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Loss of Quasiparticle Integrity in Underdoped Cuprates

UBC-MPI Quantum Matter Institute

In situ doping control of the surface of high-temperature superconductors

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ARTICLES

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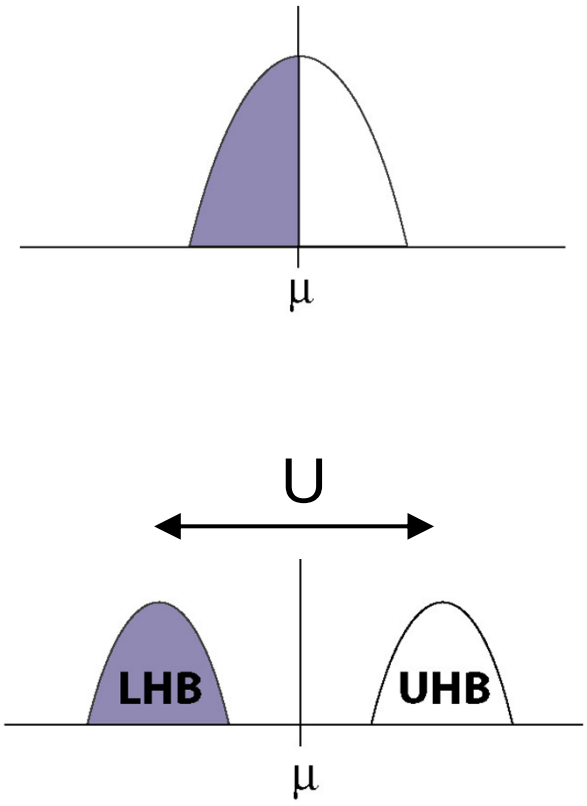
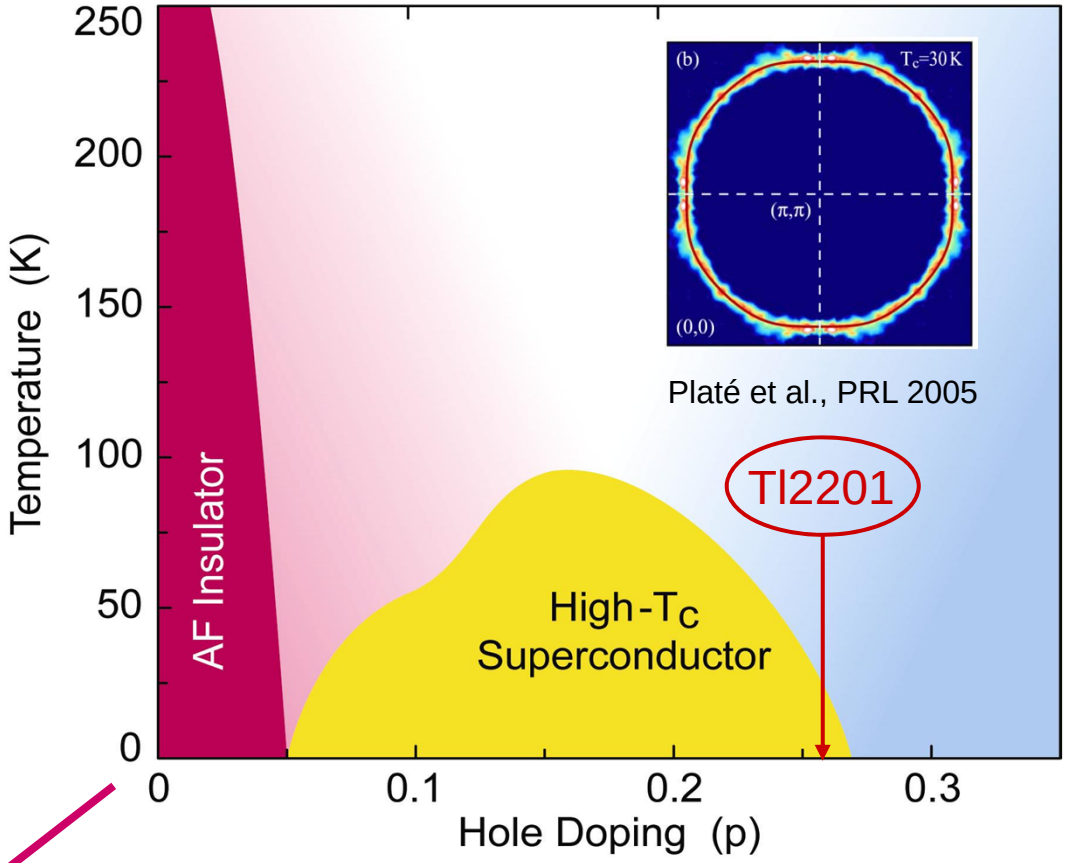
Loss of nodal quasiparticle integrity in underdoped $YBa_2Cu_3O_{6+x}$

D. Fournier[1]*, G. Levy[1], Y. Pennec[1], J. L. McChesney[2], A. Bostwick[2], E. Rotenberg[2], R. Liang[3], W. N. Hardy[1,3], D. A. Bonn[1,3], I. S. Elfimov[3] and A. Damascelli[1,3]*

From Fermi Liquid to Mott Insulator



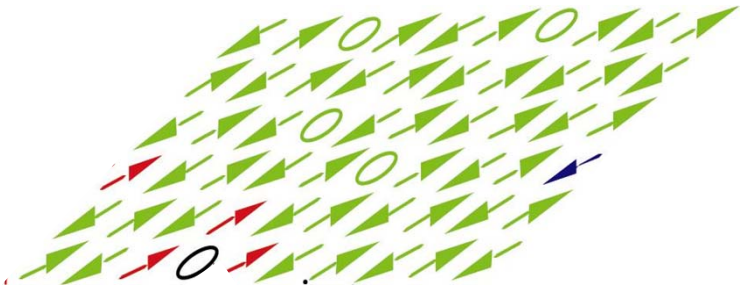


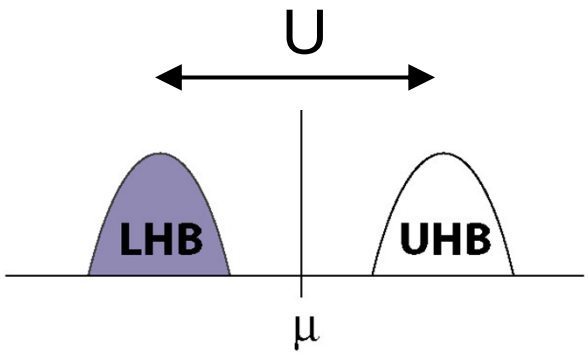
Mott insulator

Normal state properties

From Fermi Liquid to Mott Insulator

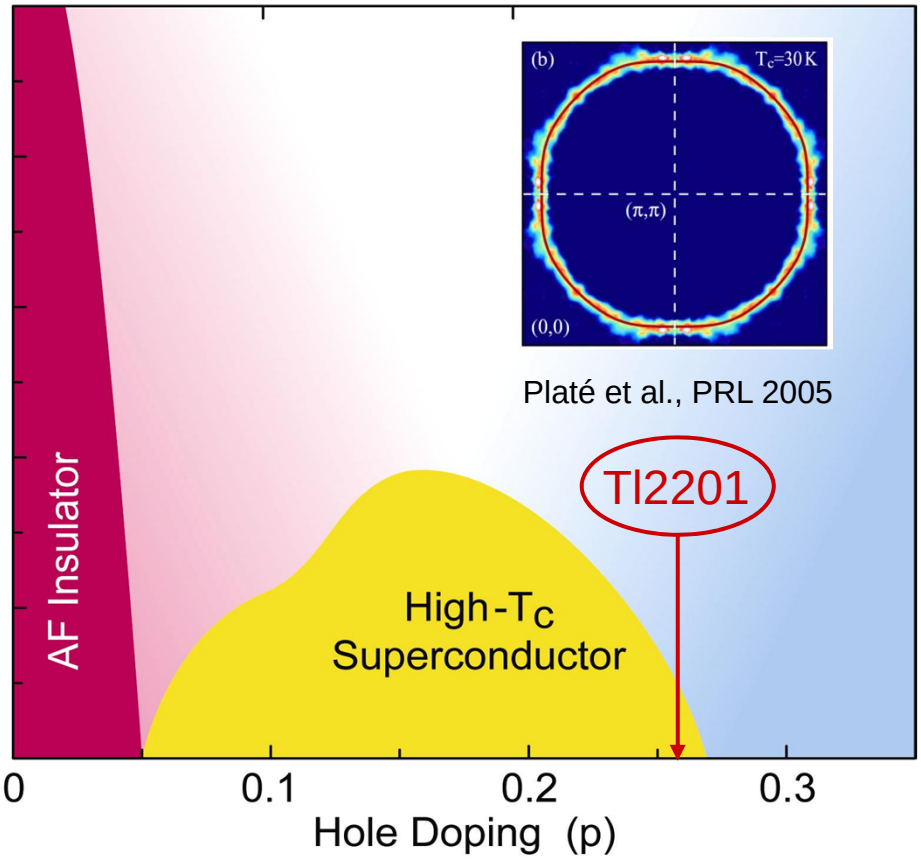
Correlations suppress Z_k





$$Z \simeq 2p/(p+1)$$

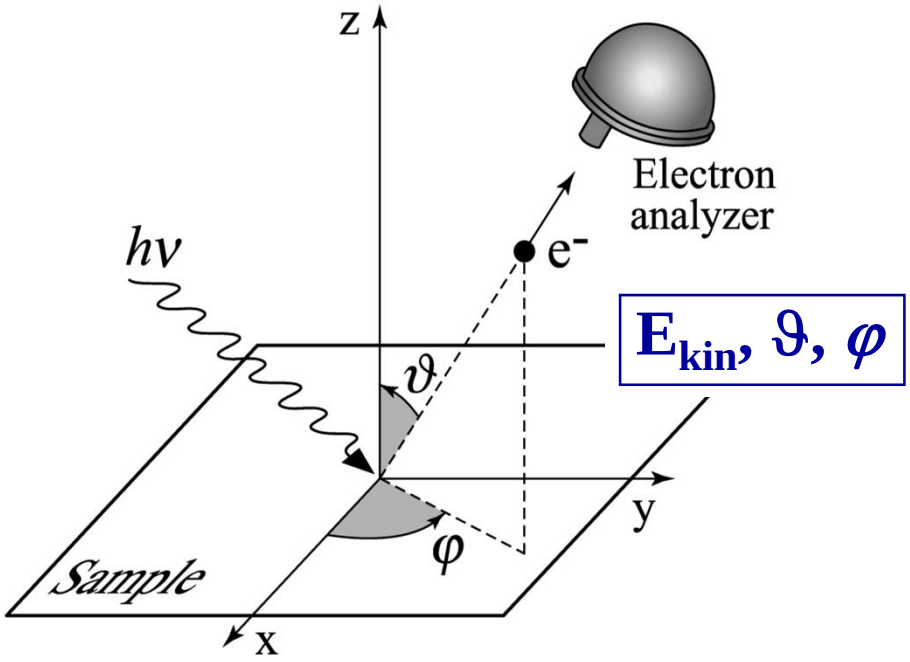
Sawatzky, Anderson, Randeria, Paramekanti, Yang, Rice, et al.



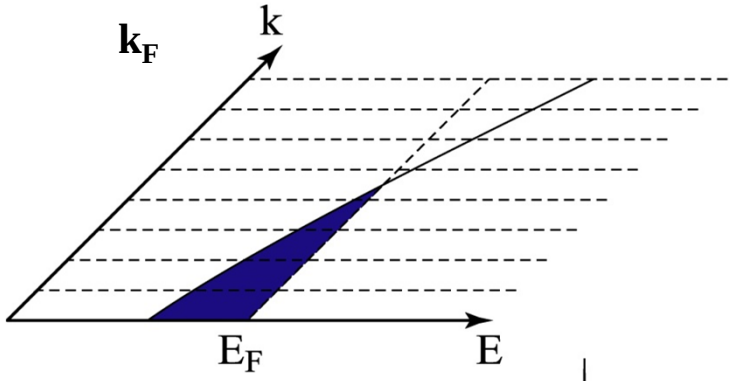
Platé et al., PRL 2005

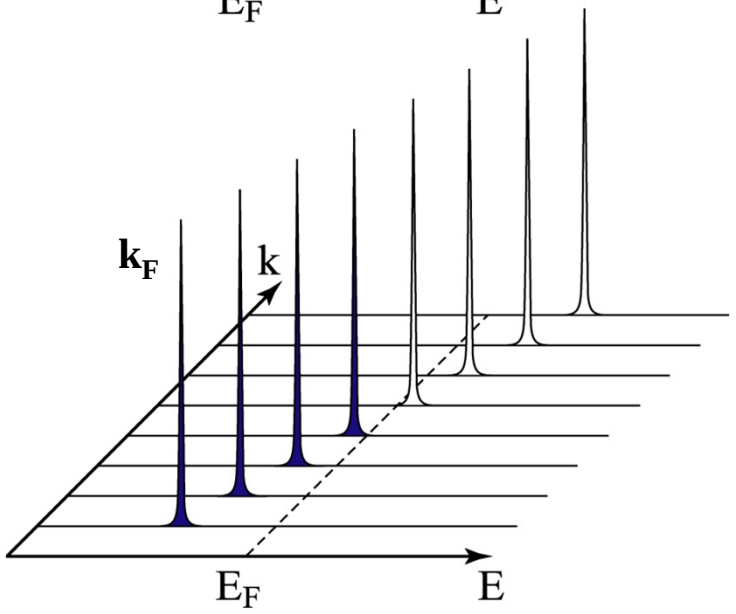
Normal state properties

Angle-Resolved Photoemission Spectroscopy



Electrons in
Reciprocal Space





Energy Conservation

$$E_{kin} = h\nu - \phi - |E_B|$$

Momentum Conservation

$$\mathbf{p}_{\parallel} = \hbar\mathbf{k}_{\parallel} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$

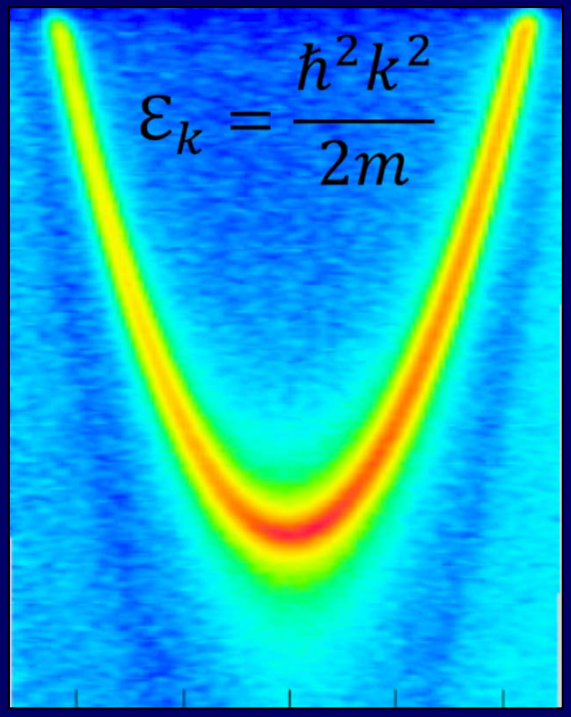
Band Velocity

$$v_k = \frac{1}{\hbar}\frac{\partial \mathcal{E}_k}{\partial k}$$

Band Mass

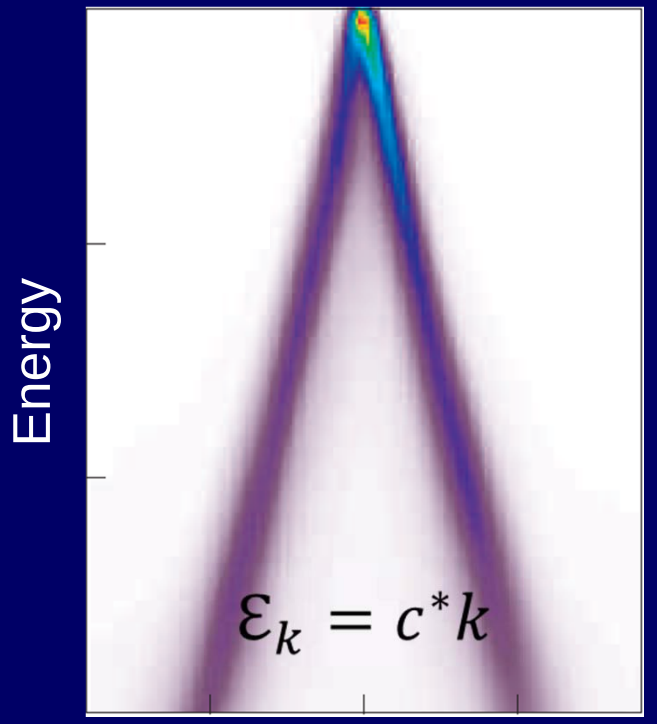
$$\frac{1}{m_k} = \frac{1}{\hbar^2}\frac{\partial^2 \mathcal{E}_k}{\partial k^2}$$

Cu surface state



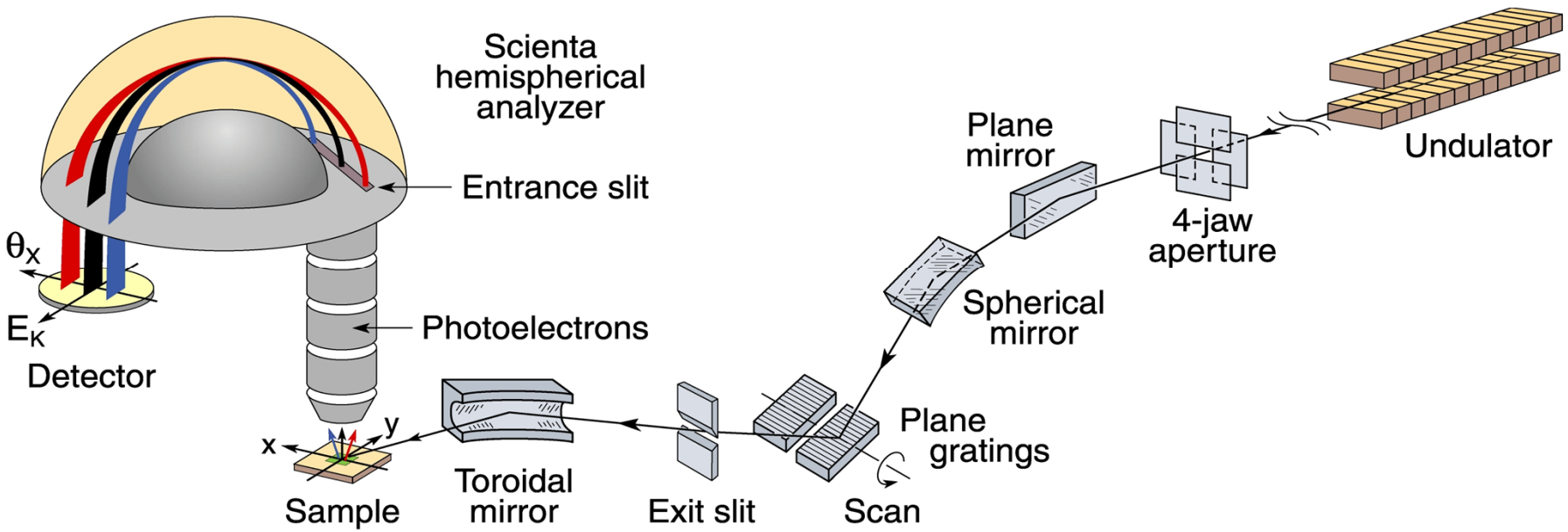
Reinert & Hufner, NJP 2005

Graphene



Zhou et al., Nat. Phys. 2006

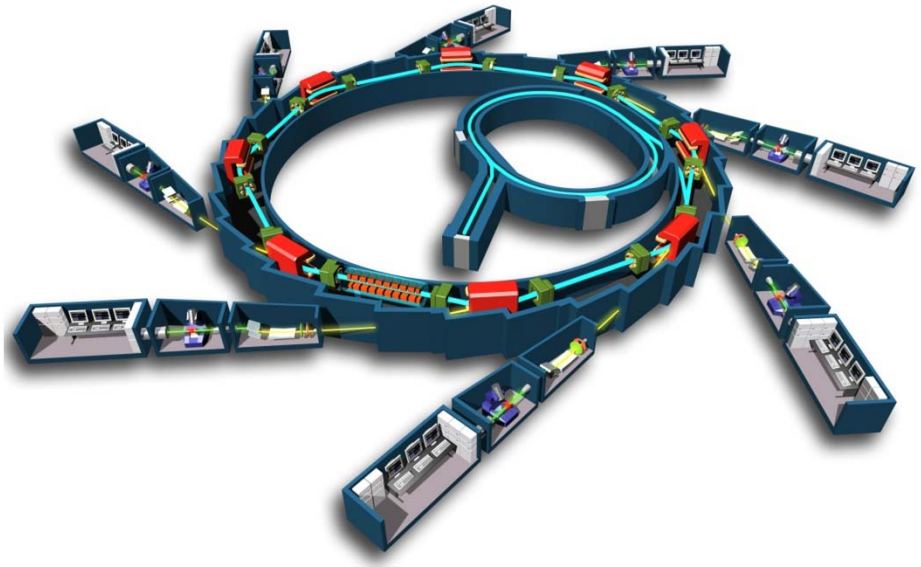
Angle-Resolved Photoemission Spectroscopy



