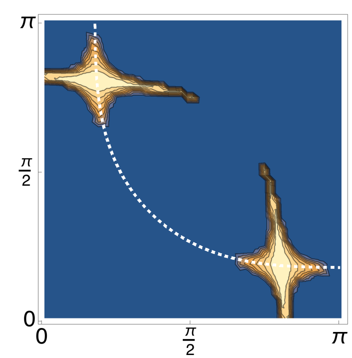


AF decreases as a function of doping $x \simeq (J_0 - J)^{\alpha}$

Degeneracy of wave vectors
0, (q,q), (q,0), (0,q) and SC at the hot spots





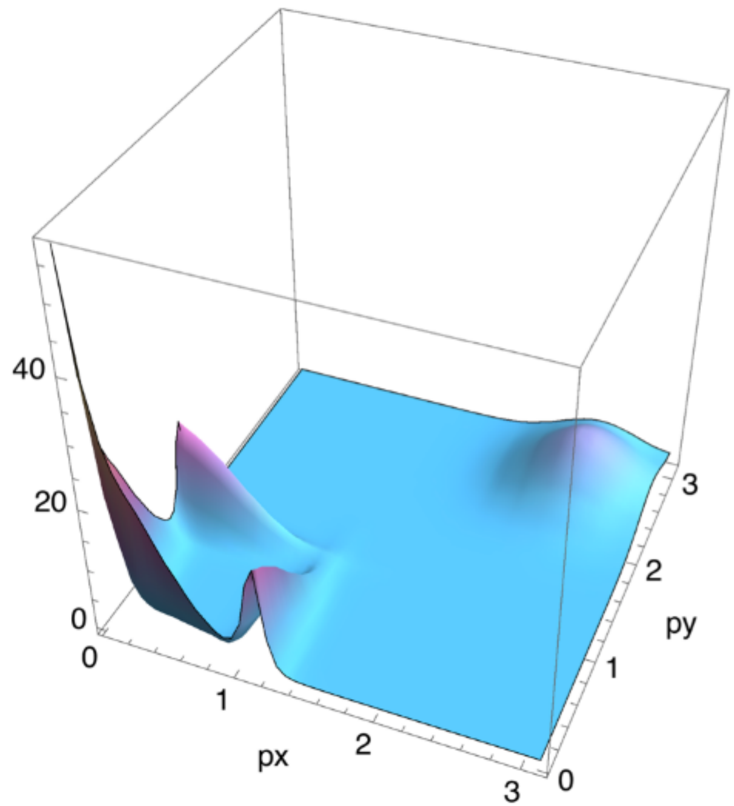
Order by disorder : SU(2) fluctuations lift the degeneracy

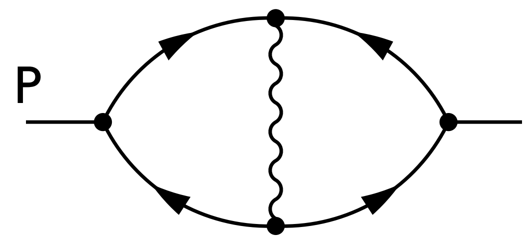
Large nematic response

and

Response along the crystal axes

a)



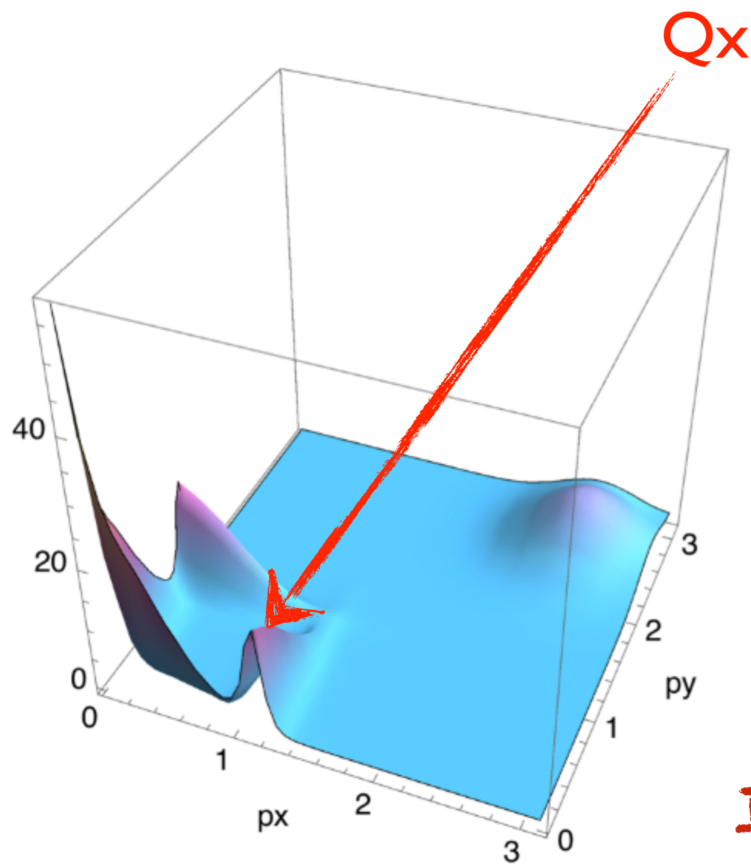


Loop currents

OK with symmetries

Intertwined orders: not competing w. others

Order by disorder : SU(2) fluctuations lift the degeneracy



a)

Large nematic response

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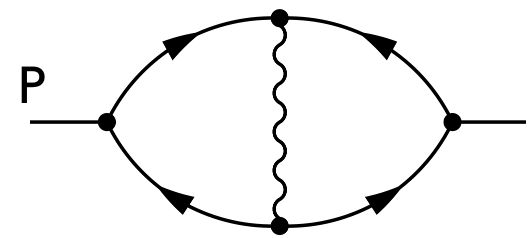