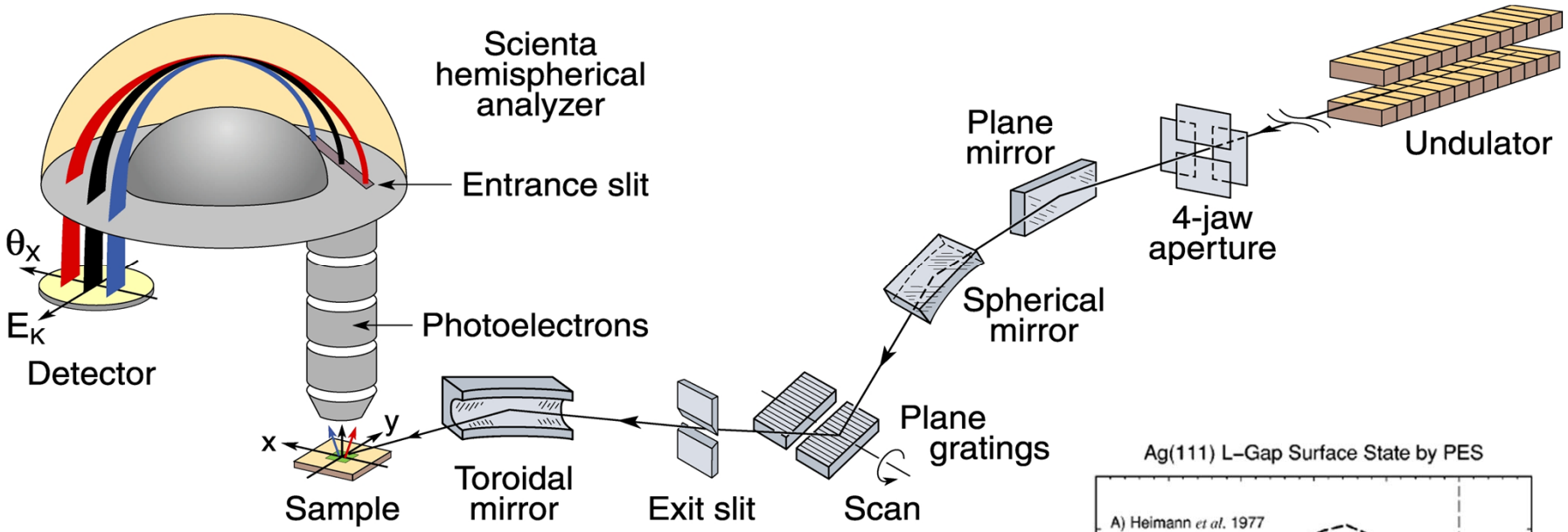
Parallel multi-angle recording

- Improved energy resolution
- Improved momentum resolution
- Improved data-acquisition efficiency

	ΔE (meV)	$\Delta\theta$
past	20-40	2°
now	1-10	0.2°



Angle-Resolved Photoemission Spectroscopy



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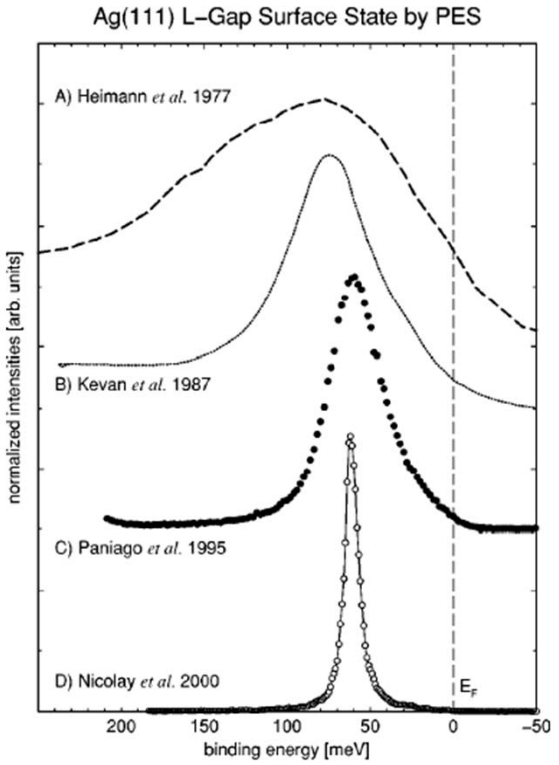

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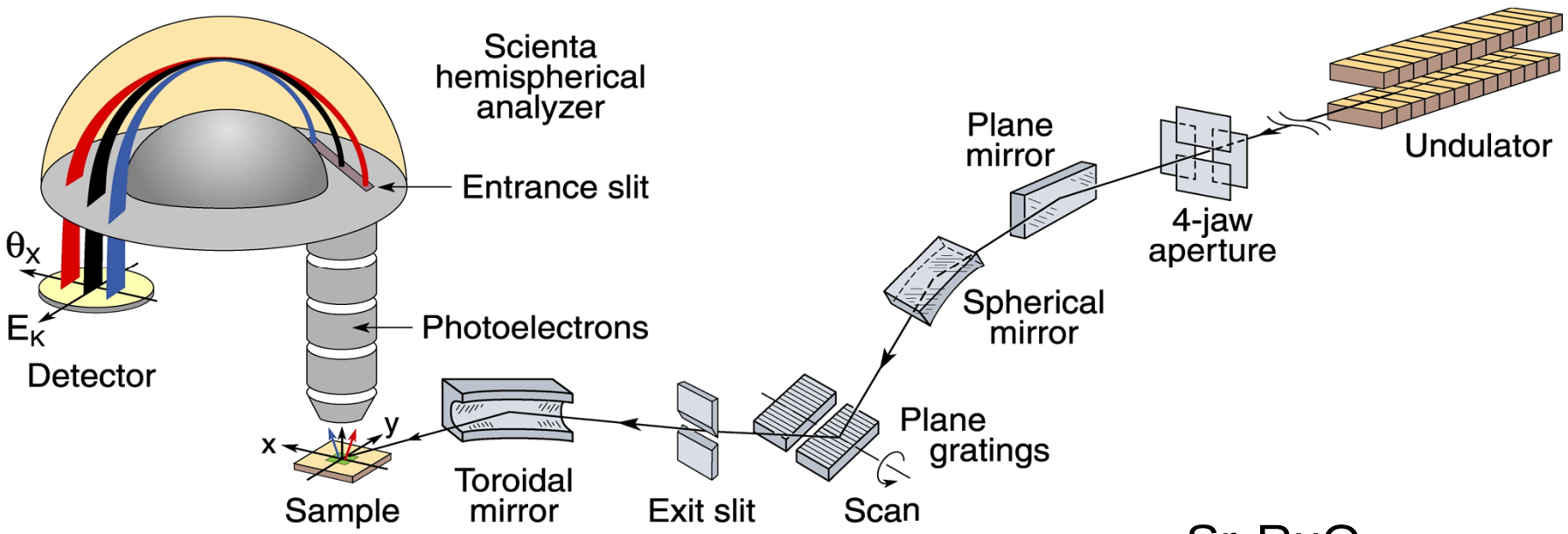

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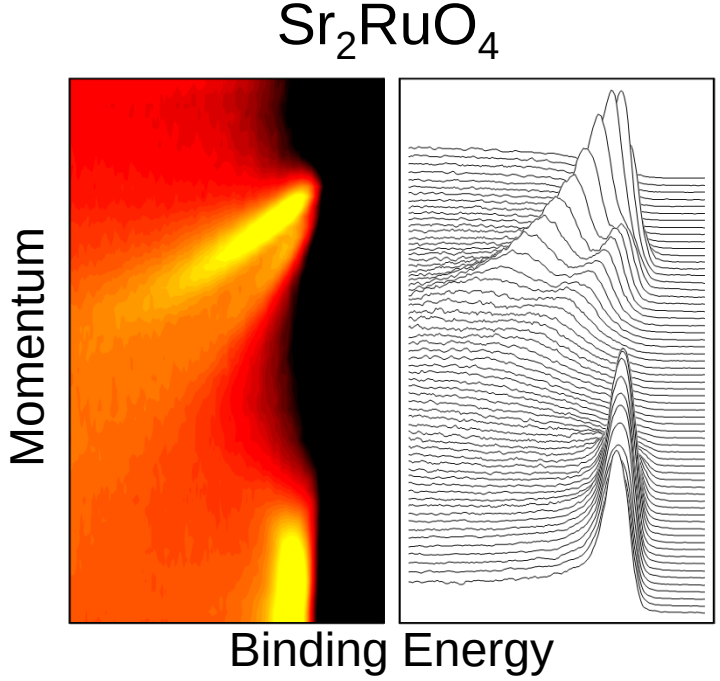

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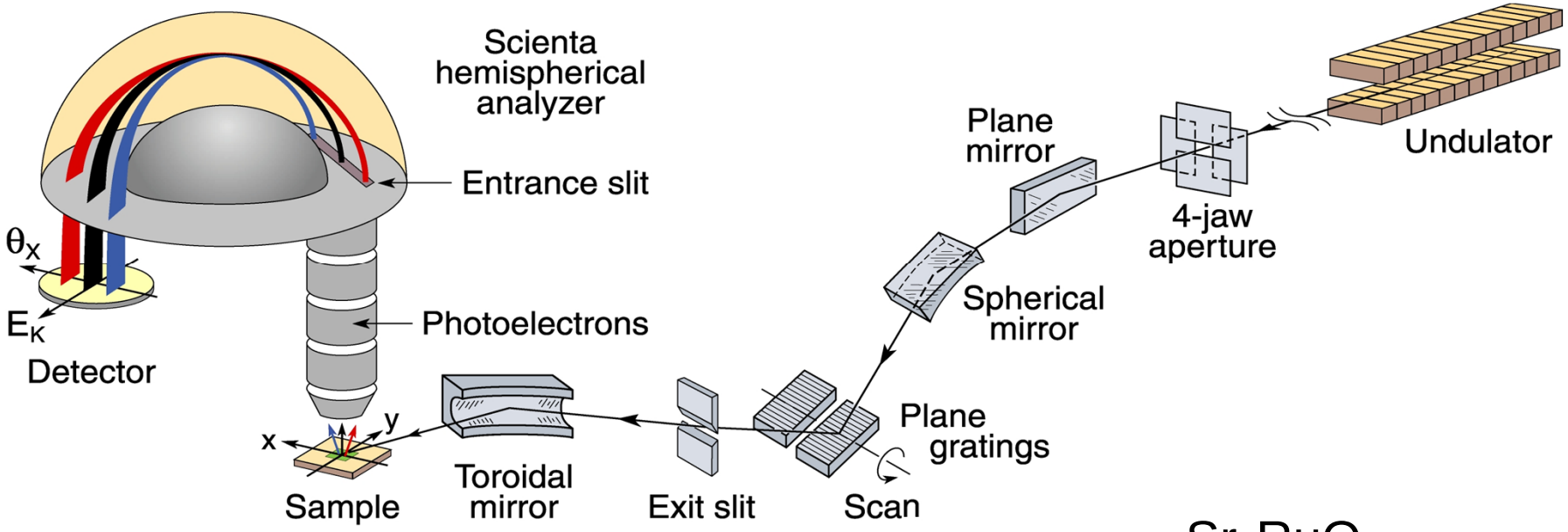

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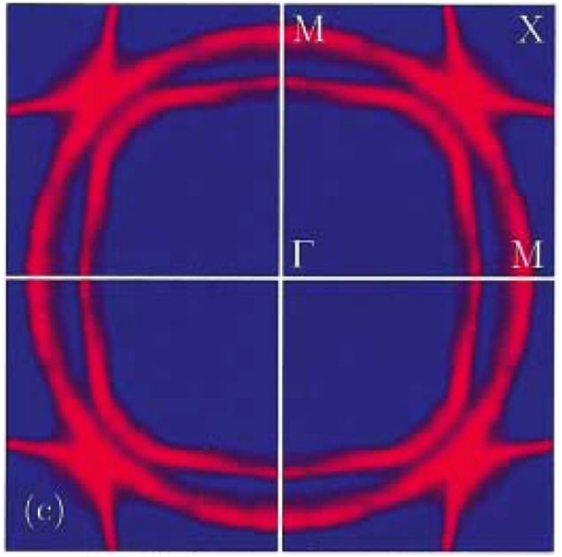
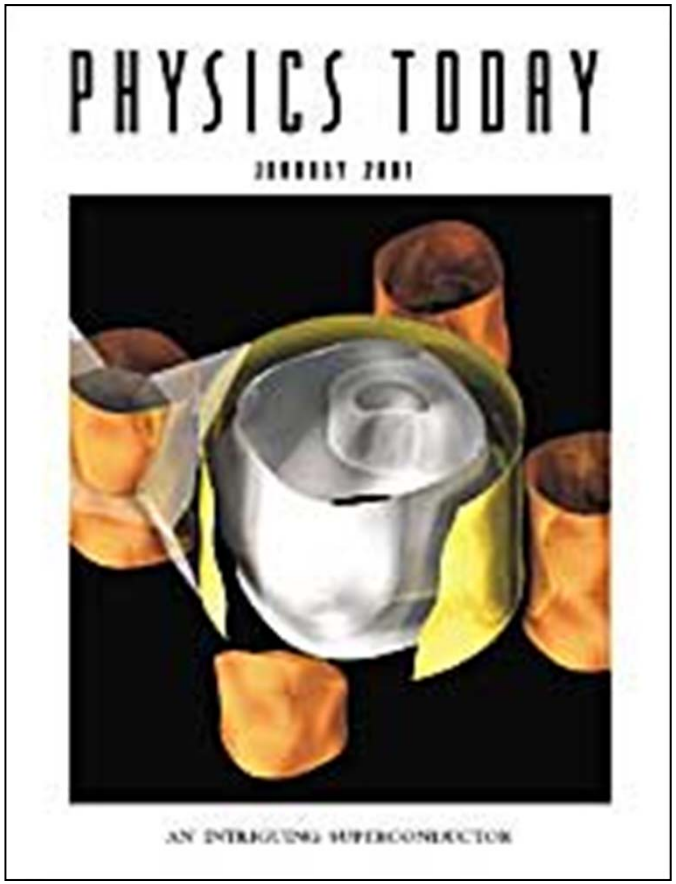
Sr_2RuO_4



A. Damascelli *et al*., PRL **85**, 5194 (2000)

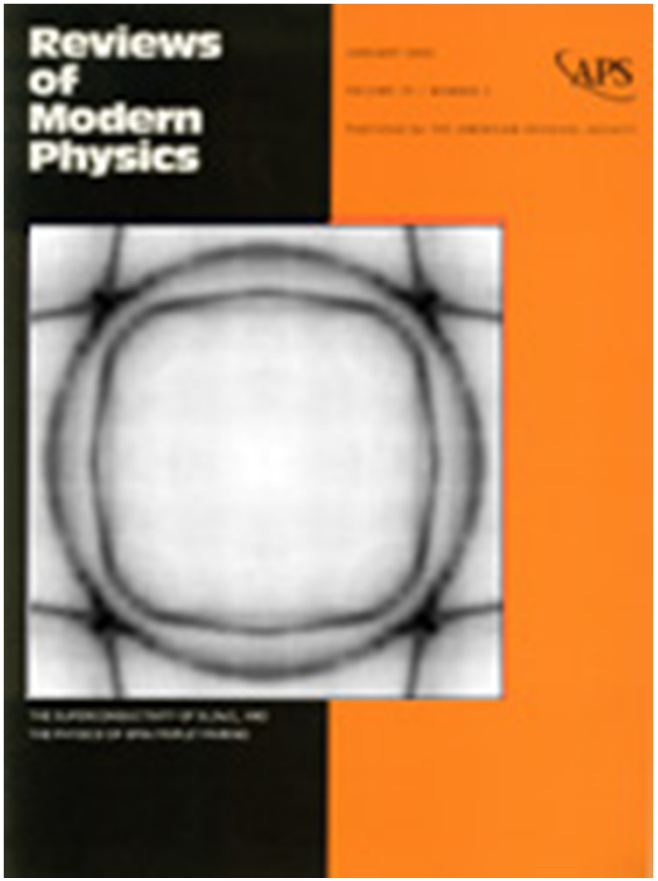
The Fermi Surface of Sr_2RuO_4

de Haas-van Alphen



Bergemann, Mackenzie, Julian, Maeno

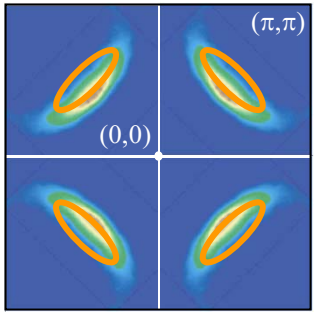
ARPES



Damascelli, Hussain, Shen

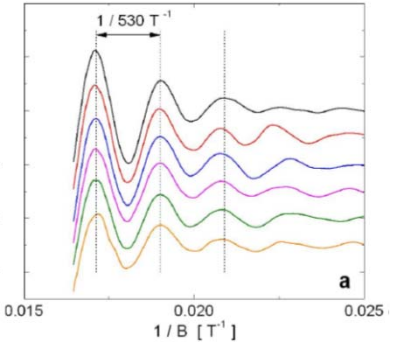
Fermiology across the Cuprate Phase Diagram