Loop currents

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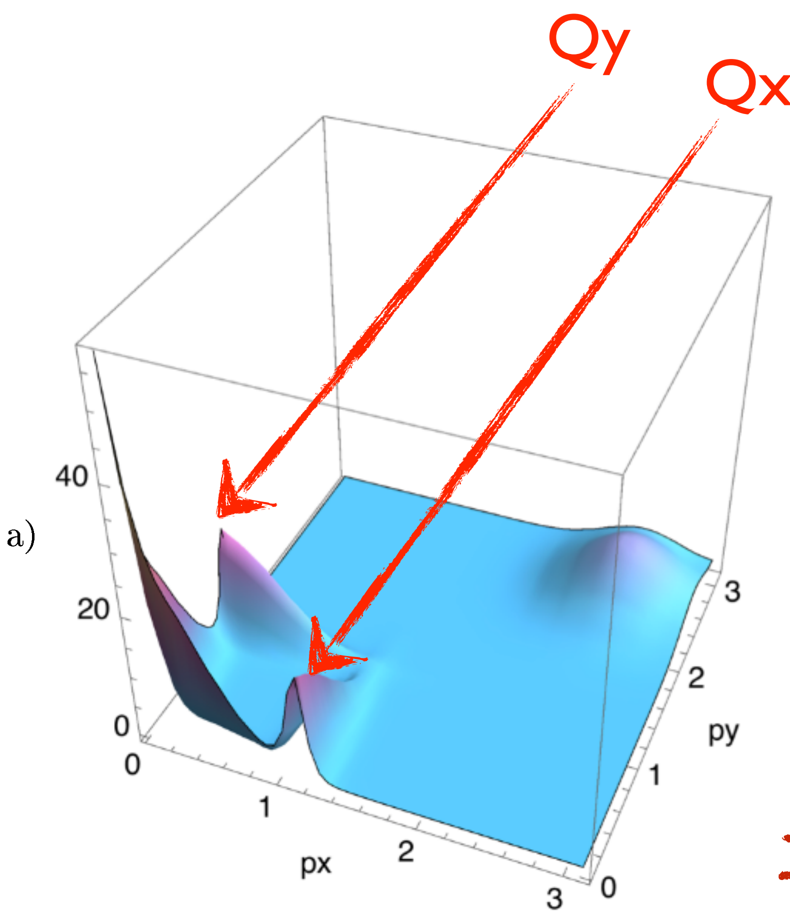
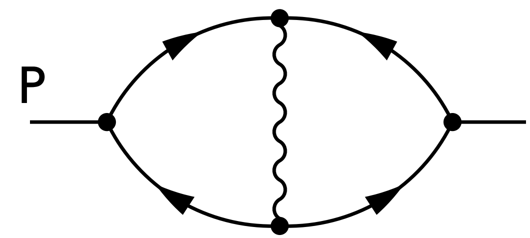


Large nematic response
and
Response along the crystal axes



Loop currents
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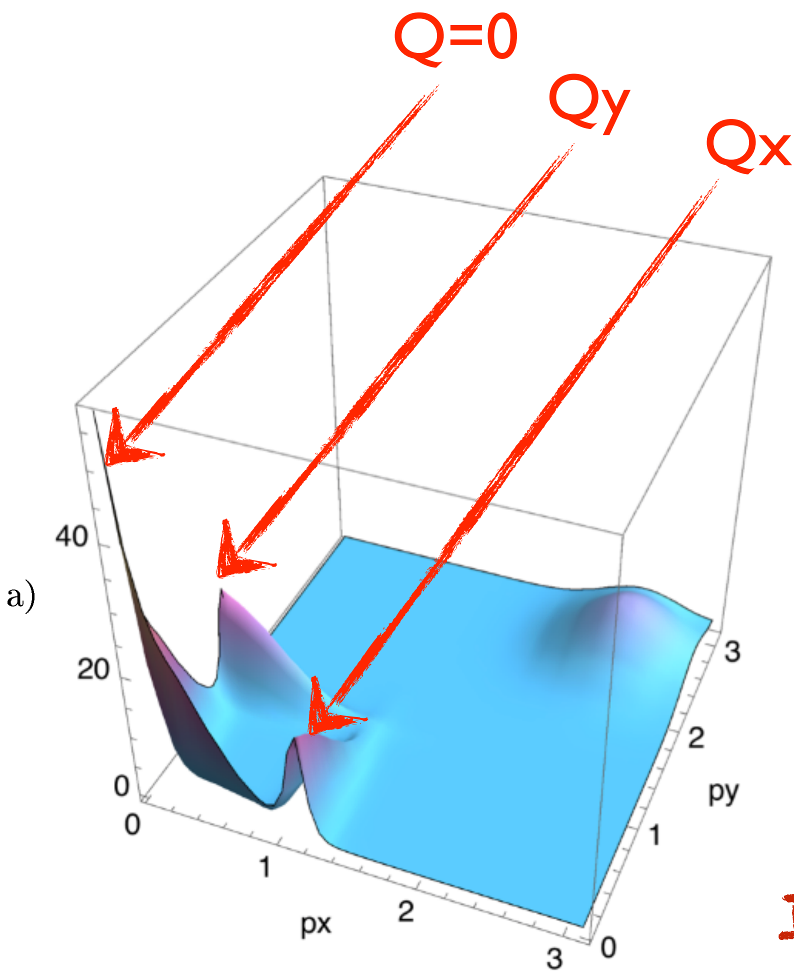
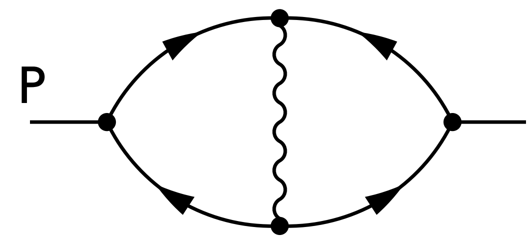
Order by disorder : SU(2) fluctuations lift the degeneracy