CCOC - x=0.12



ARPES – Shen (05)

YBCO - x=0.10

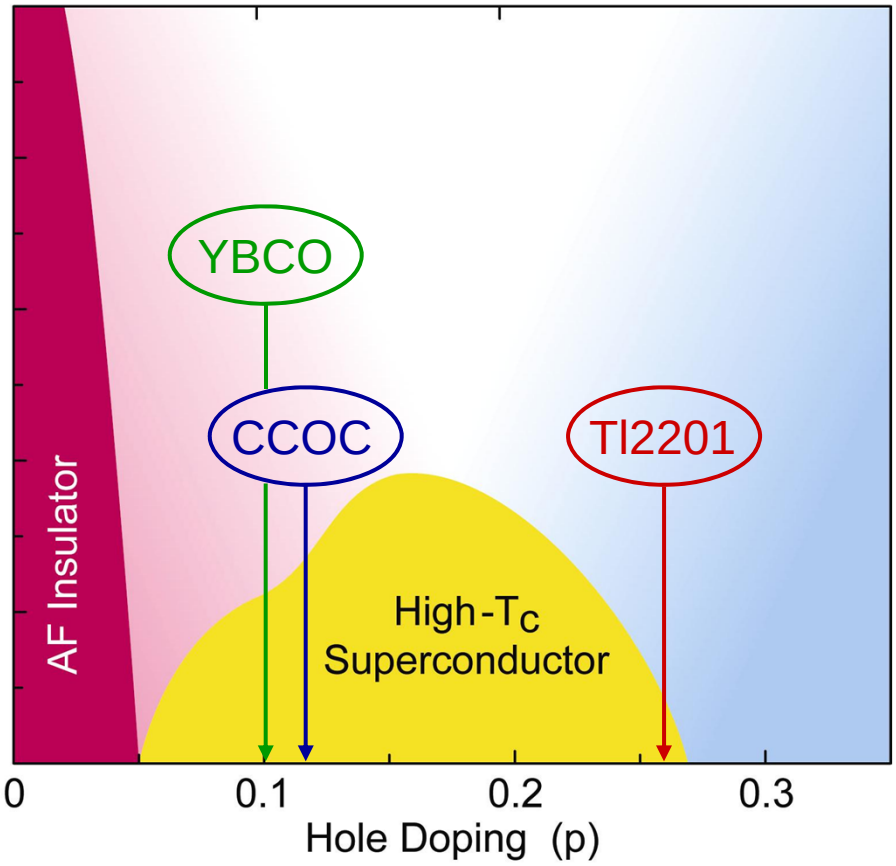


QO – Doiron-Leyraud (07)

ARPES on YBCO6.5

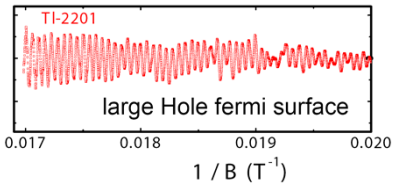
Overdoped Tl2201

Quantitative agreement between single-particle and transport probes

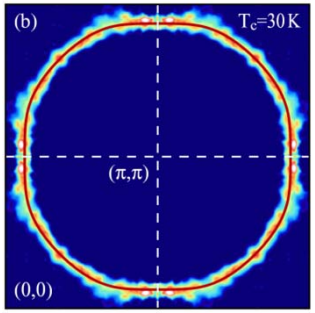


Can this be the gateway to a unified picture for underdoped cuprates?

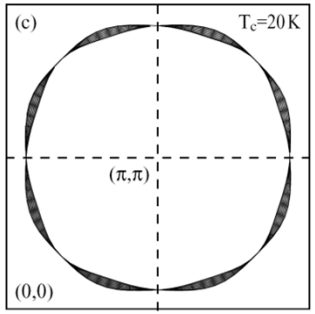
Tl2201 - x=0.26



dHvA – Vignolle (08)

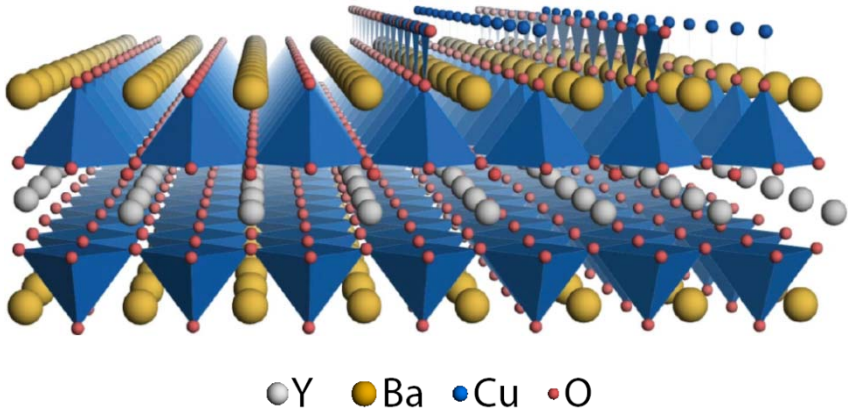


ARPES – Platé (05)

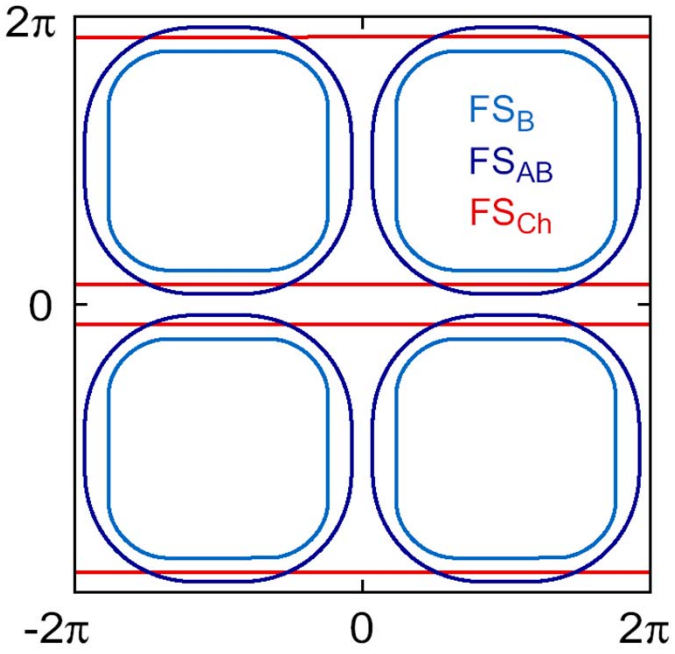


AMRO – Hussey (03)

Fermiology of Underdoped YBCO



Elfimov, Sawatzky, Damascelli PRB **77**, 060504 (2008)



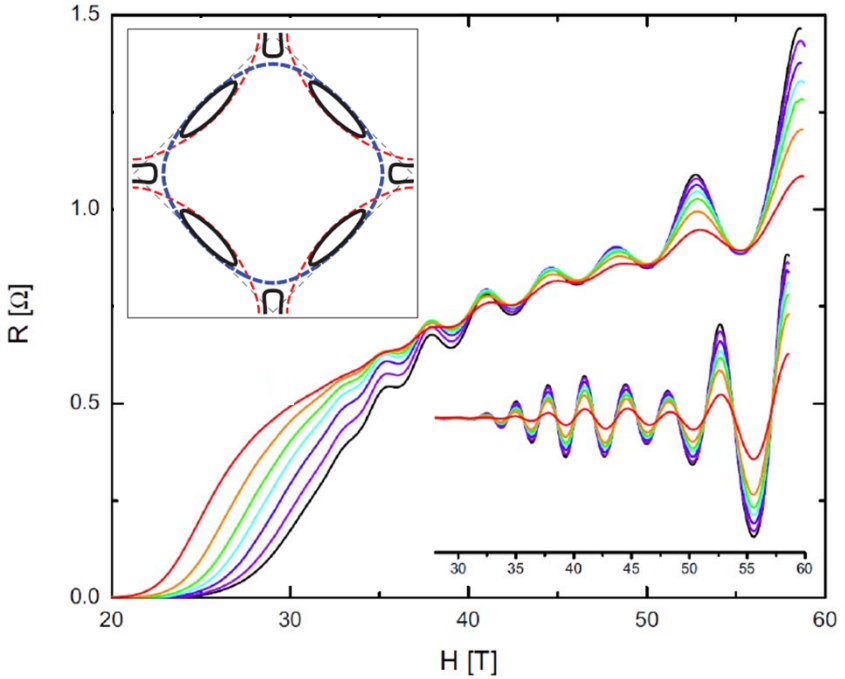
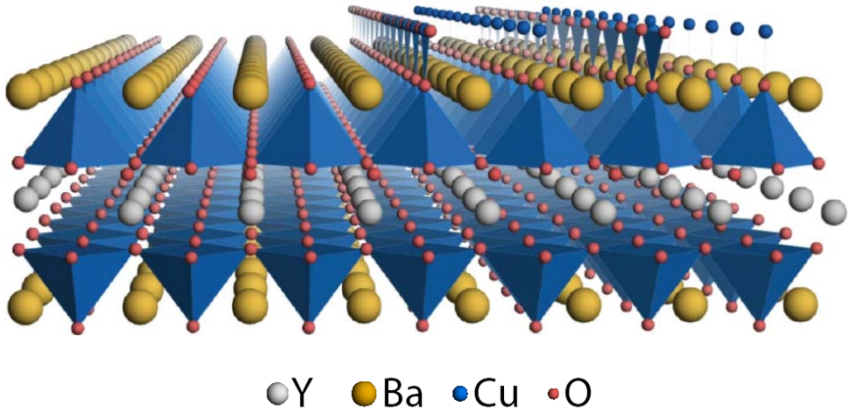


Table 1 | Fit parameters for two warped Fermi surfaces.

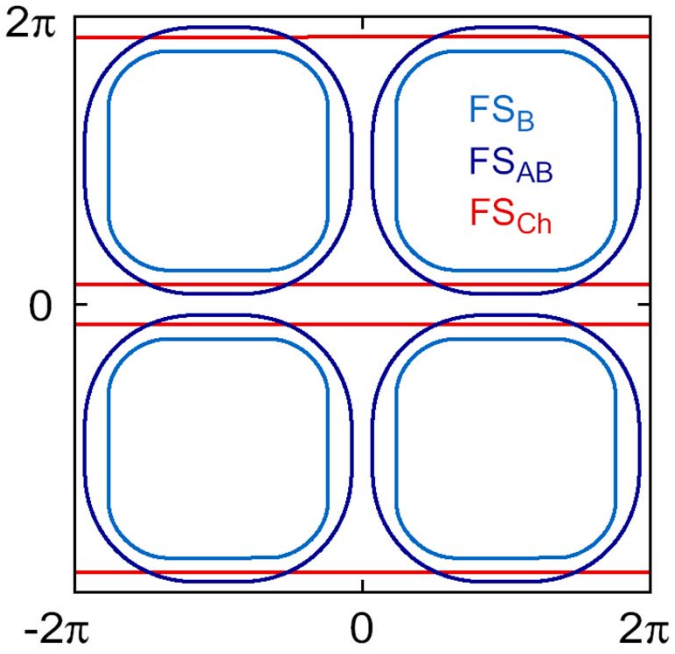
	Surface 1	Surface 2
F (T)	478	526
ΔF (T)	37.7	3.5
m^*/m_e	1.5	1.7
gm_s/m_e	2.1	3.2
l_{free} (Å)	387	325
γ	3.5	1.1
A	13	18.5

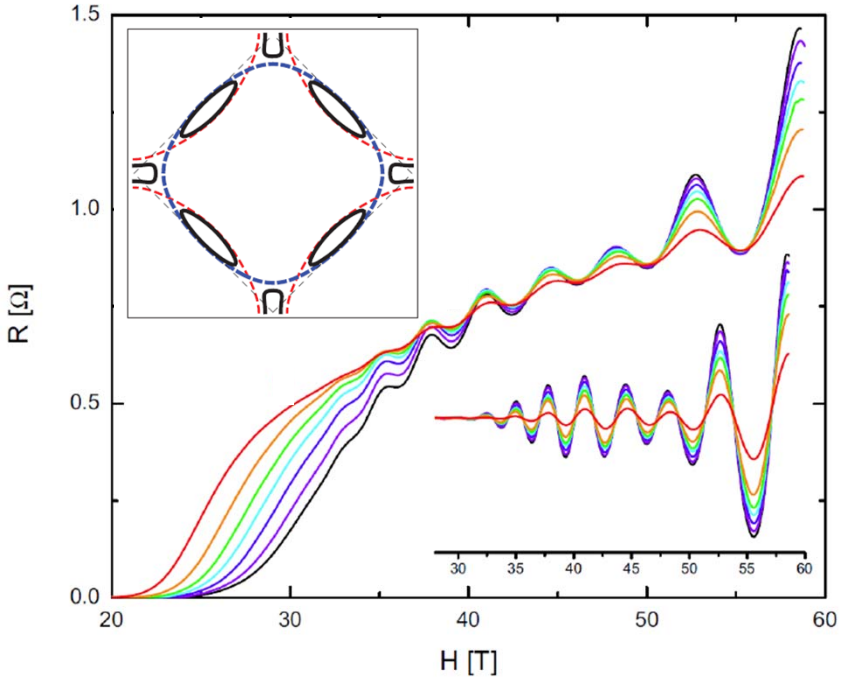
B.J. Ramshaw et al., Nature Physics (2010)

Fermiology of Underdoped YBCO



Elfimov, Sawatzky, Damascelli PRB **77**, 060504 (2008)





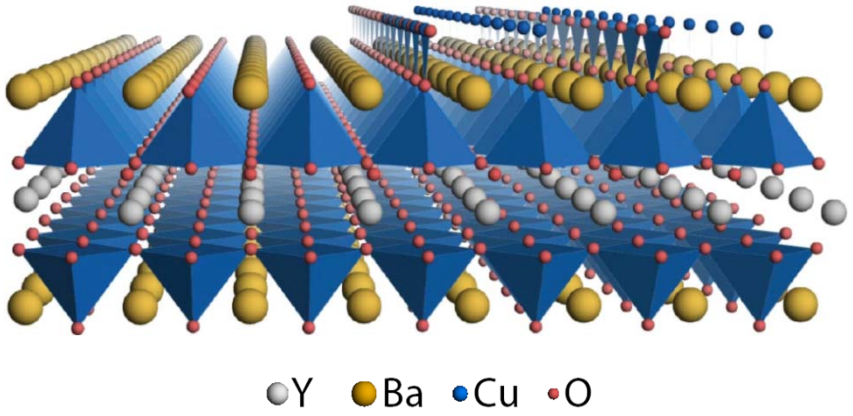
QO suggest Fermi liquid behavior in the very underdoped regime

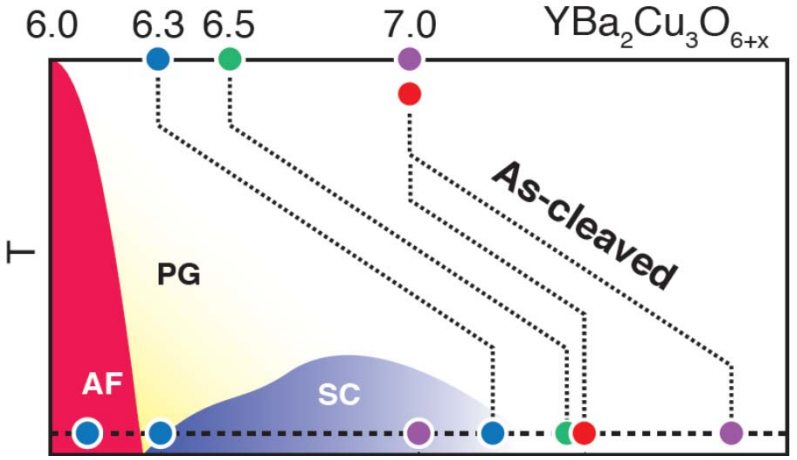
Small pockets are also not in LDA

Competing ordering?

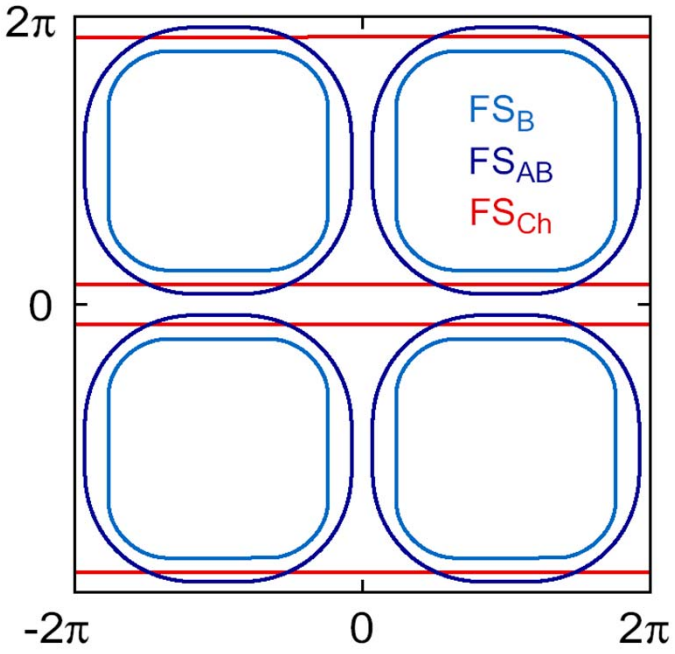
B.J. Ramshaw et al., Nature Physics (2010)

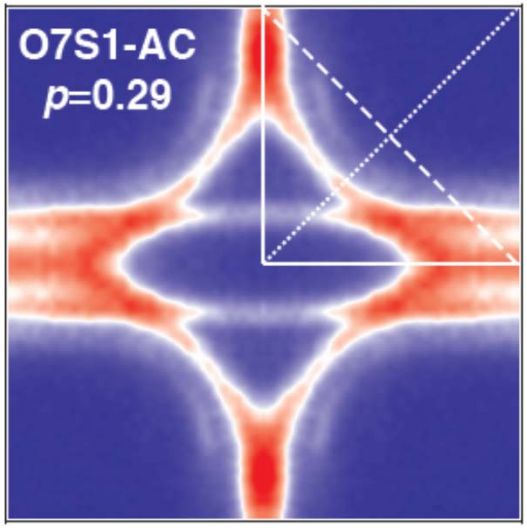
Fermiology of Underdoped YBCO





Elfimov, Sawatzky, Damascelli PRB **77**, 060504 (2008)