Large nematic response

and

Response along the crystal axes



Loop currents

OK with symmetries

Intertwined orders: not competing w. others

Experiments

ARPES

INS in Hg1201

Anomalous transport

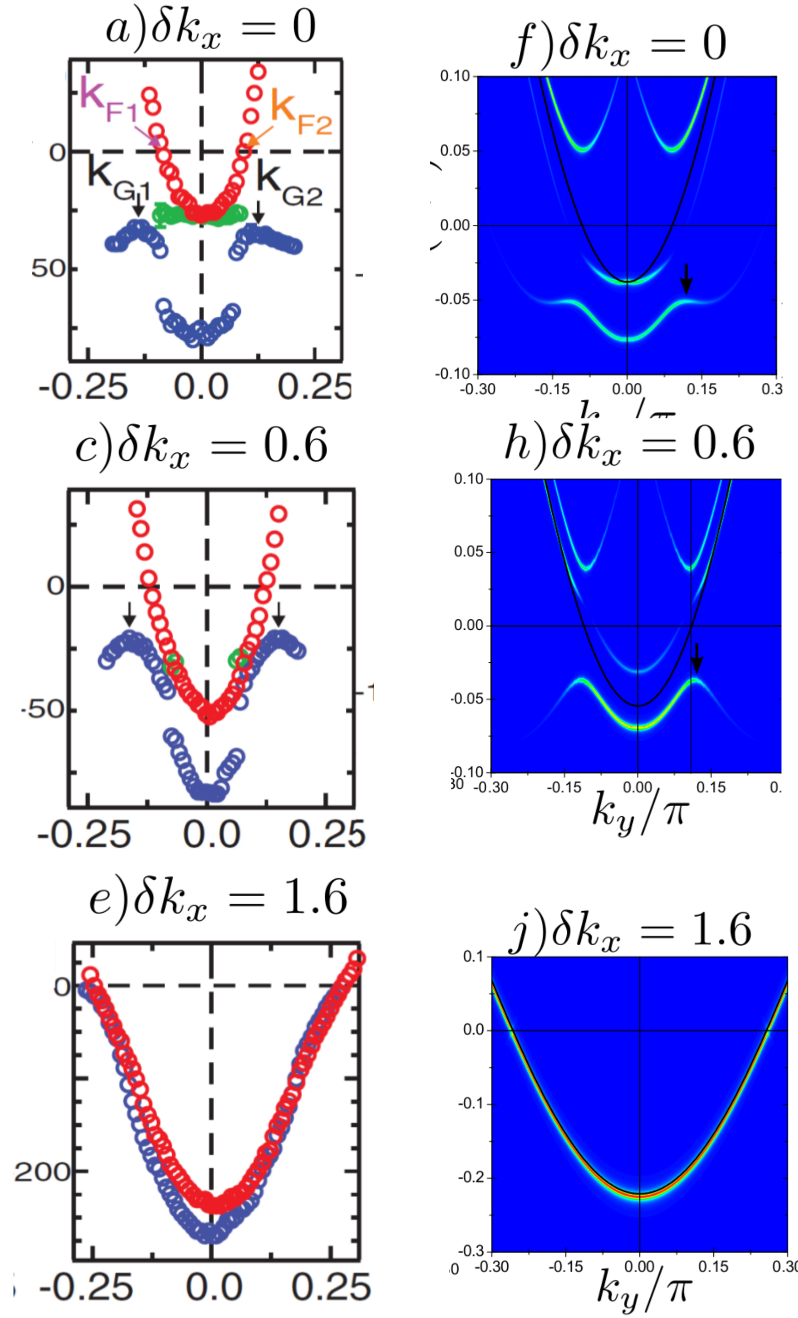
Raman: A1g resonance

ARPES

INS in Hg1201

Anomalous transport

Raman: A1g resonance



ARPES

INS in Hg1201

Anomalous transport

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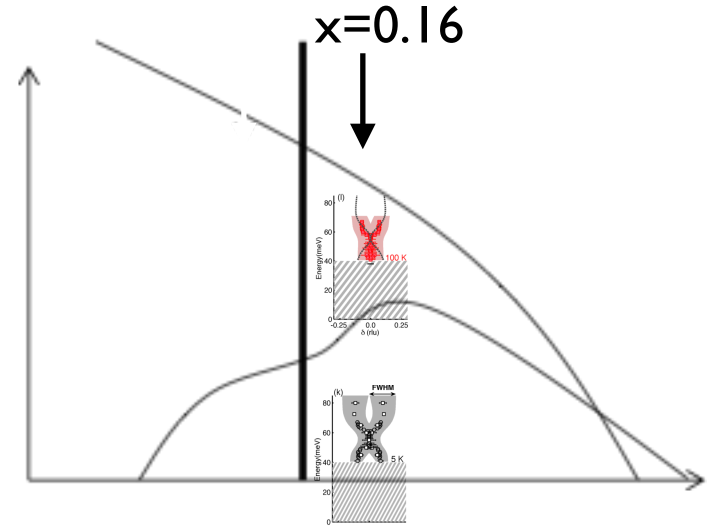
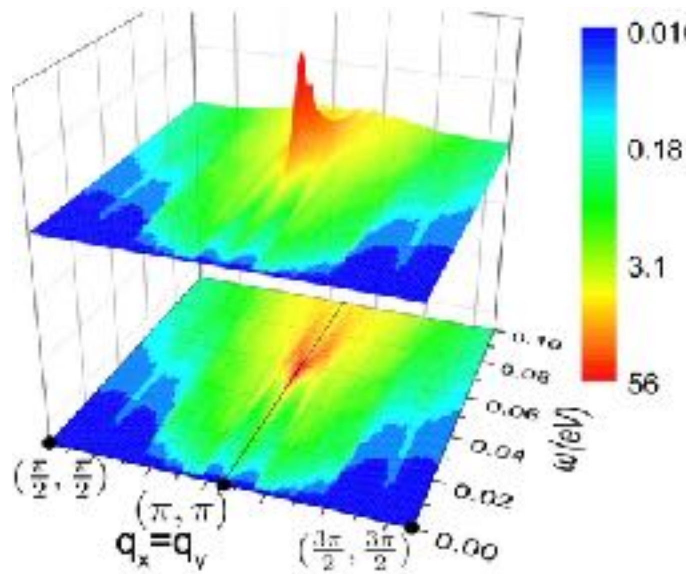


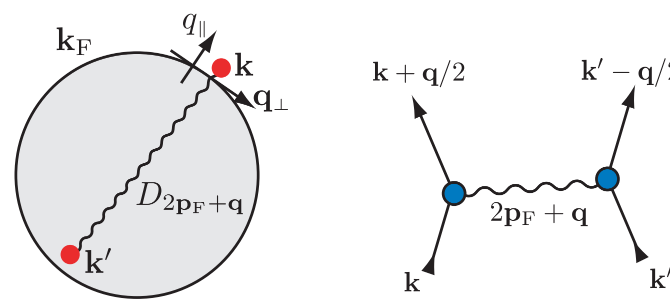


ARPES

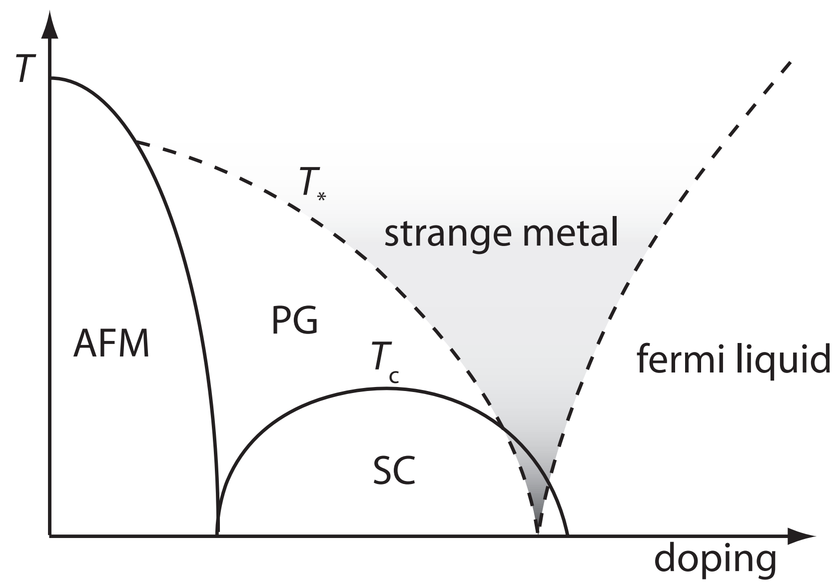
$$\rho \sim T/\log T$$

$$\Sigma \sim i\epsilon_n/\log|\epsilon_n|$$

INS in Hg1201



Anomalous transport



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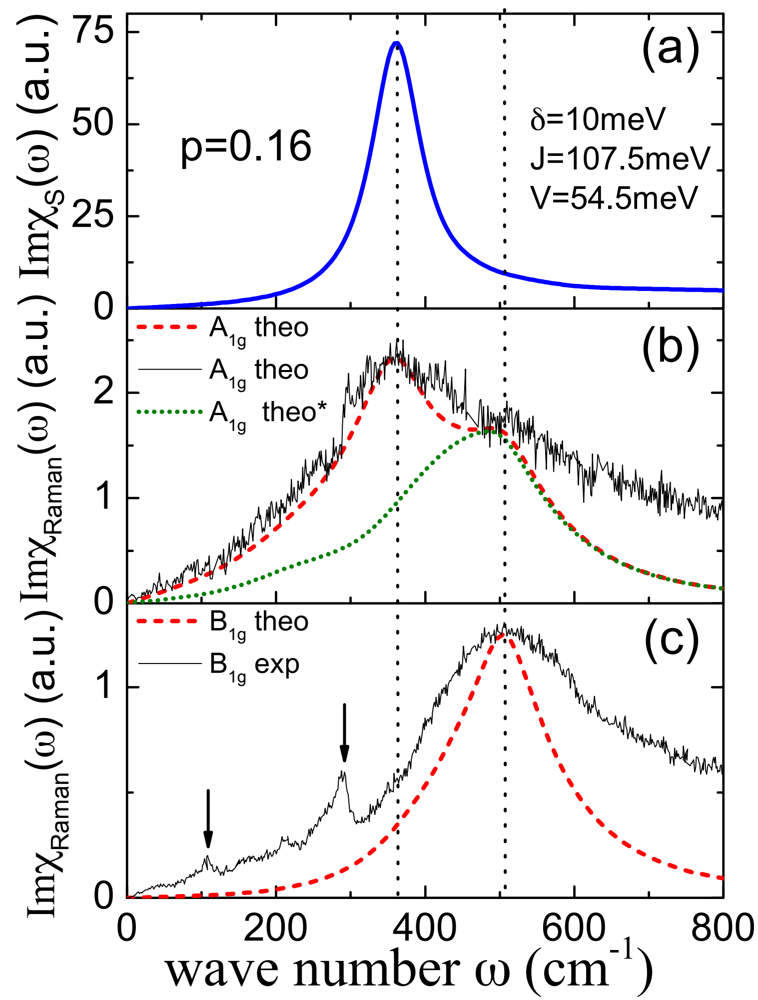

Conclusions

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

• Quasi- degeneracy between charge and SC levels is treated within SU(2) rotations and non linear σ-model

• Local structures, or skyrmions, are a signature of the model

• Experiments looked at : ARPES, transport (strange metal phase), Raman spectroscopies, Hall effect (evolution of carriers # with doping)…

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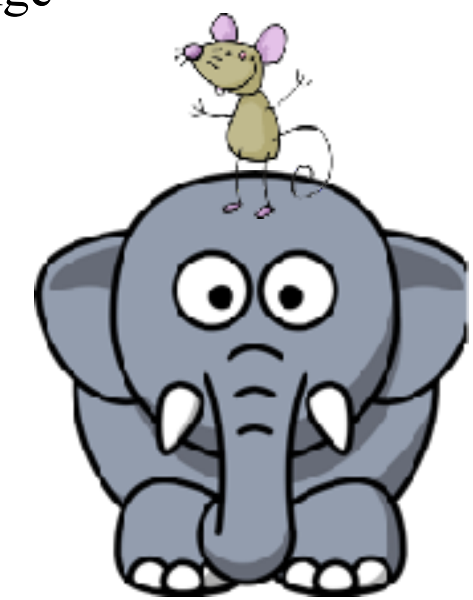


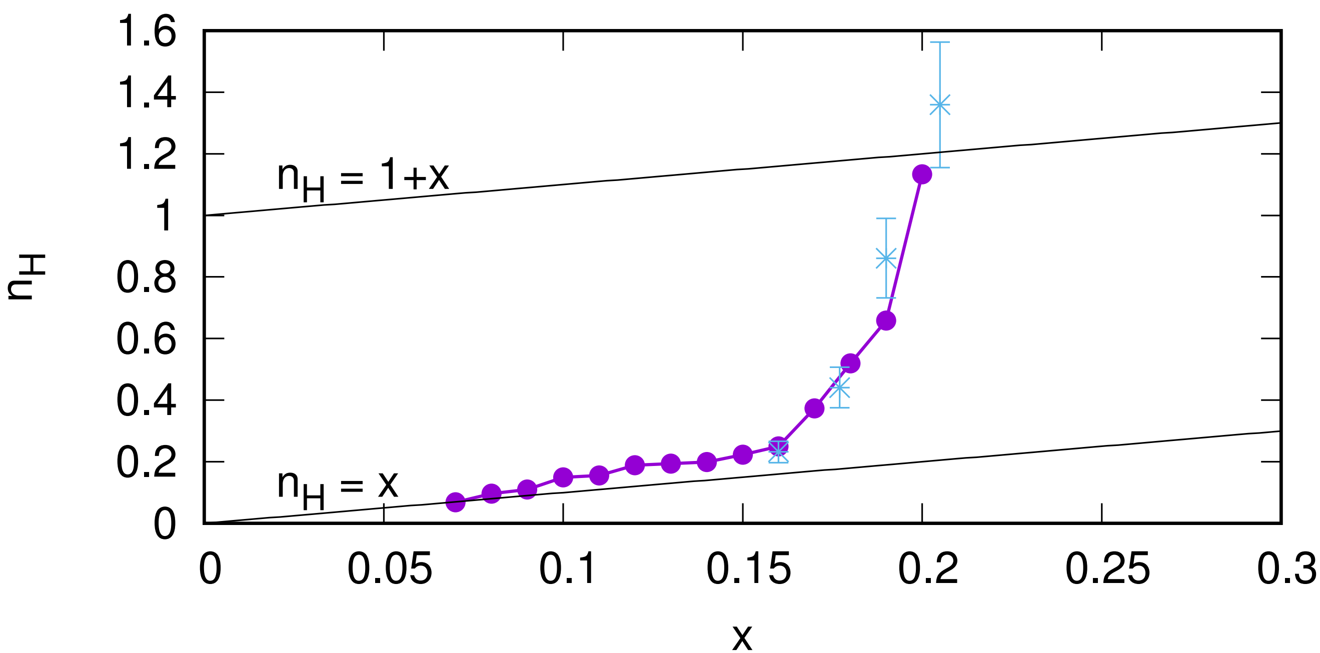
Hall resistivity

$$\sigma_{xx} = -\frac{2\pi e^2}{VN}\sum_k v_x(k)^2 \int d\omega \frac{\partial f(\omega)}{\partial \omega} A(k,\omega)^2$$