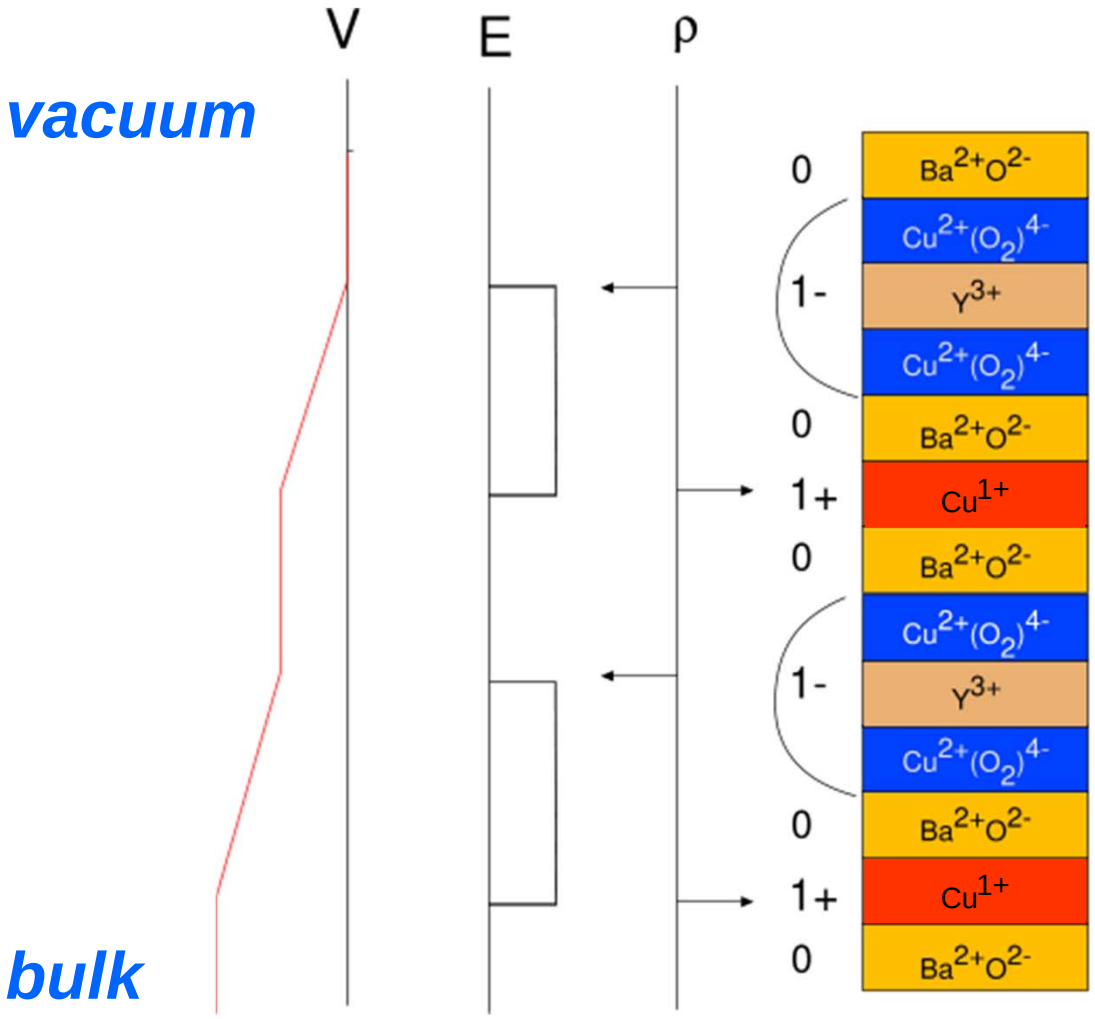




D. Fournier et al., Nature Physics **6**, 905 (2010)

Electronic Surface Reconstruction in $YBa_2Cu_3O_{6.0}$

Polar catastrophe



Electronic Surface Reconstruction in $YBa_2Cu_3O_{6.0}$

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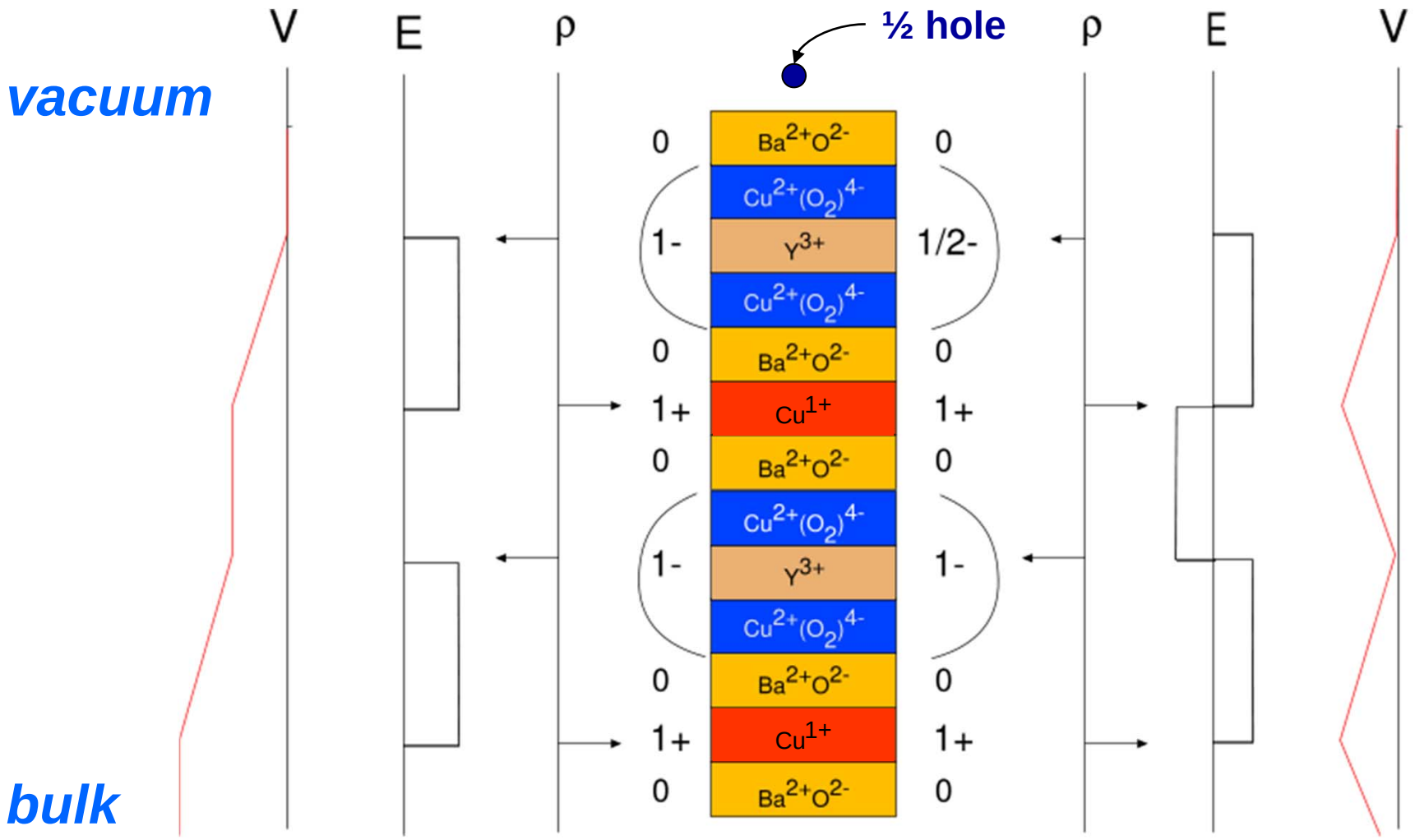
Self-doping of YBCO surface



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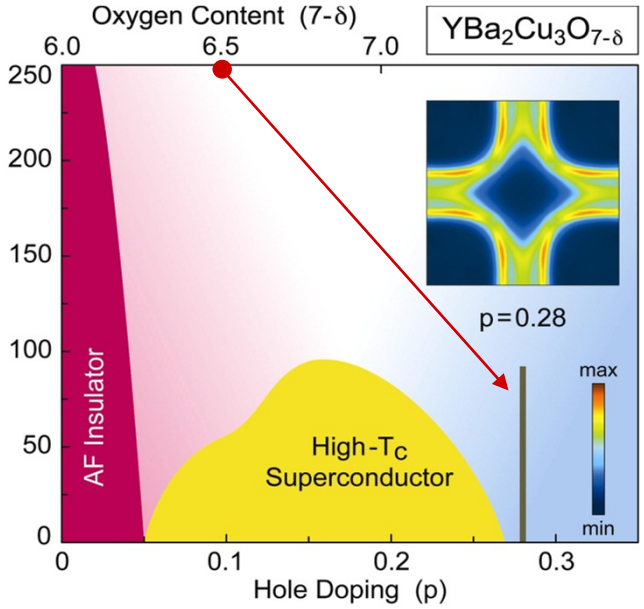
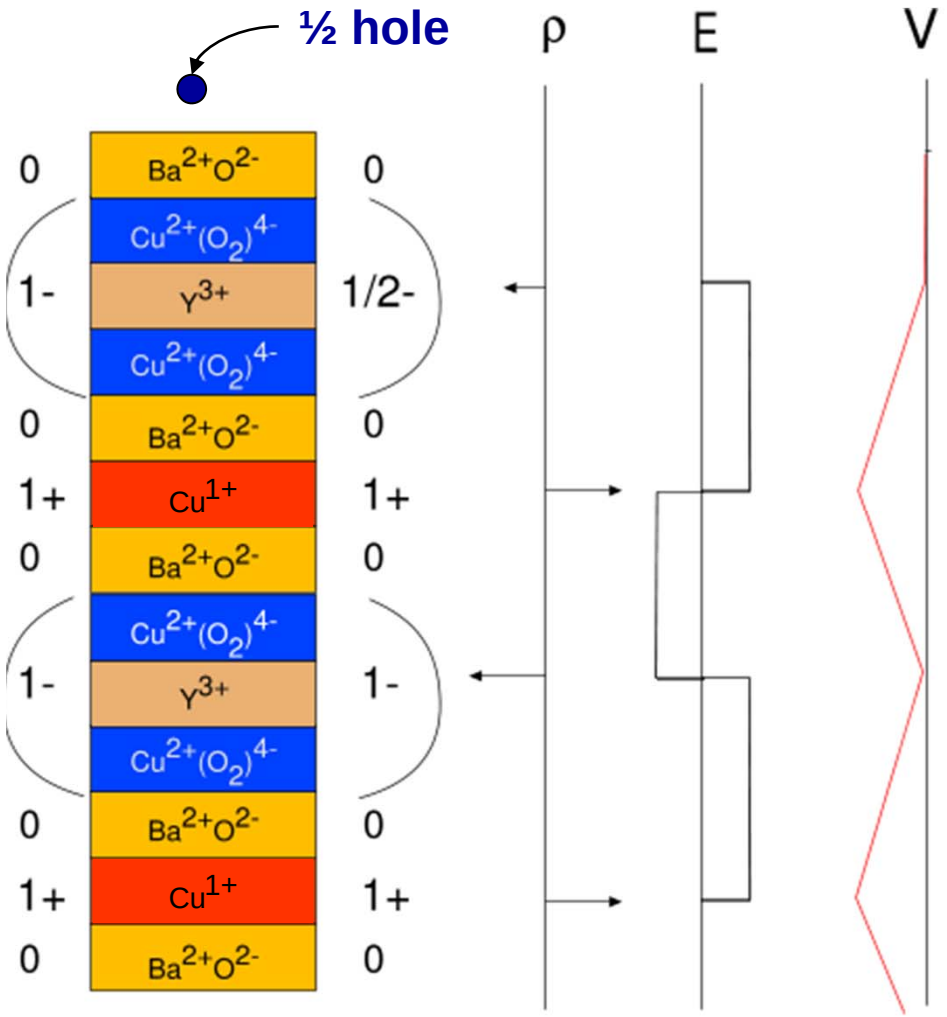
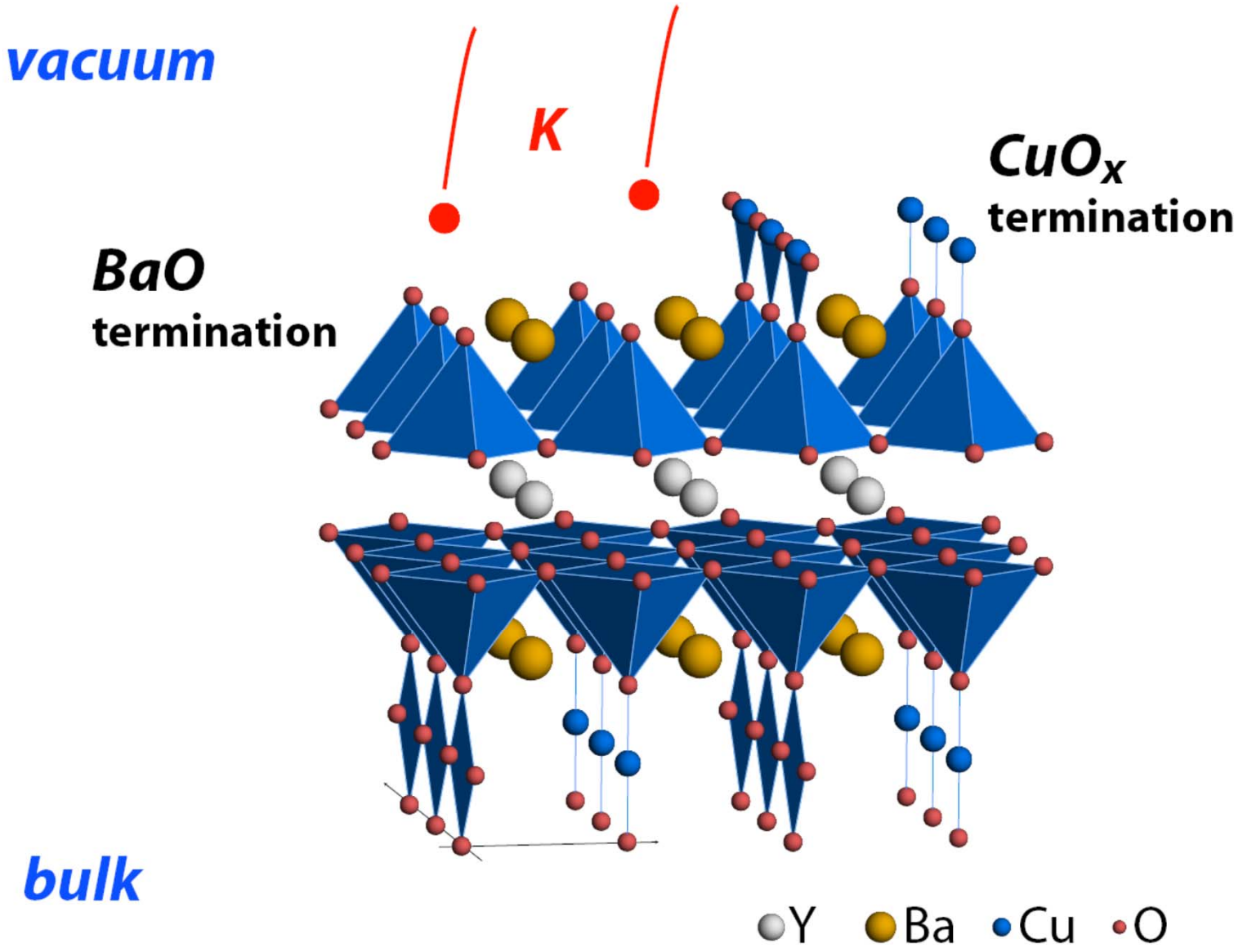


Self-doping

Overdoping

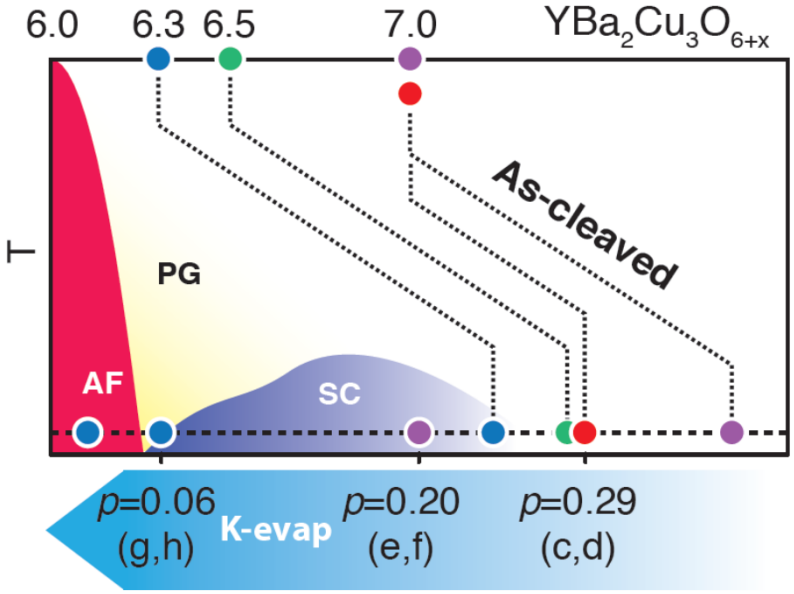


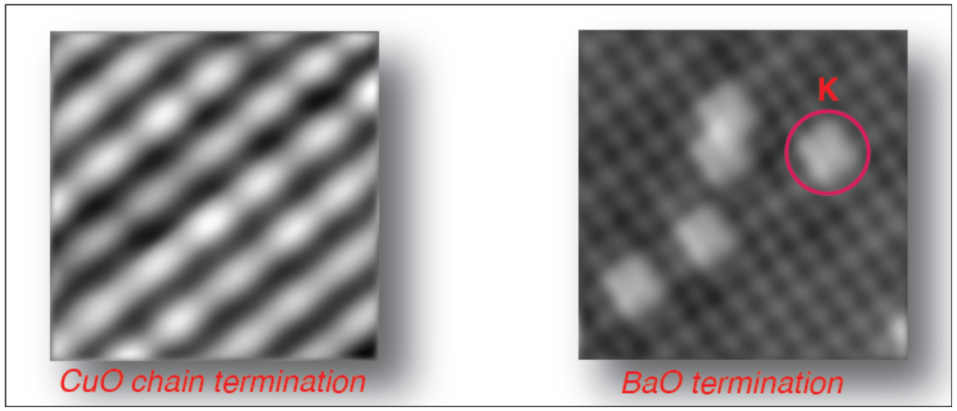
Fixing the YBCO surface self-doping by K deposition



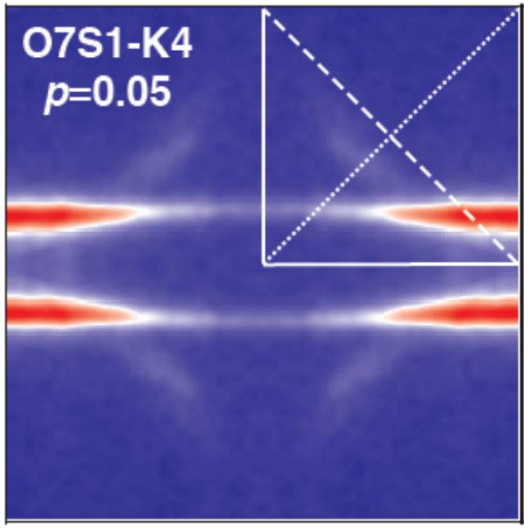
Hossain et al., Nature Physics **4**, 527 (2008)