$$R_H = \frac{\sigma_{xy}}{(\sigma_{xx})^2}, \; n_H = \frac{V}{eR_H}$$

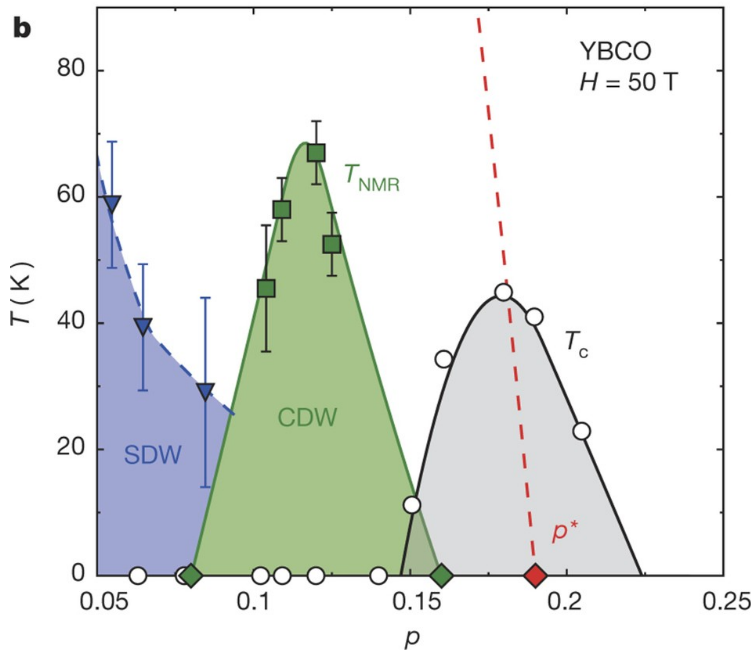
$$\sigma_{xy} = -\frac{4\pi^2 e^3}{3VN}\sum_k v_x(k)\left(v_x(k)\frac{\partial v_y(k)}{\partial k_y} - \frac{v_y(k)\left(\partial v_y(k)\right)}{\partial k_x}\right)\int d\omega \frac{\partial f(\omega)}{\partial \omega} A(k,\omega)^3$$

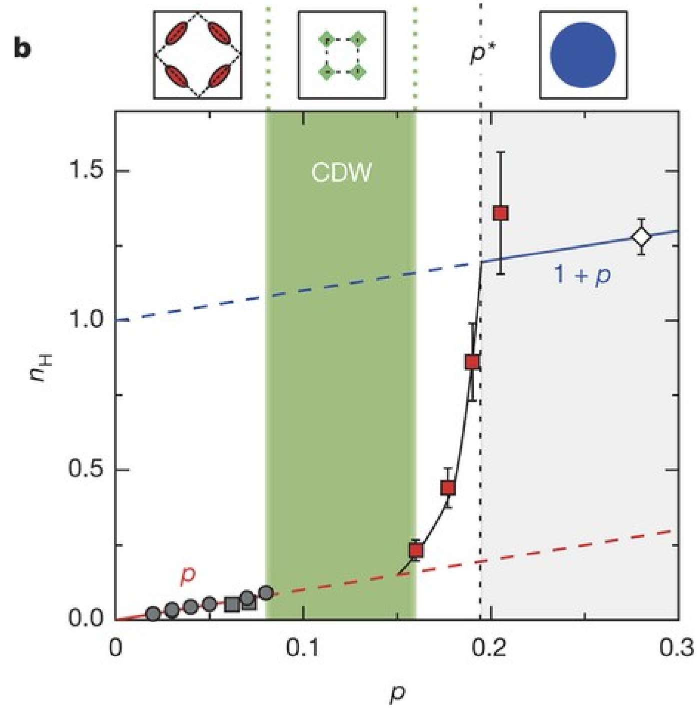
$$\mathrm{G(k,\omega)} = \frac{1}{\omega - \xi_k - B\,\frac{M(k)^2}{\omega + \xi_k}}$$