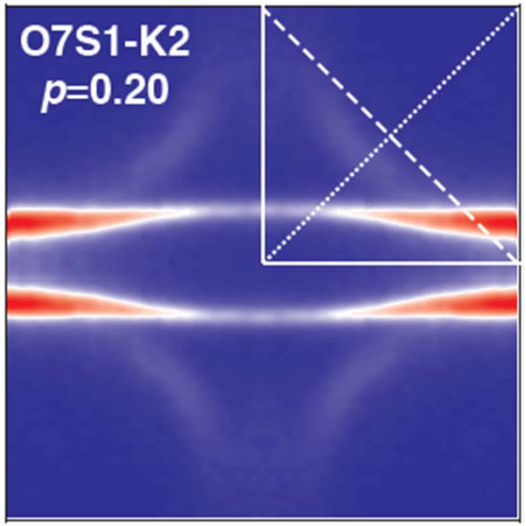
ARPES on K-deposited YBCO: counting carriers

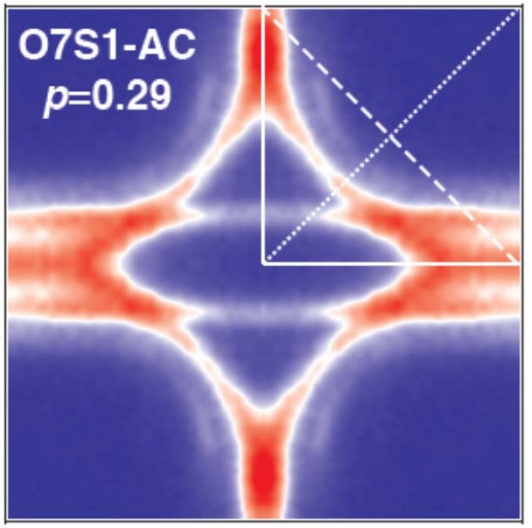




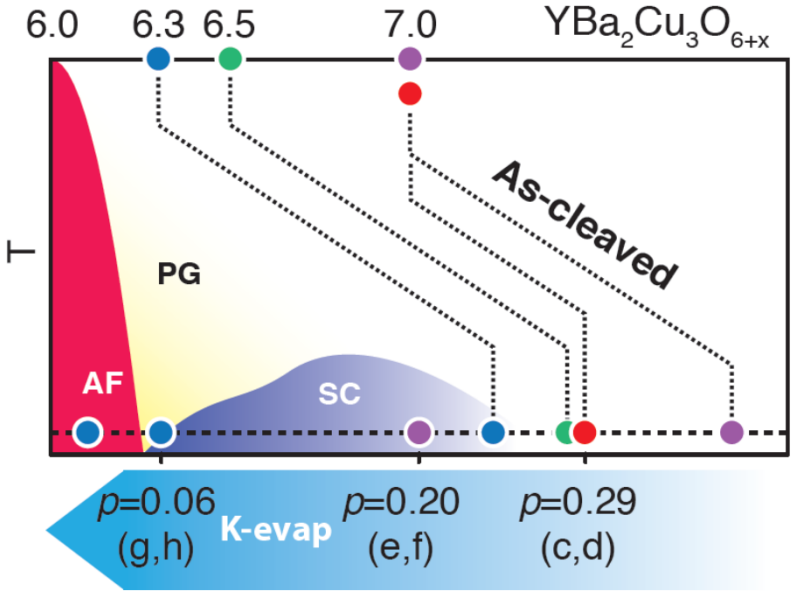
D. Fournier, Nature Physics **6**, 905 (2010)

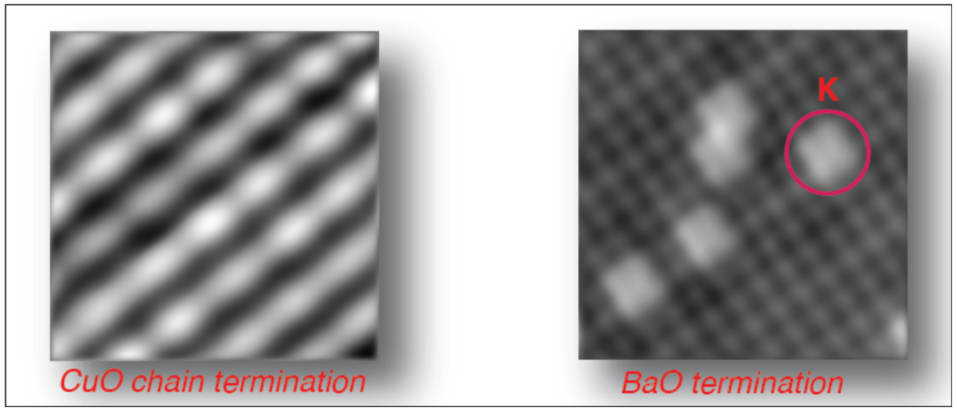




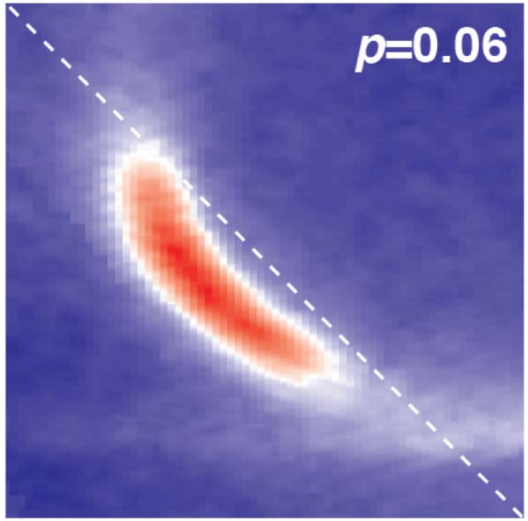


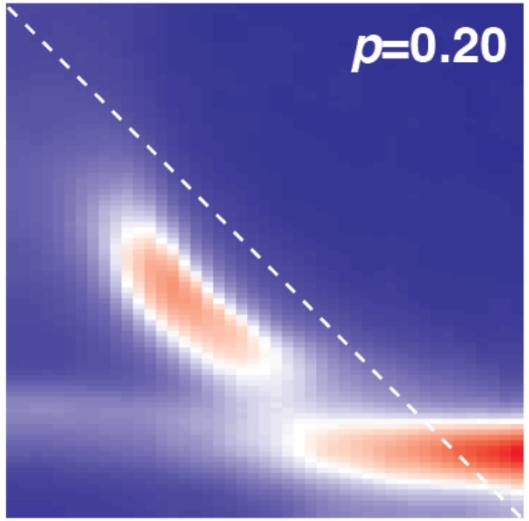
ARPES on K-deposited YBCO: arcs vs. pockets

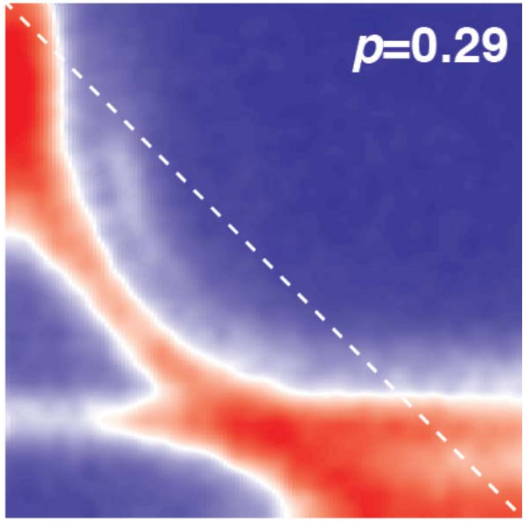




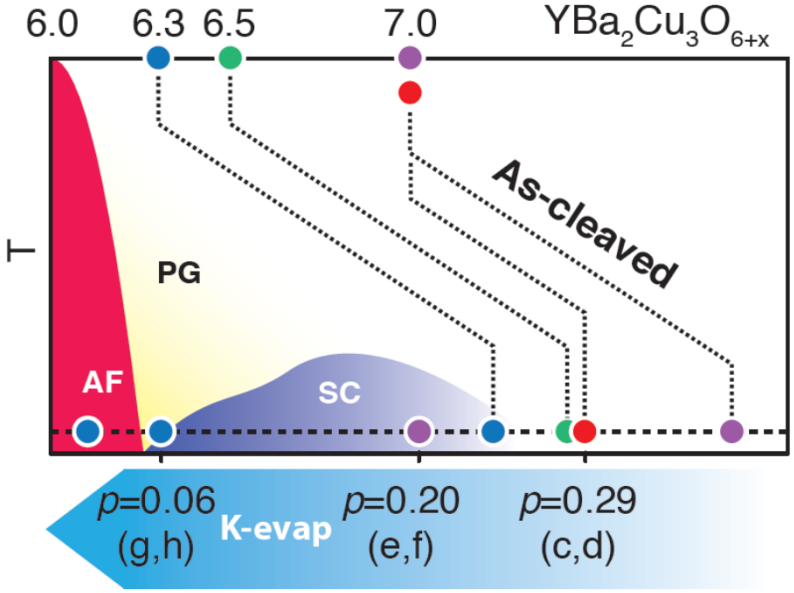
Fournier et al., Nature Physics **6**, 905 (2010)







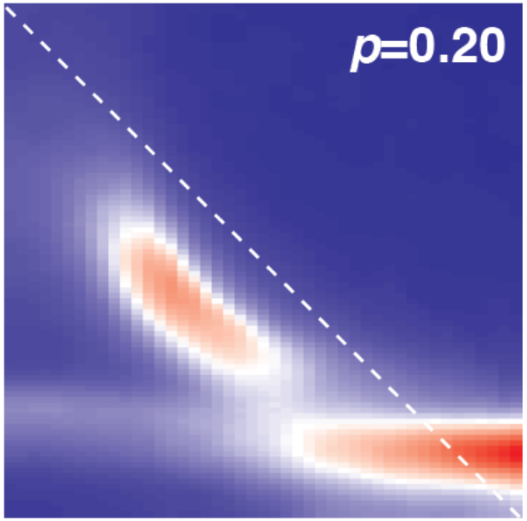
ARPES on K-deposited YBCO: SP and pseudogap

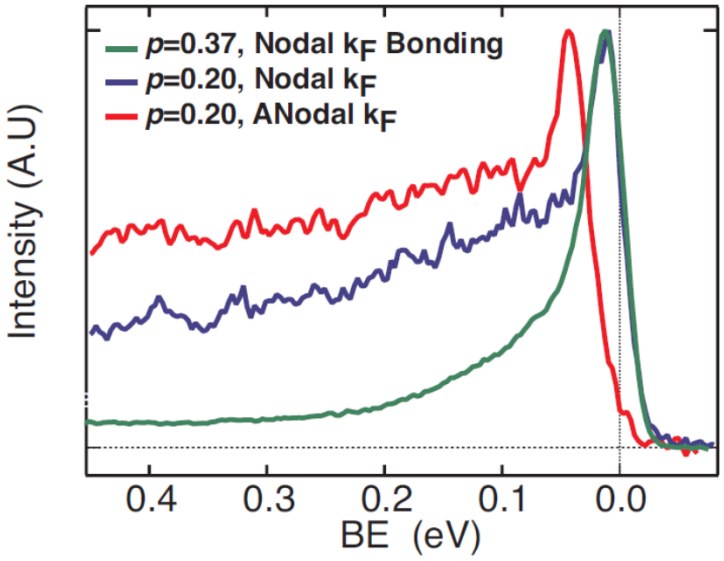


K doping provides access to the whole phase diagram (FS, dispersion, SC gap)

The FS collapses in 4 disconnected arcs

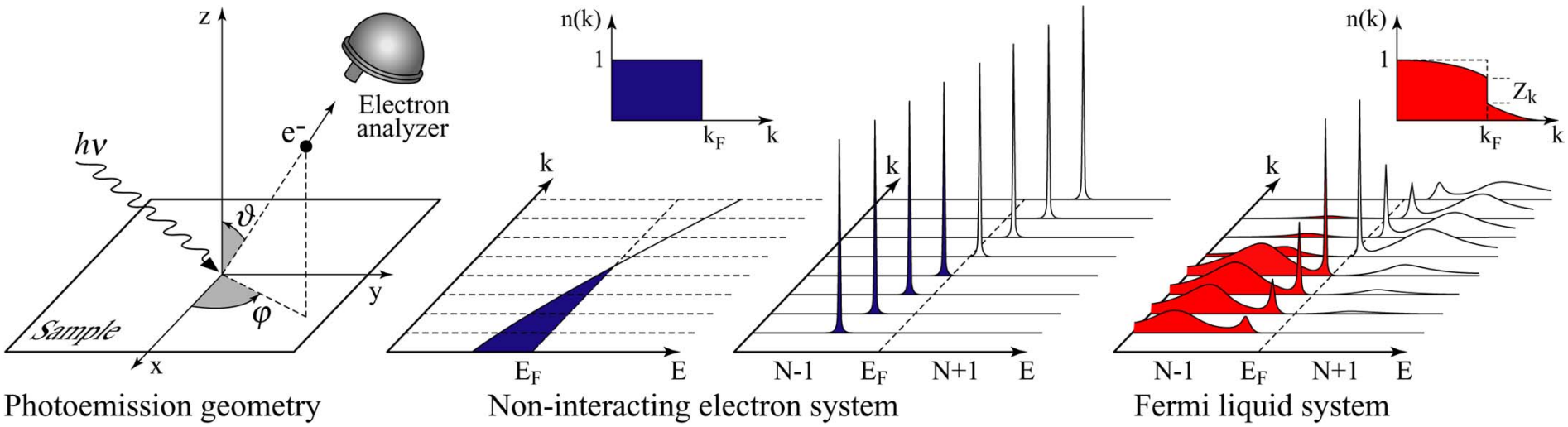
NO evidence for pockets in ARPES !!





ARPES: The One-Particle Spectral Function

A. Damascelli, Z. Hussain, Z.-X Shen, Rev. Mod. Phys. **75**, 473 (2003)



Photoemission intensity: $I(k,\omega)=I_0\,|M(k,\omega)|^2 f(\omega)\,A(k,\omega)$

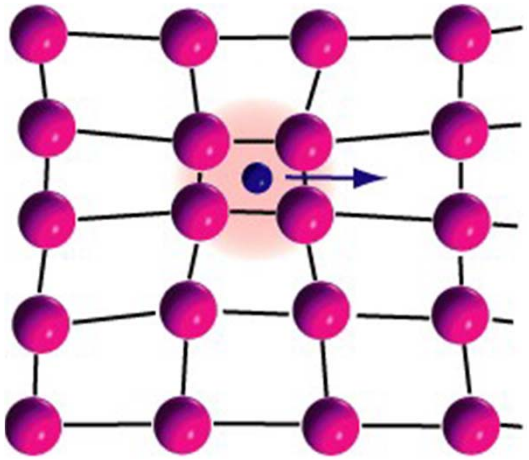
Single-particle spectral function

$$A(\mathbf{k},\omega)=-\frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega-\epsilon_{\mathbf{k}}-\Sigma'(\mathbf{k},\omega)]^2+[\Sigma''(\mathbf{k},\omega)]^2}$$

$\Sigma(k,\omega)$: the "self-energy" captures the effects of interactions

Renormalization of Polaronic Quasiparticles

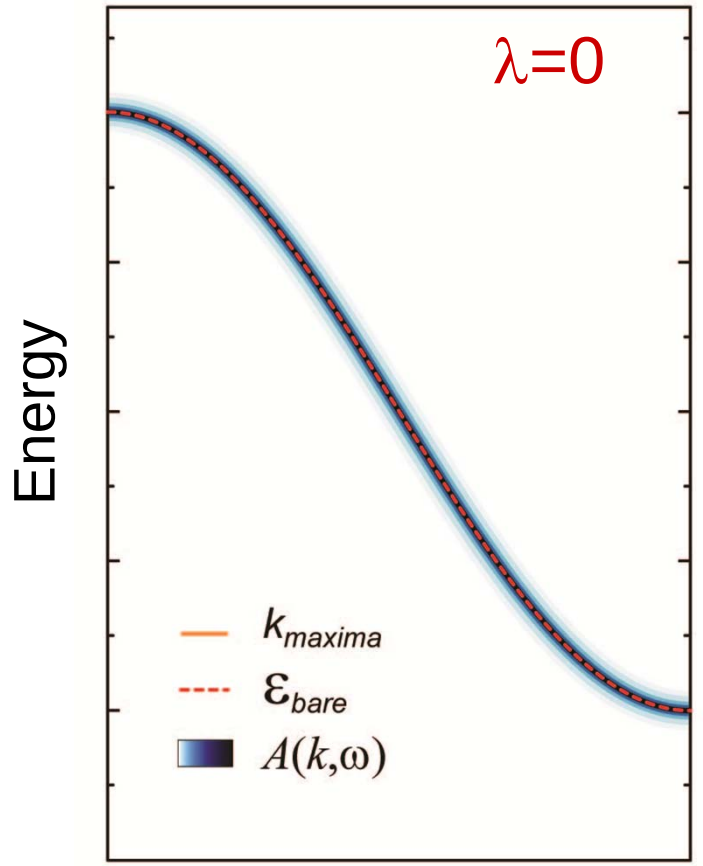
$$\mathcal{H} = \sum_k \varepsilon_k^b c_k^\dagger c_k + \Omega \sum_Q b_Q^\dagger b_Q + \frac{g}{\sqrt{N}} \sum_{k,Q} c_{k-Q}^\dagger c_k (b_Q^\dagger + b_{-Q})$$



$$A(\mathbf{k},\omega) = Z_{\mathbf{k}} \frac{\Gamma_{\mathbf{k}}/\pi}{(\omega - \varepsilon_{\mathbf{k}})^2 + \Gamma_{\mathbf{k}}^2} + A_{inc}$$

$$m^* > m \qquad |\varepsilon_{\mathbf{k}}| < |\epsilon_{\mathbf{k}}|$$

$$\tau_{\mathbf{k}} = 1/\Gamma_{\mathbf{k}}$$



Veenstra, Goodvin, Berciu, Damascelli, PRB **82**, 012504 (2010)

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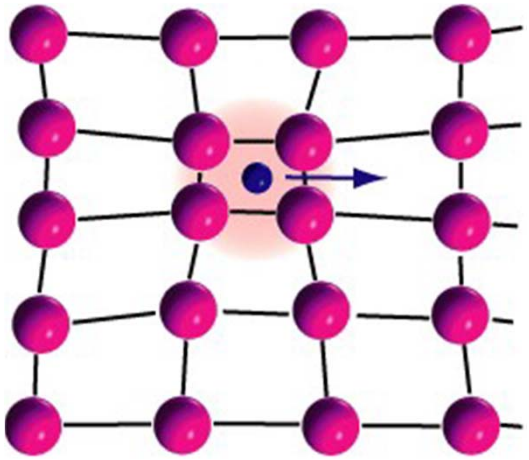

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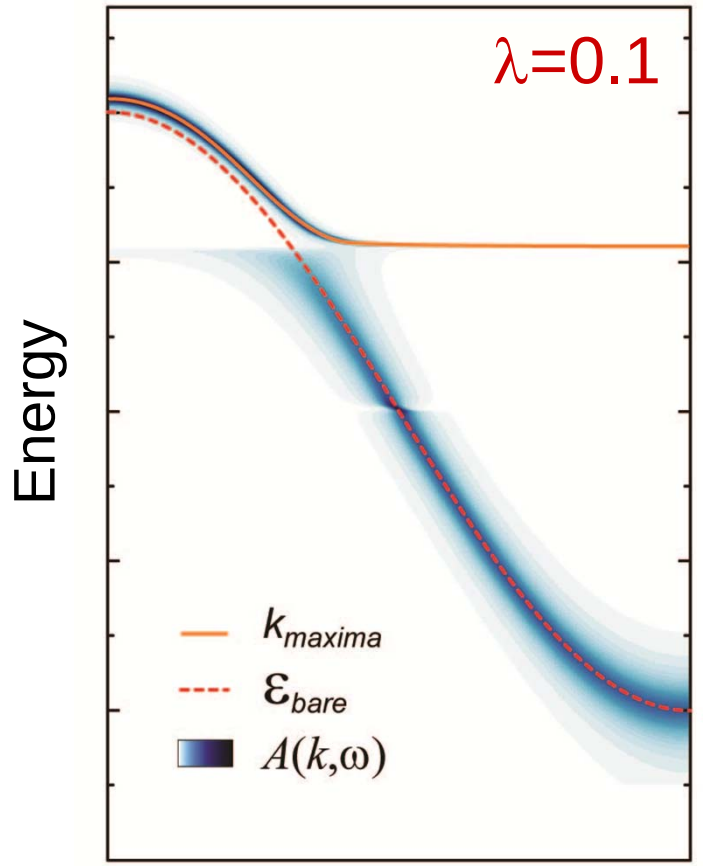

Veenstra, Goodvin, Berciu, Damascelli, PRB **82**, 012504 (2010)

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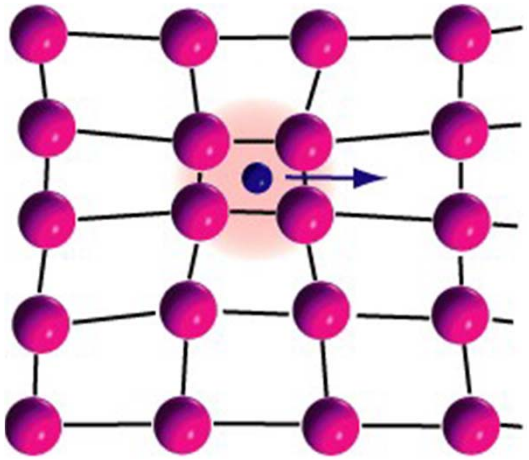

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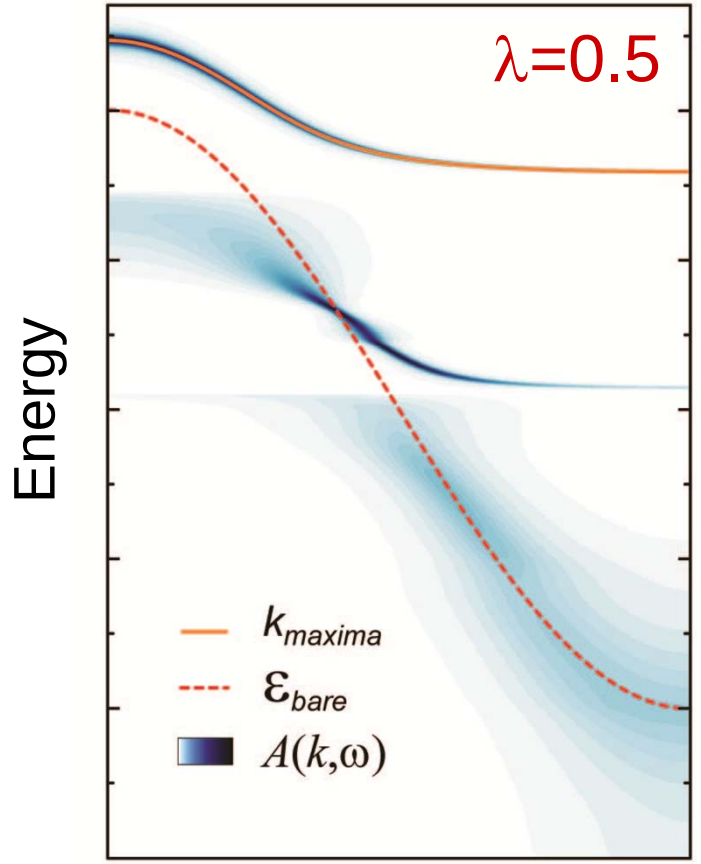

Veenstra, Goodvin, Berciu, Damascelli, PRB **82**, 012504 (2010)

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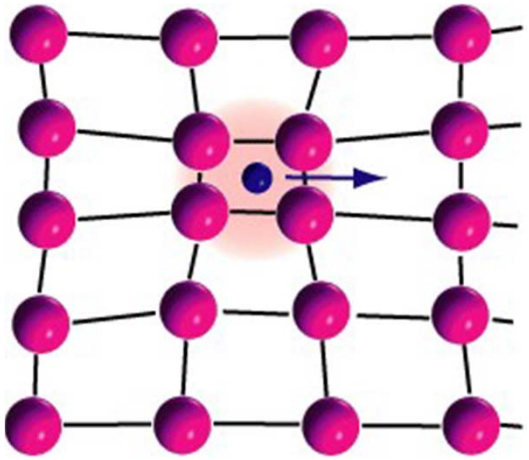

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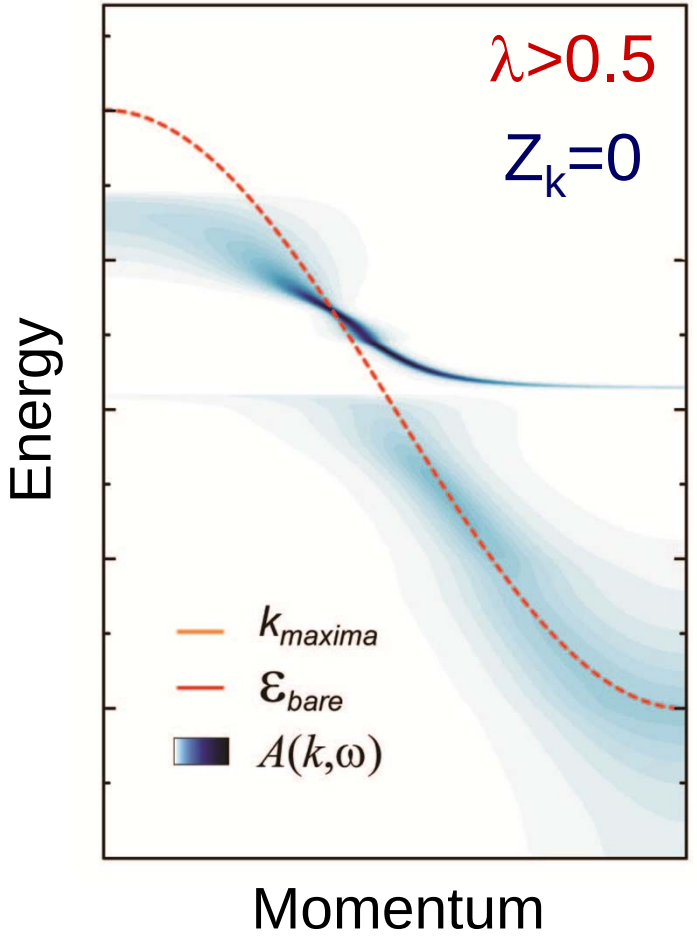

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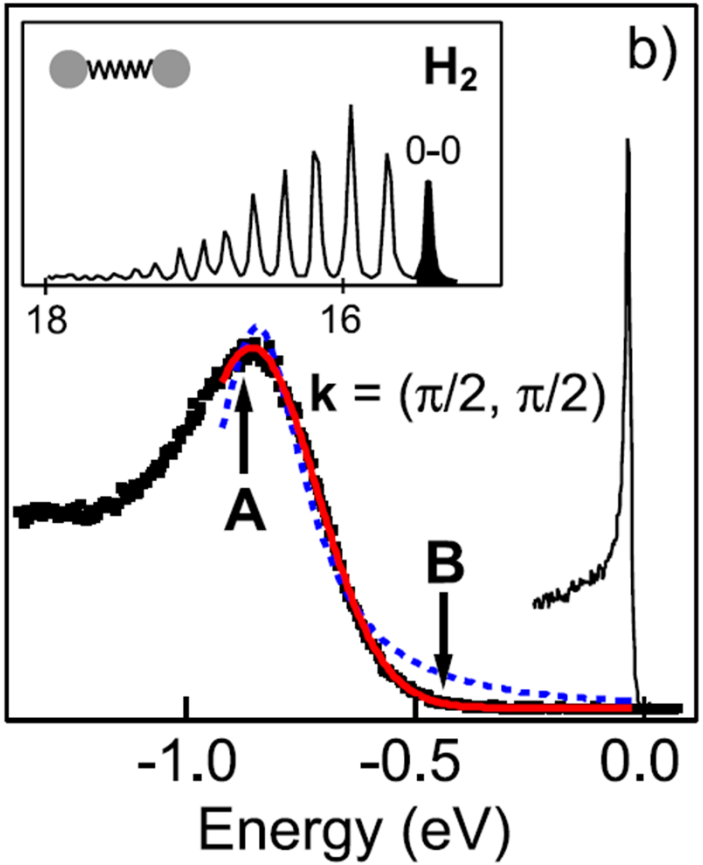
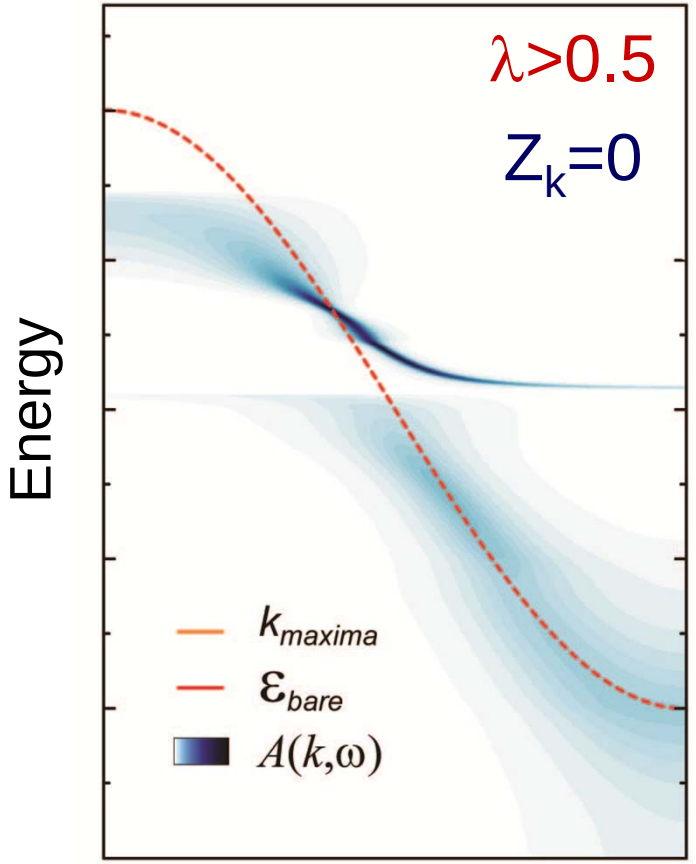
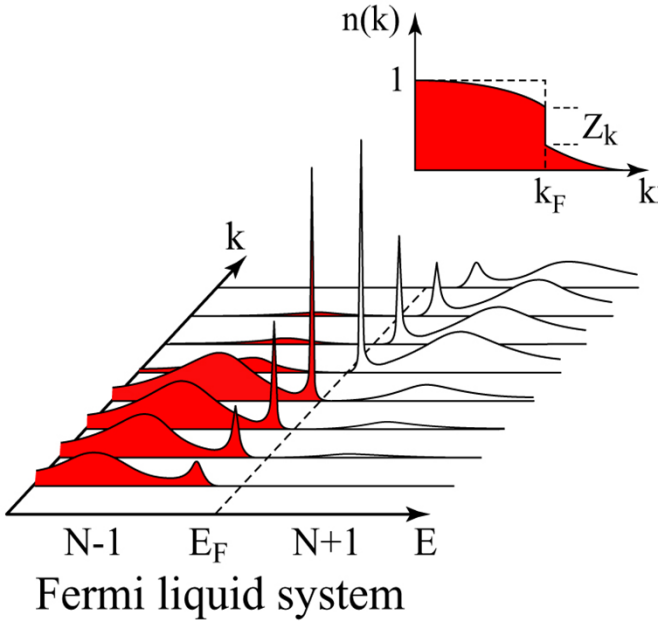


K.M. Shen et al., PRL **93,** 267002 (2004)

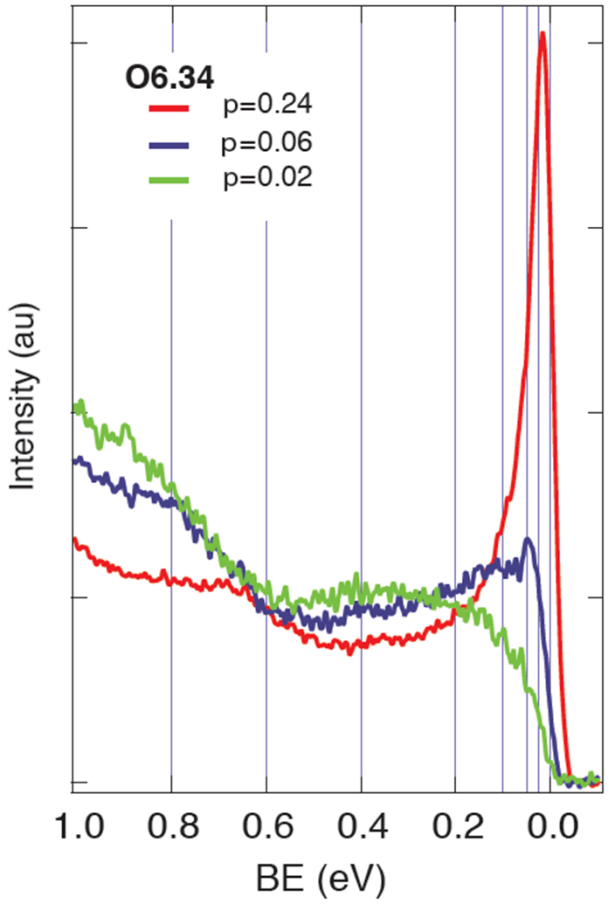


Veenstra, Goodvin, Berciu, Damascelli, PRB **82**, 012504 (2010)

Quasiparticle Coherence across the Phase Diagram



Fermi liquid system



$$Z_k = \int I_{coh}(k,\omega)\, d\omega / \int I(k,\omega)\, d\omega$$

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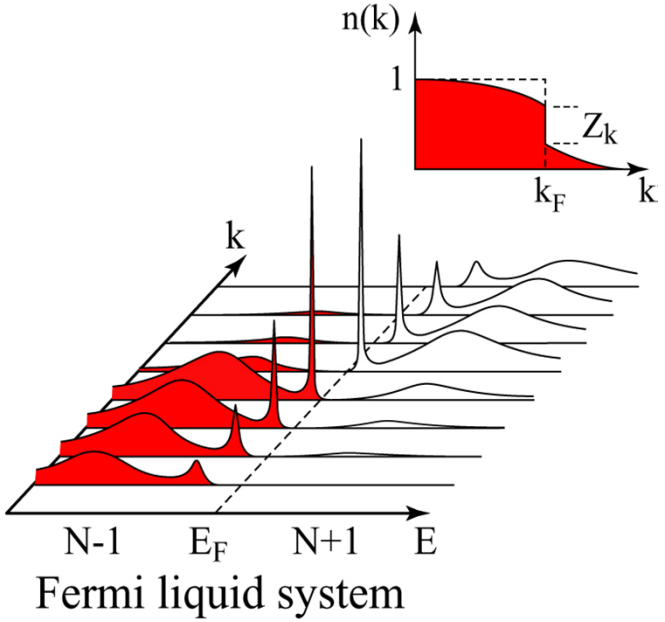

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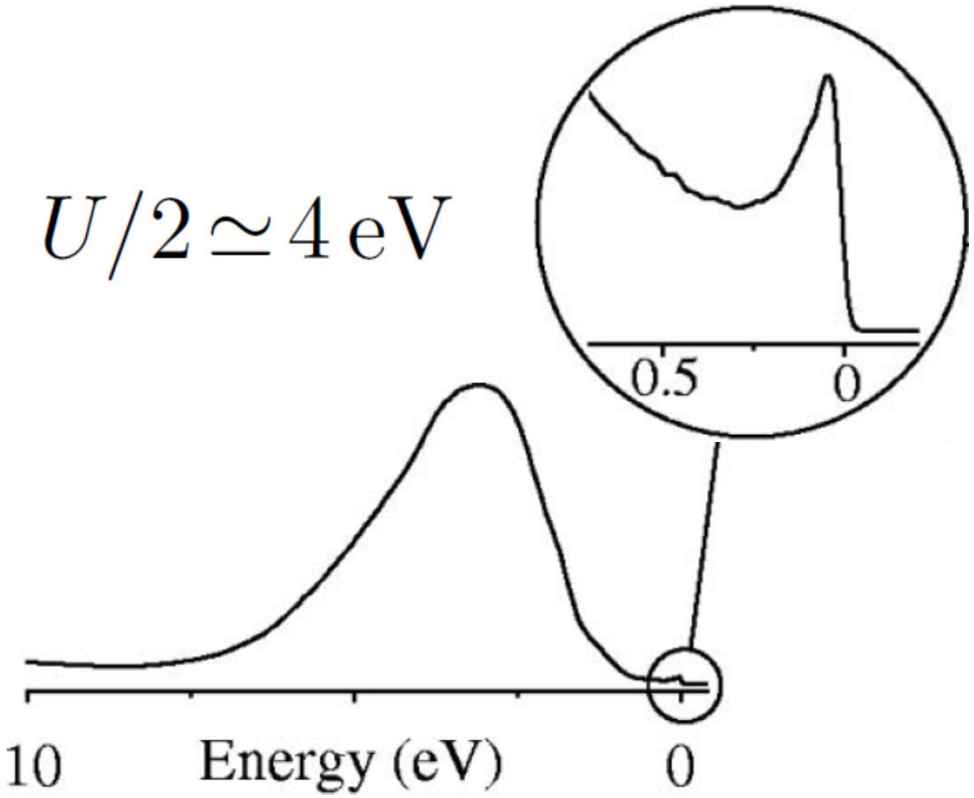

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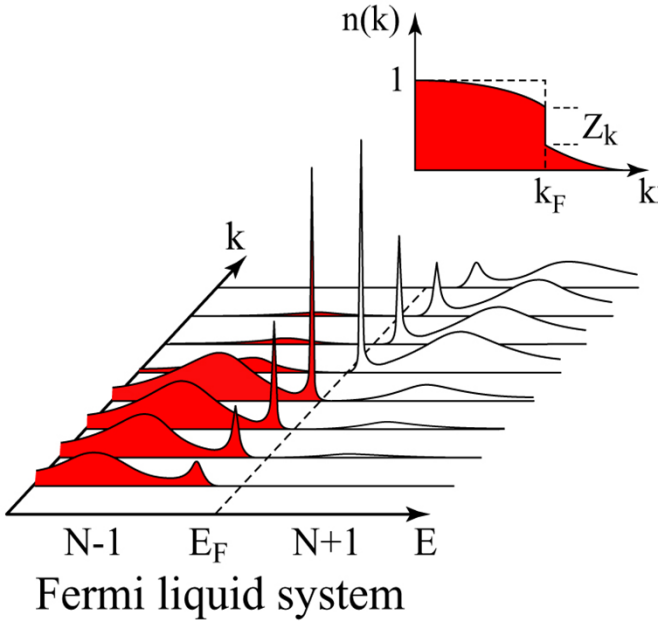