Badoux et al 2016

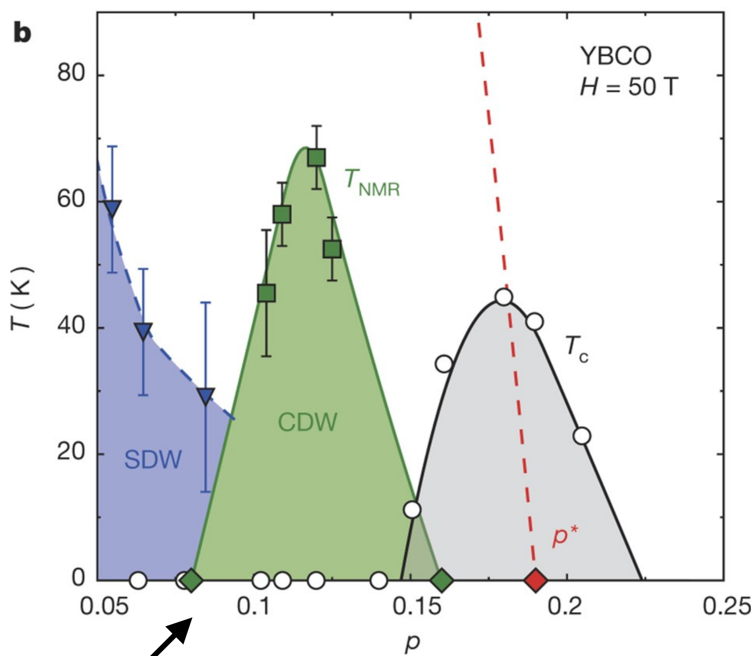
Badoux et al., 2016

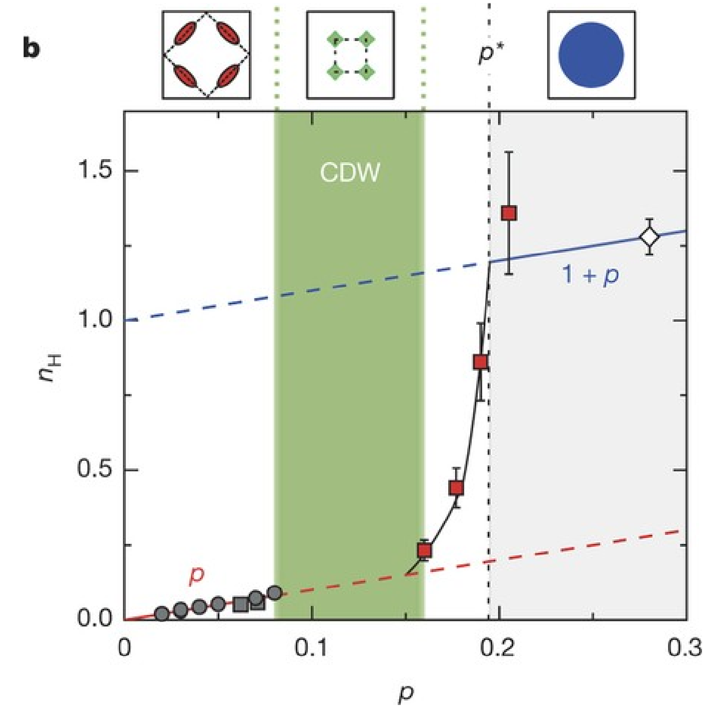


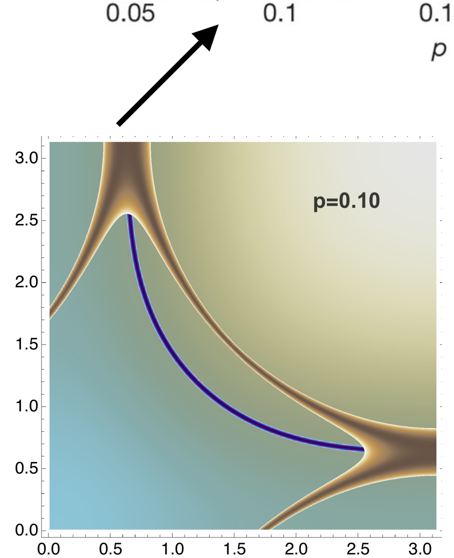


AF correlations -> Fermi Arcs -> p

Badoux et al., 2016







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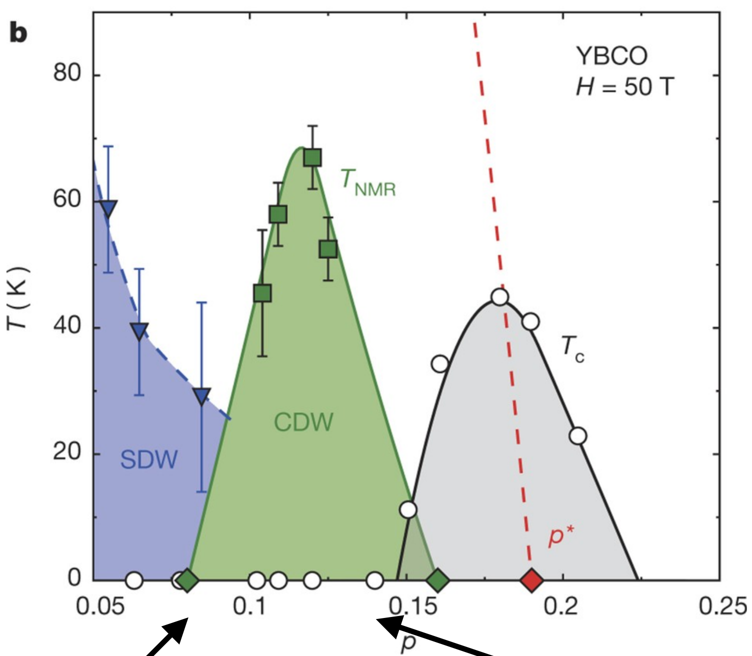