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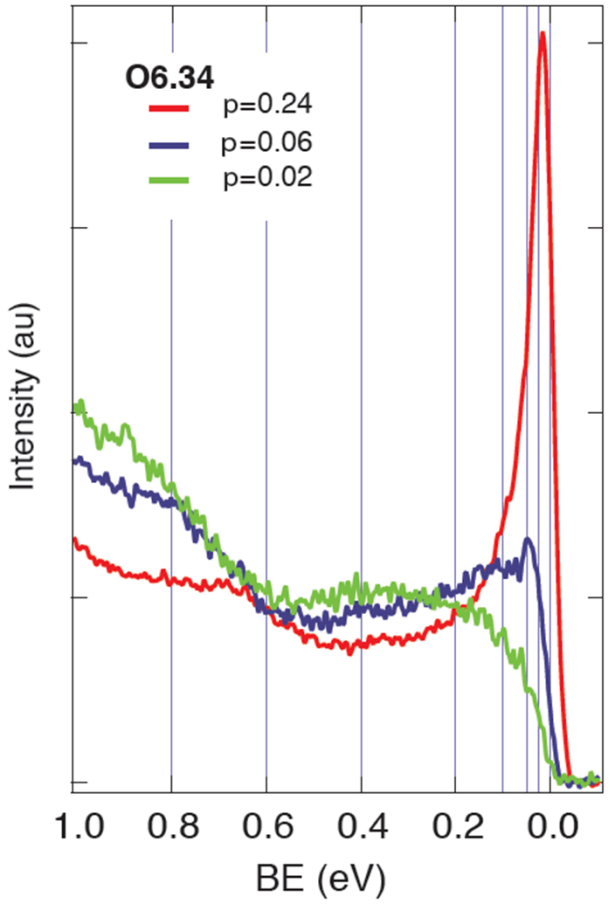

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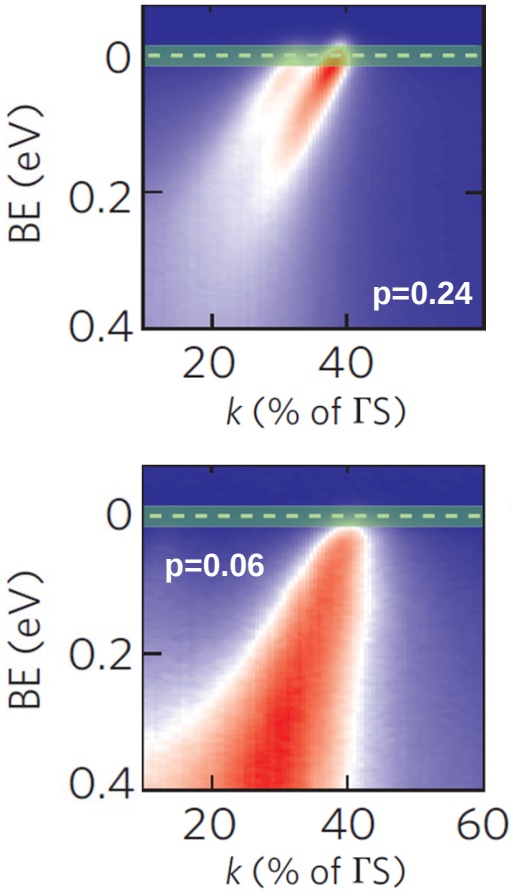

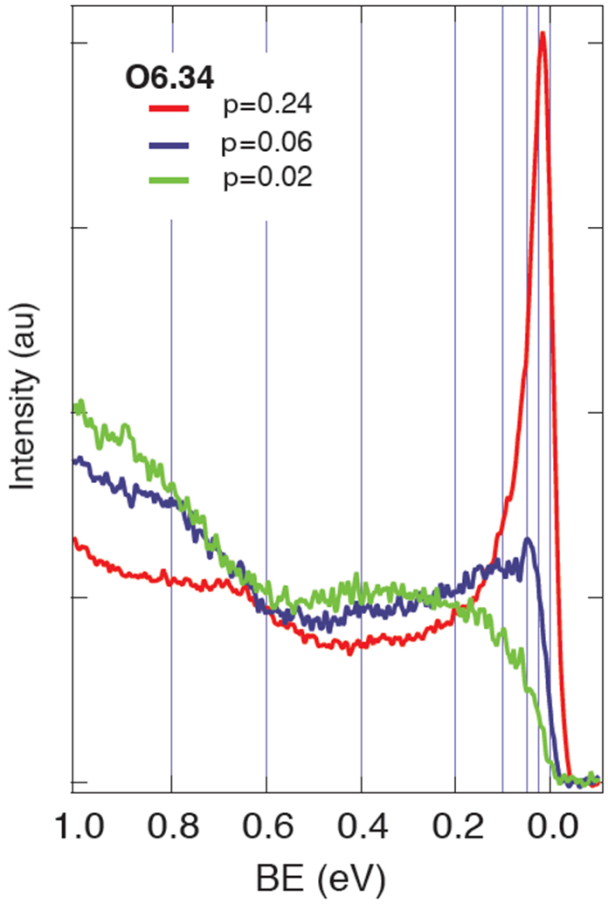

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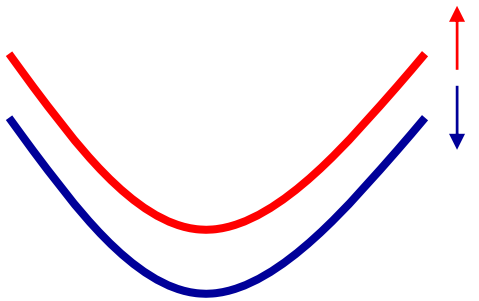
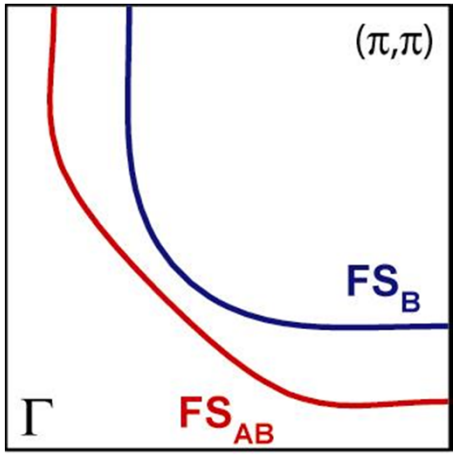
Bilayer Band Splitting and Quasiparticle Integrity

$$\epsilon^{B,AB}(k) = \epsilon(k) \mp t_{\perp}^{eff}(k) = \epsilon(k) \mp Z_k t_{\perp}^{LDA}(k)$$

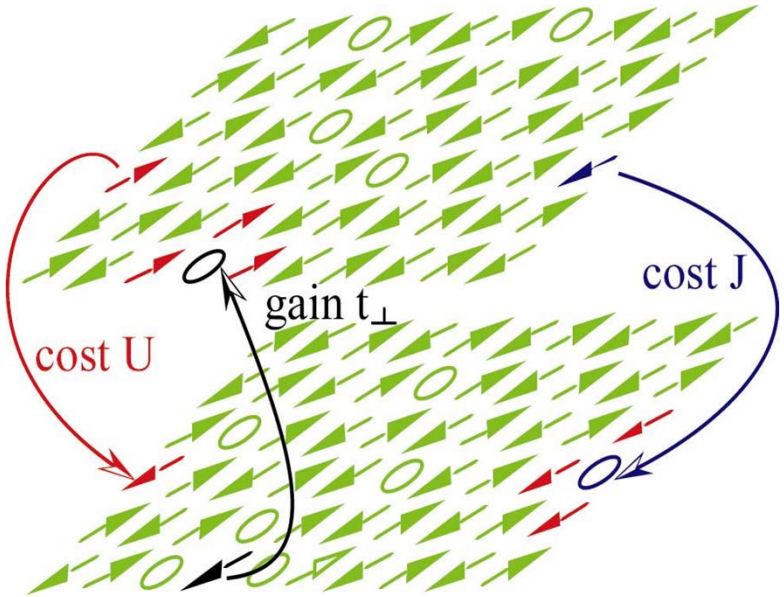
Bilayer band splitting
Anti-bonding & Bonding



FS with bilayer splitting



Correlations suppress Z_k

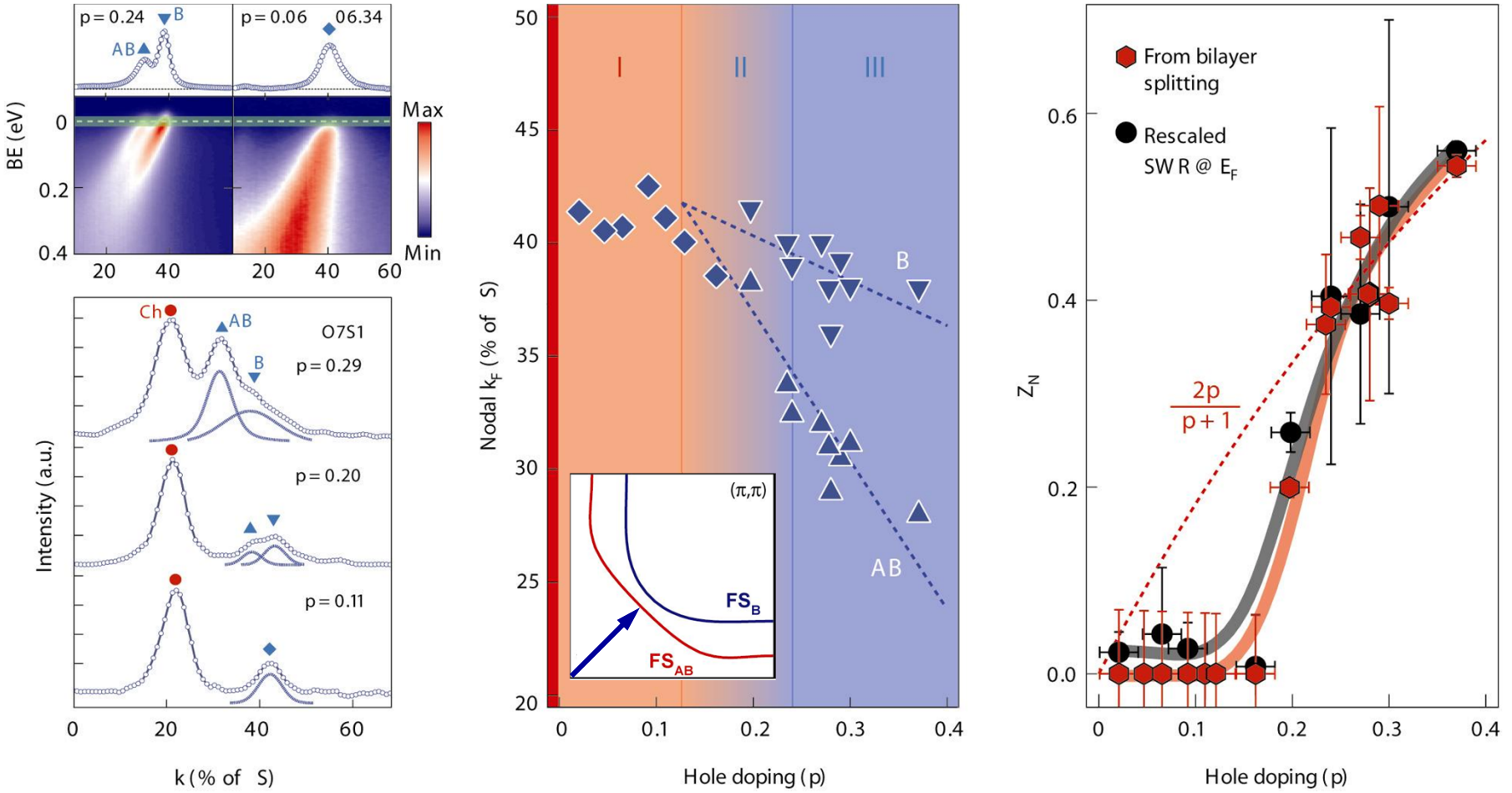


$$Z \simeq 2p/(p+1)$$

Sawatzky, Anderson, Randeria, Rice, et al.

Bilayer band splitting and quasiparticle coherence

$$Z_N = \Delta\epsilon_N^{B,AB}/2t_\perp^{LDA}(N)$$



Fournier et al., Nature Physics **6**, 905 (2010)

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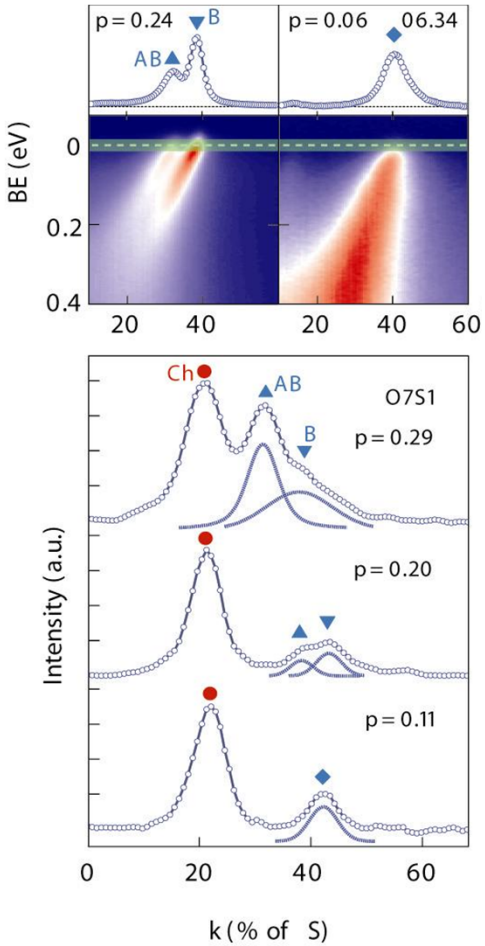
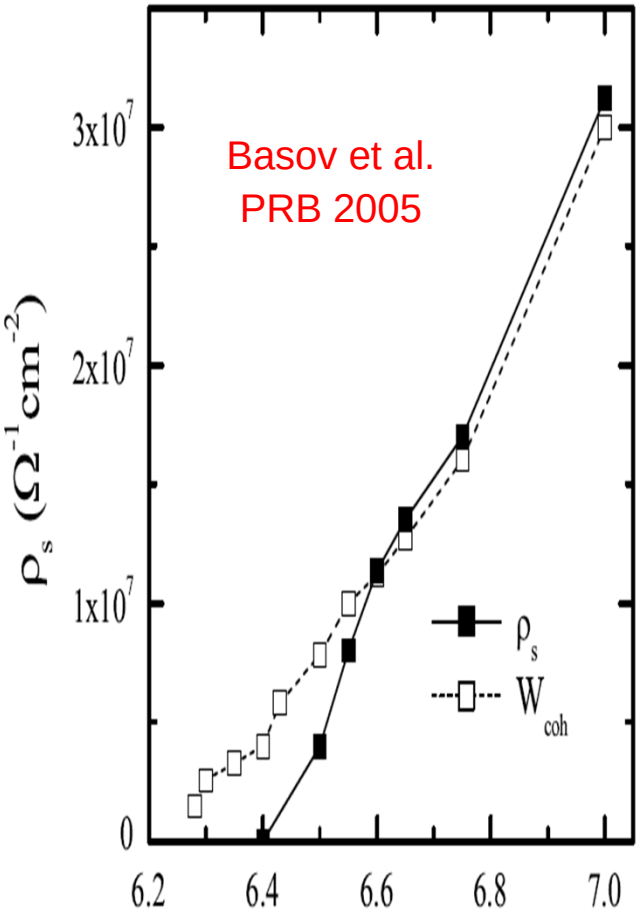
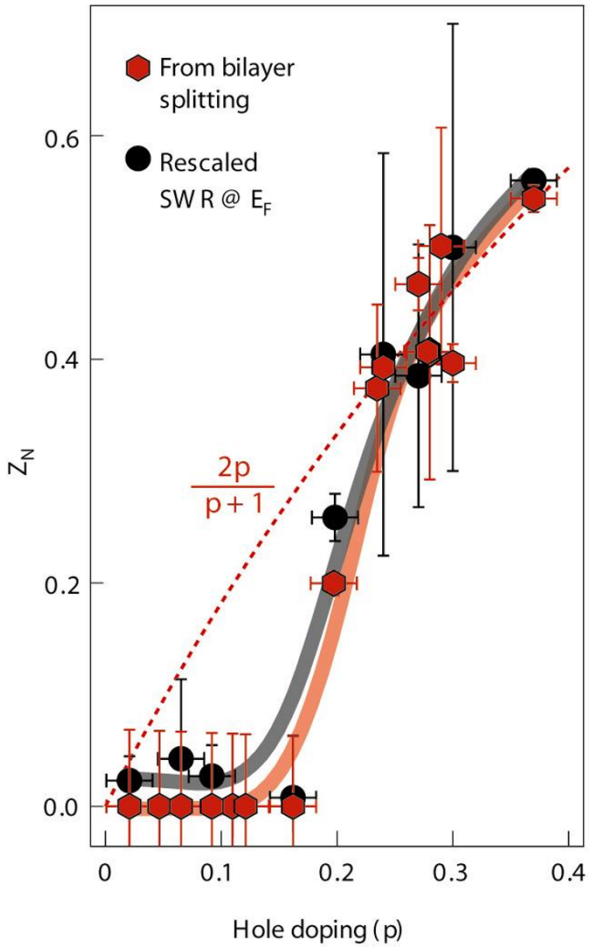




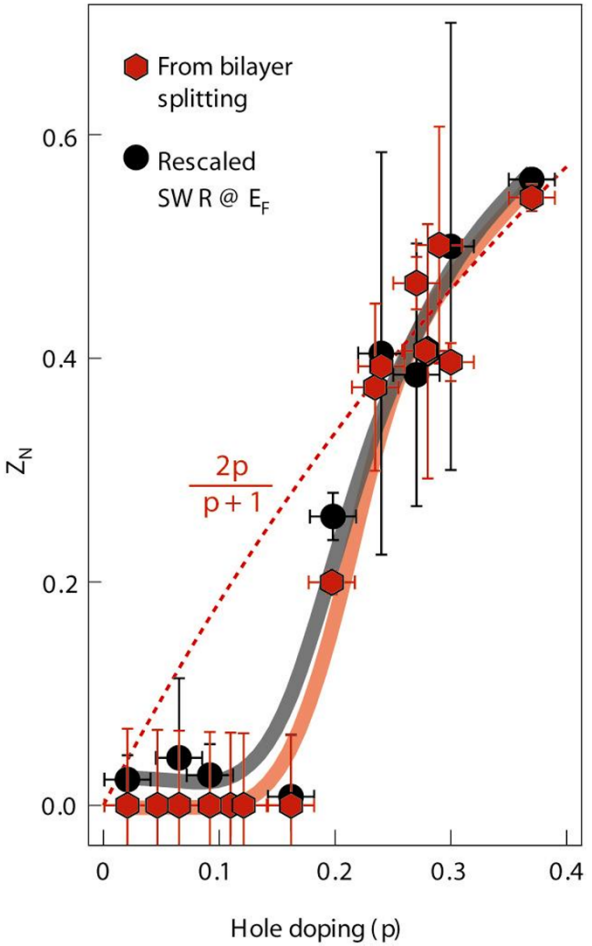


Fournier et al., Nature Physics **6**, 905 (2010)

Bilayer band splitting and quasiparticle coherence

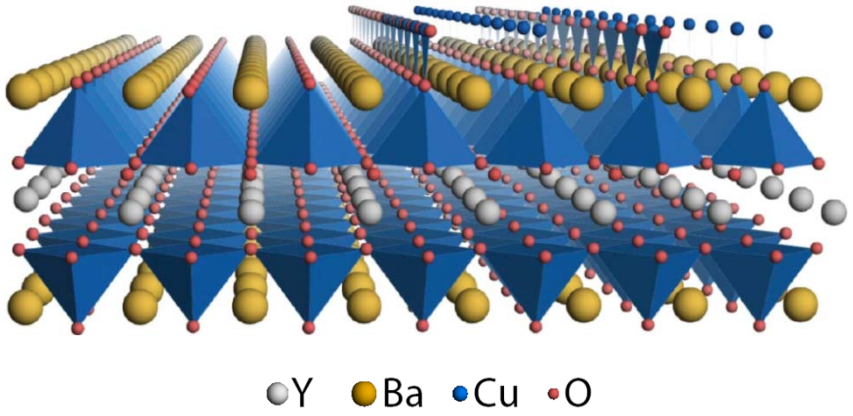
$$Z_N = \Delta\epsilon_N^{B,AB}/2t_\perp^{LDA}(N)$$

- Quantitative estimate of Z
- Agreement with 2p/(p+1) for x>0.23
- Isotropic Z_N~0.54 and Z_{AN}~0.50
- Vanishing Z_N below 15-10%
- $t_\perp$~10meV consistent with QO
- Z even smaller for pockets' "other side"
- Pseudogap? Loss of coherent SW
- Fermi surface? Luttinger's counting?