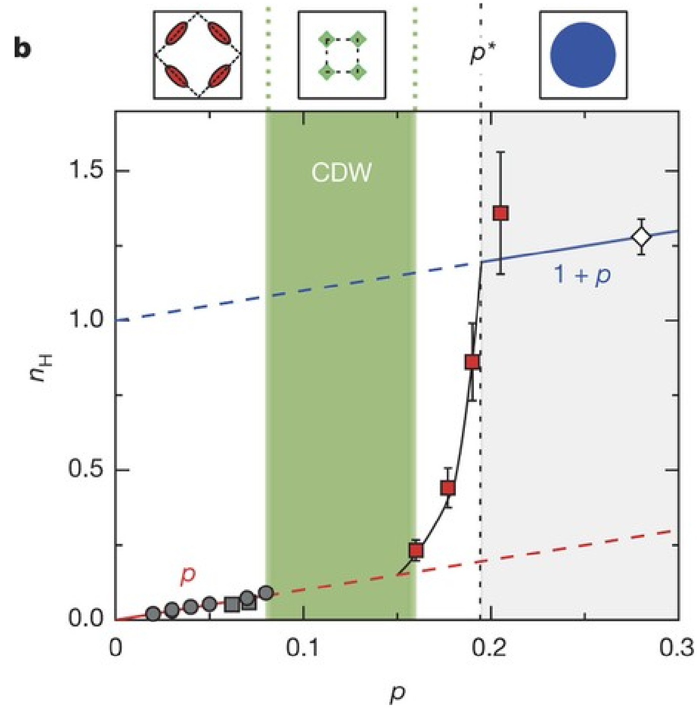

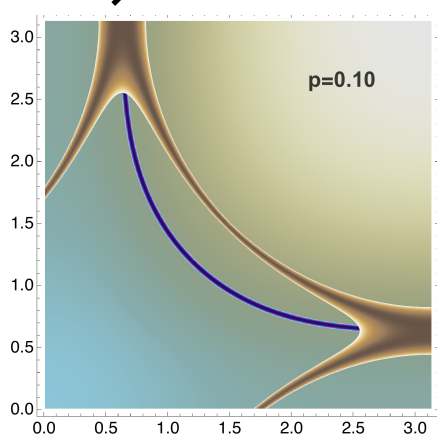

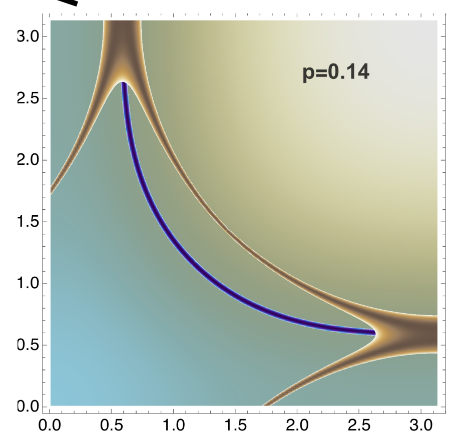

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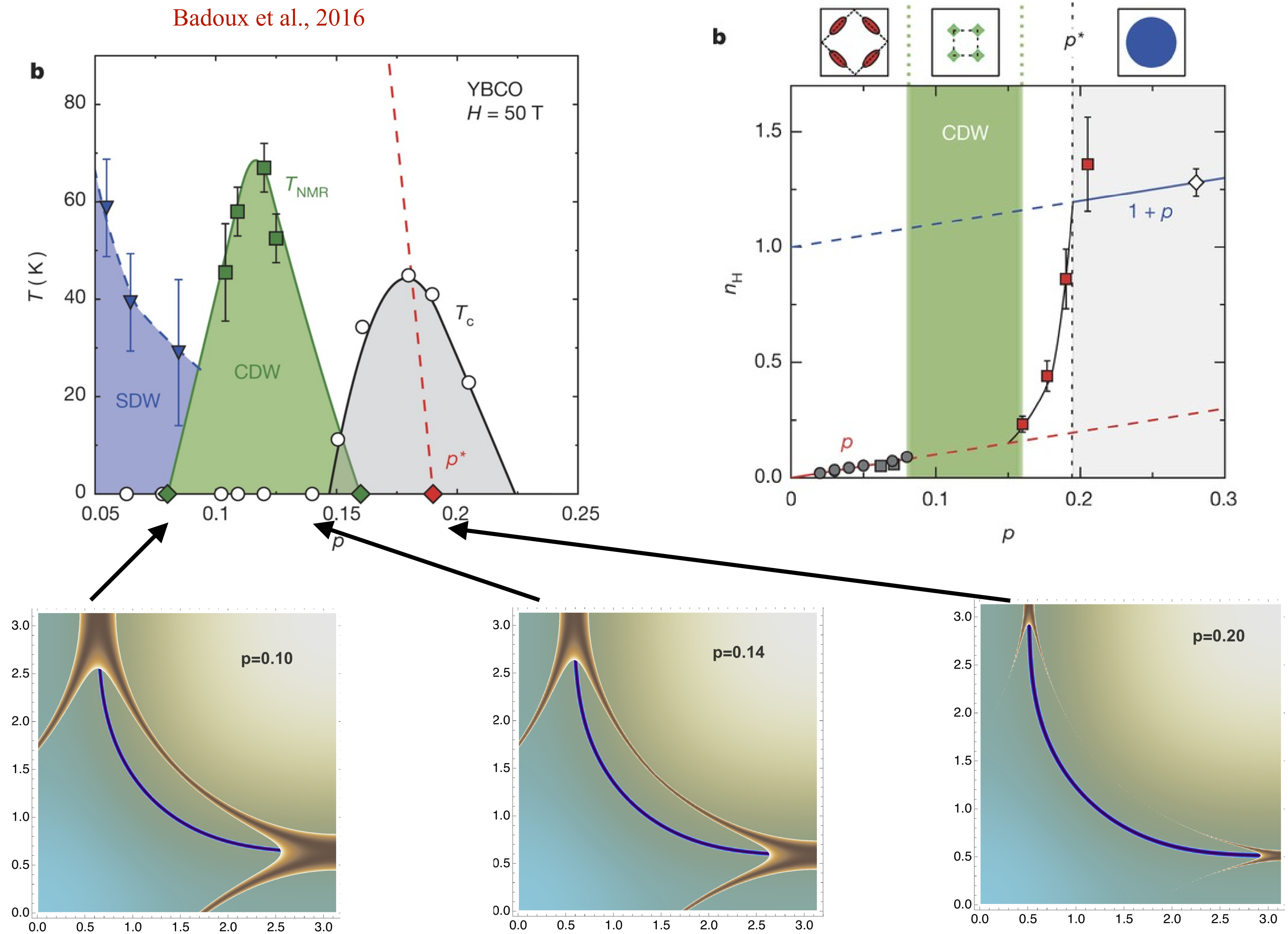

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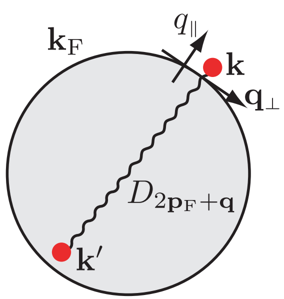
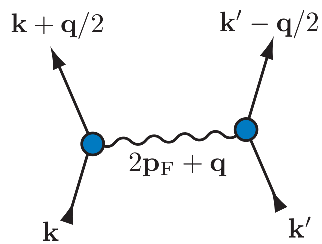
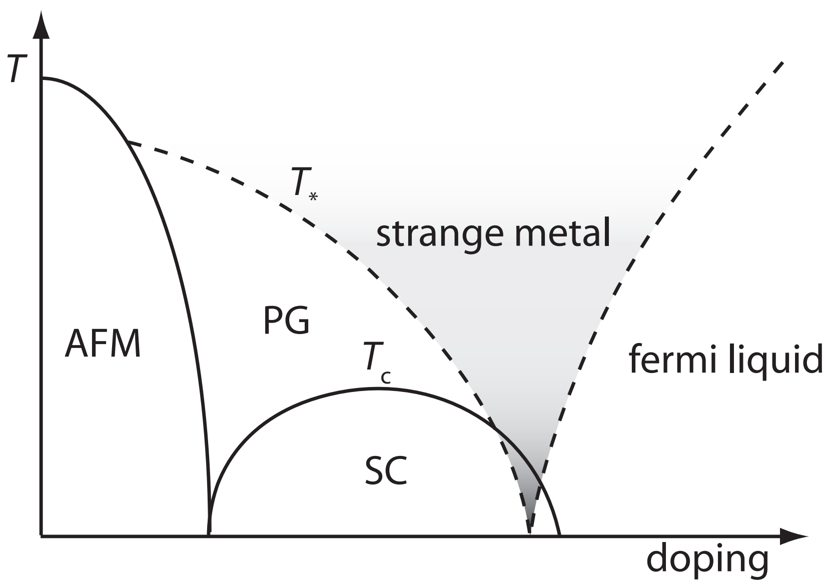
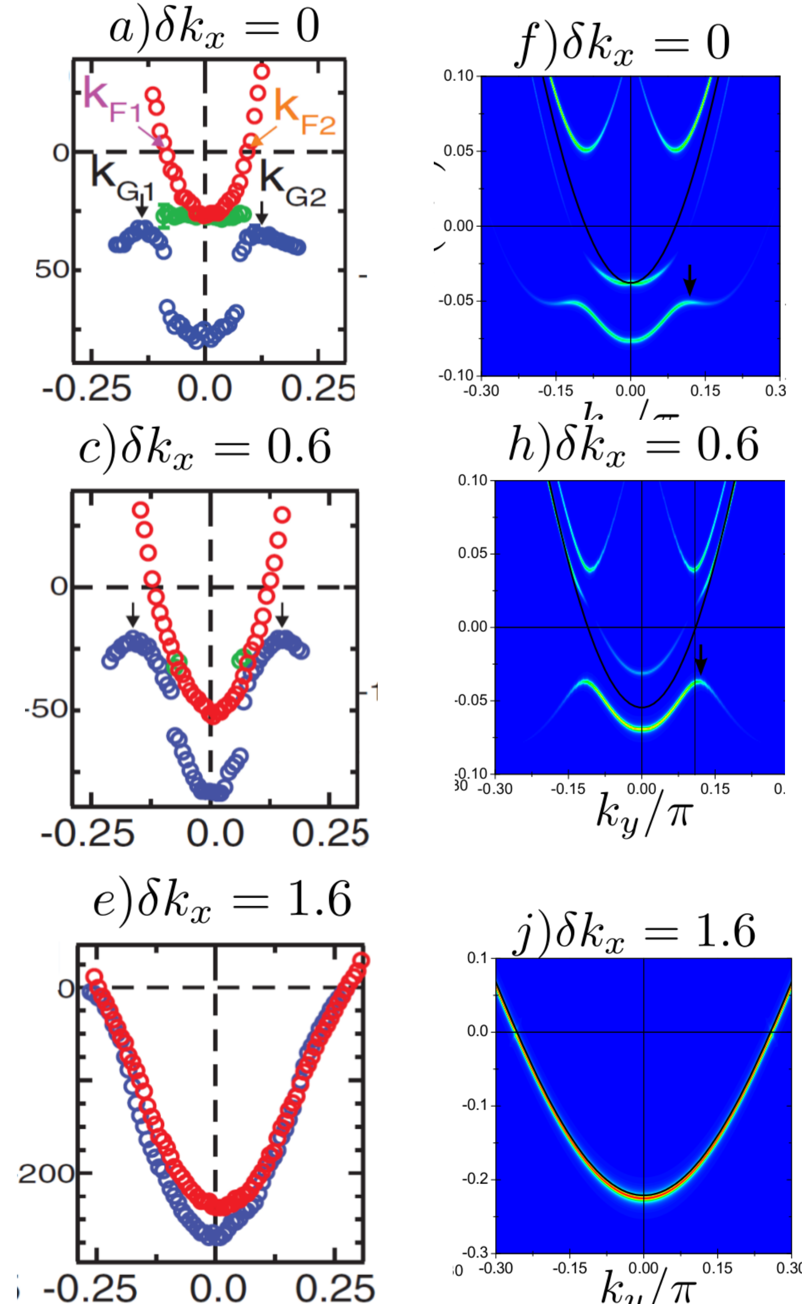
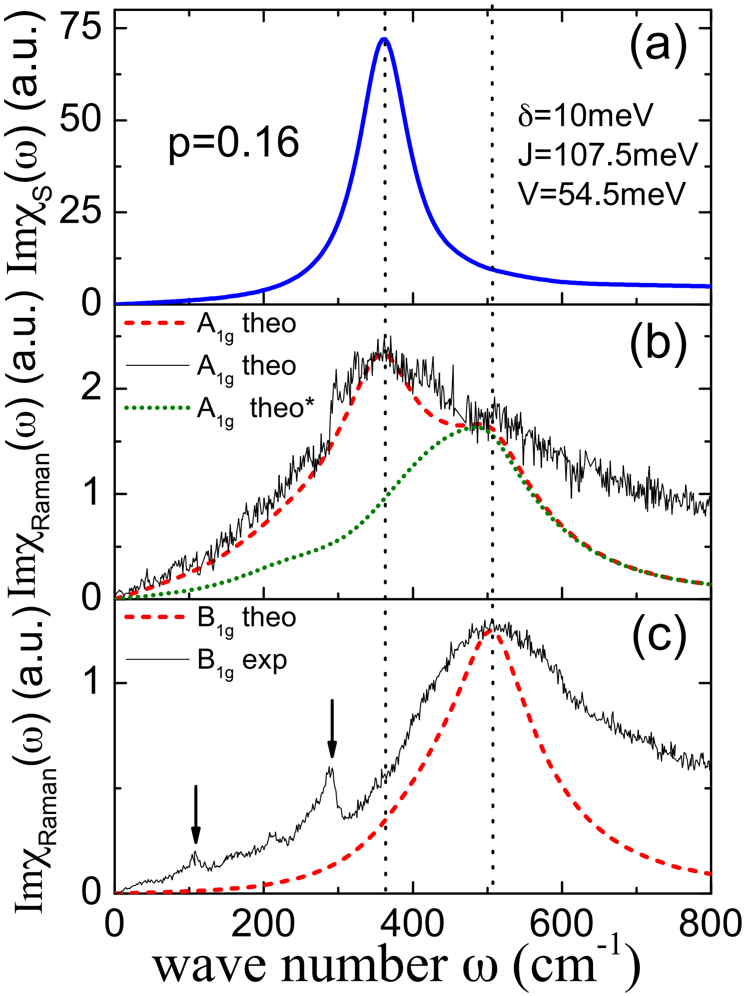


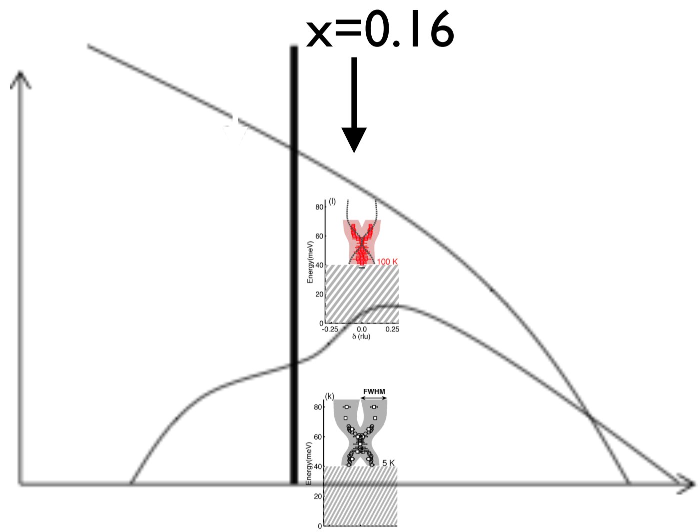




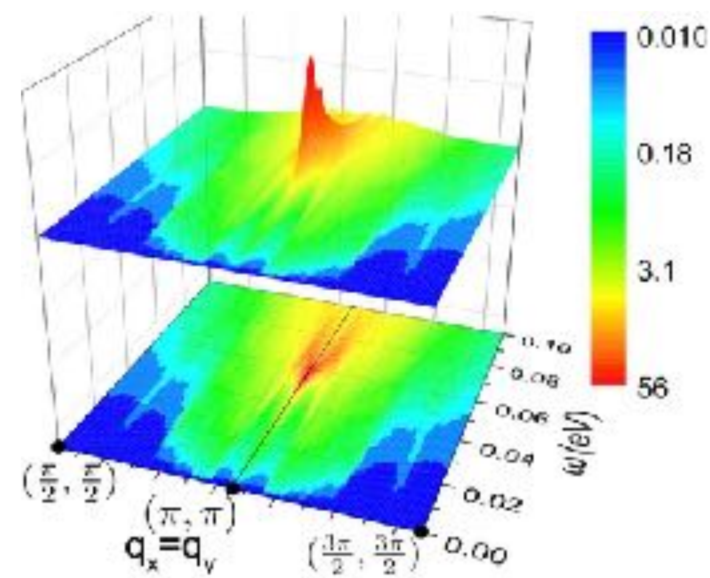




p=0.16
δ=10meV
J=107.5meV
V=54.5meV
(a)
(b)
(c)
A1g theo
A1g theo
A1g theo*
B1g theo
B1g exp
wave number ω (cm-1)



x=0.16



0.010
0.18
3.1
56
ω[eV]
qx=qy