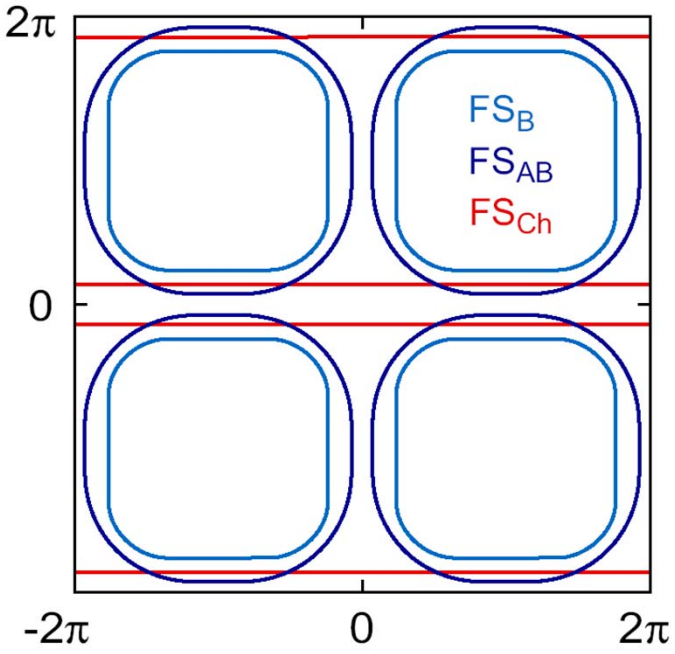


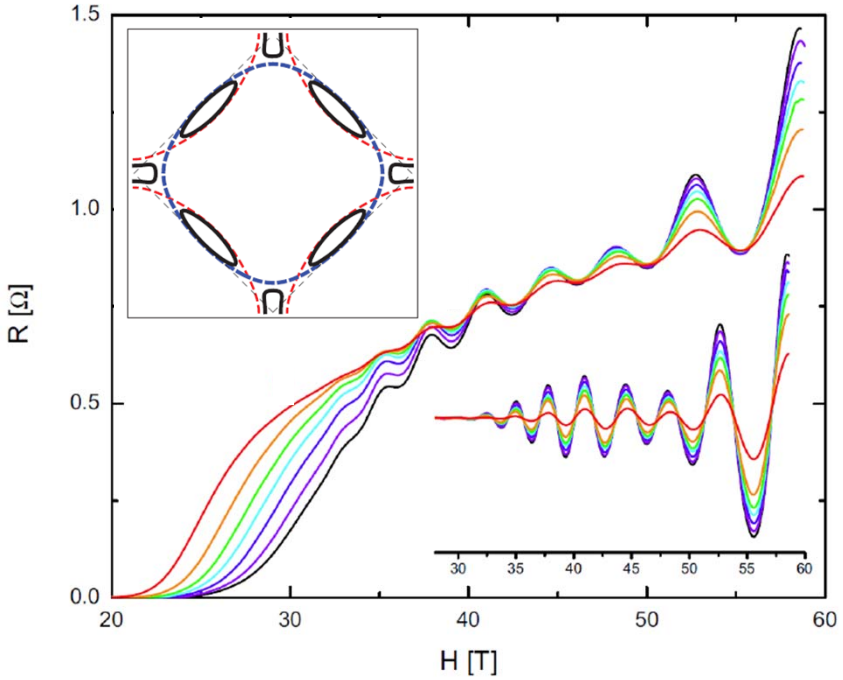
Fournier et al., Nature Physics **6**, 905 (2010)

Fermiology of Underdoped YBCO



Elfimov, Sawatzky, Damascelli PRB **77**, 060504 (2008)





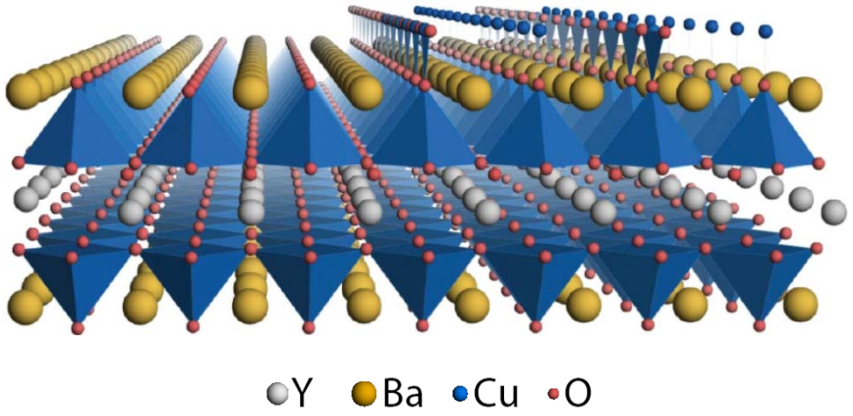
QO suggest Fermi liquid behavior in the very underdoped regime

Small pockets are also not in LDA

Competing ordering?

B.J. Ramshaw et al., Nature Physics (2010)

Fermiology of Underdoped YBCO



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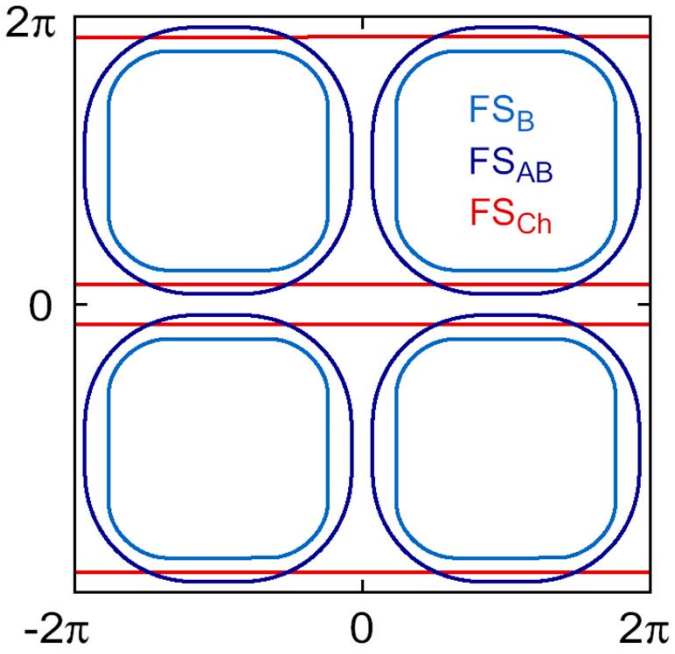

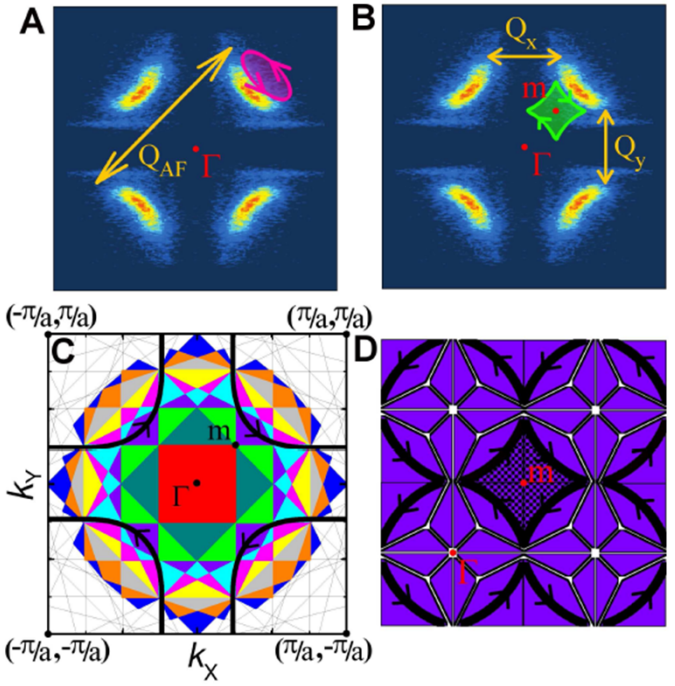

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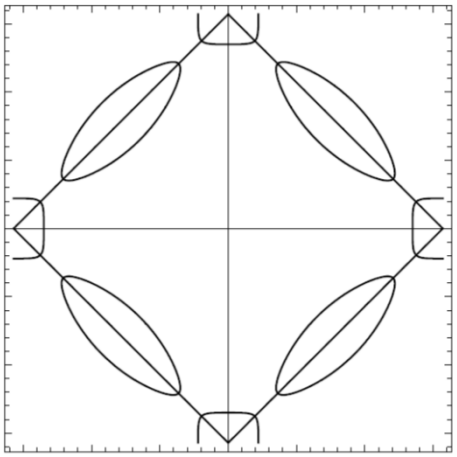
S. Sebastian et al., (2011)

What about hole & electron pockets in ARPES?

D-Density Wave

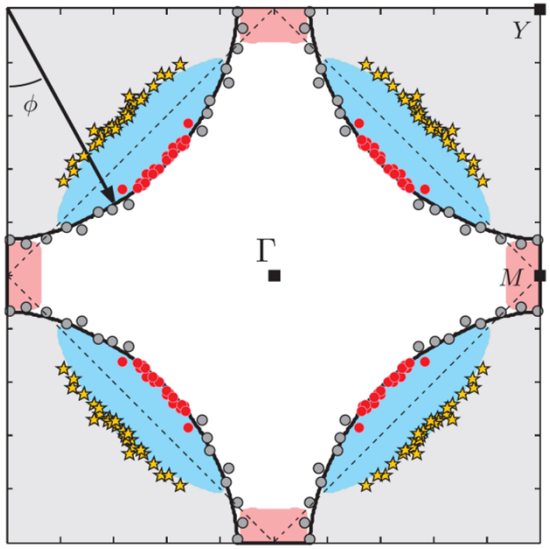


Chakravarty, Kee, arXiv:0710.0608

ARPES on LSCO

Possible detection of hole pocket?

Luttinger counting demands electron pockets

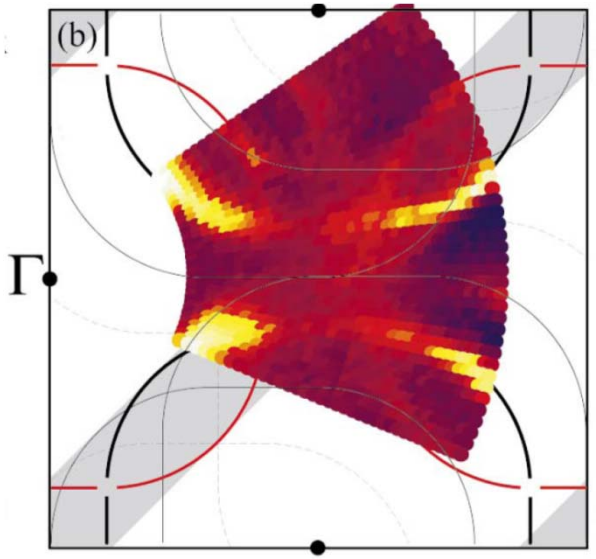


Chang, Mesot, NJP **10,** 103016 (2008)

ARPES on Bi2212

Hole pocket were observed?

NO: Structural Folding of FS



Aebi (PRL 94); Golden (PRL 00, 06)

Ostensible Hole Pockets: structural effect?

Electron Pockets: NO direct evidence !

What about hole & electron pockets in ARPES?

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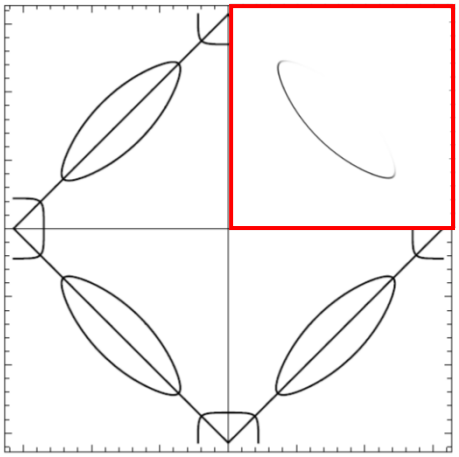

Chakravarty, Kee, arXiv:0710.0608

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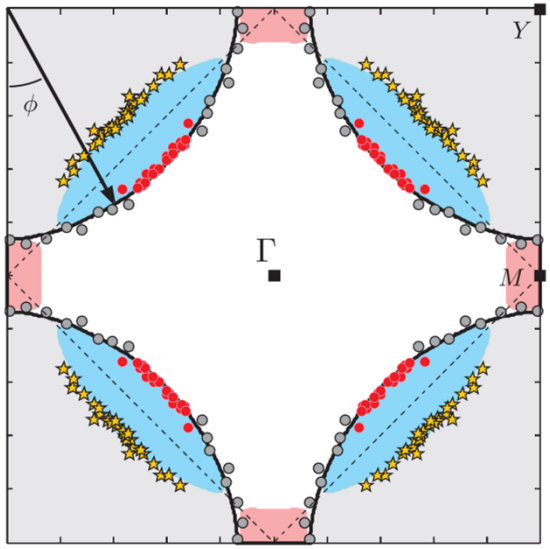
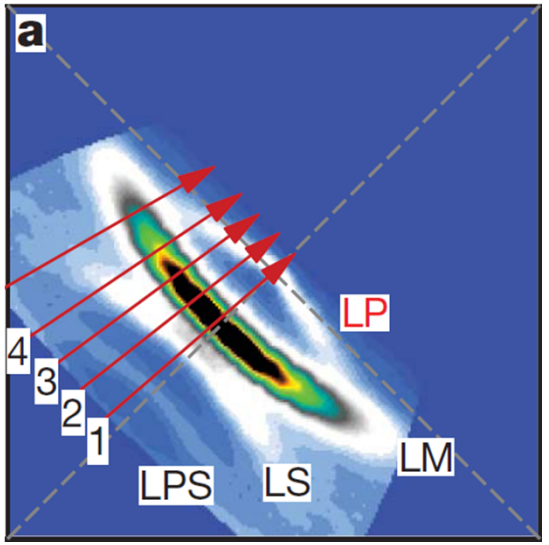


Chang, Mesot, NJP **10,** 103016 (2008)

ARPES on La-Bi2201

Hole pocket were observed?

Replica of primary FS?



Meng, Zhou, Nature **462**, 335 (2009)

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Electron Pockets: NO direct evidence

What about hole & electron pockets in ARPES?

PRL 96, 107007 (2006) PHYSICAL REVIEW LETTERS week ending 17 MARCH 2006

Experimental Proof of a Structural Origin for the Shadow Fermi Surface of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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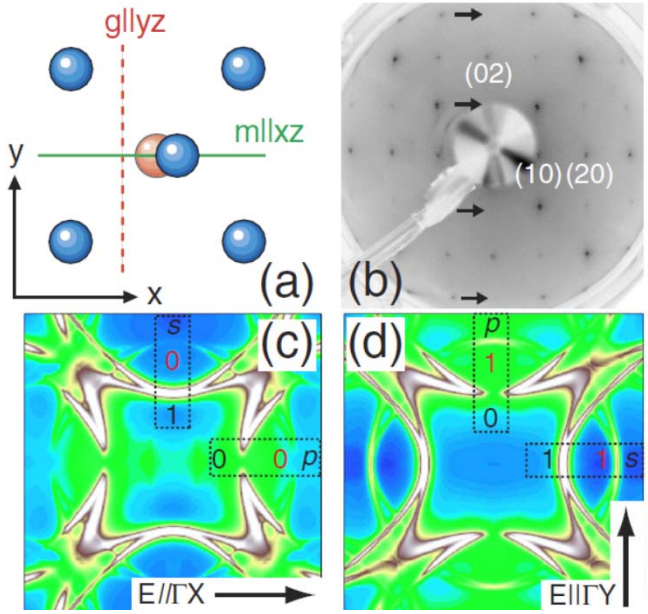

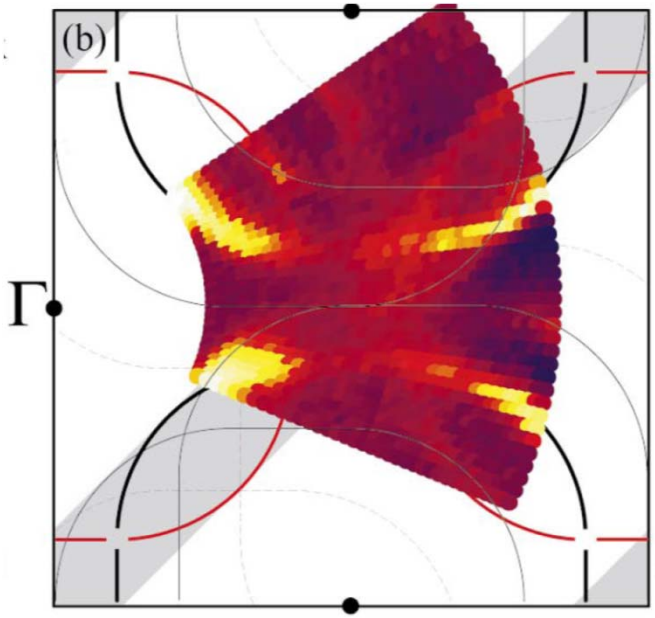

Structural Origin of Apparent Fermi Surface Pockets in Angle-Resolved Photoemission of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

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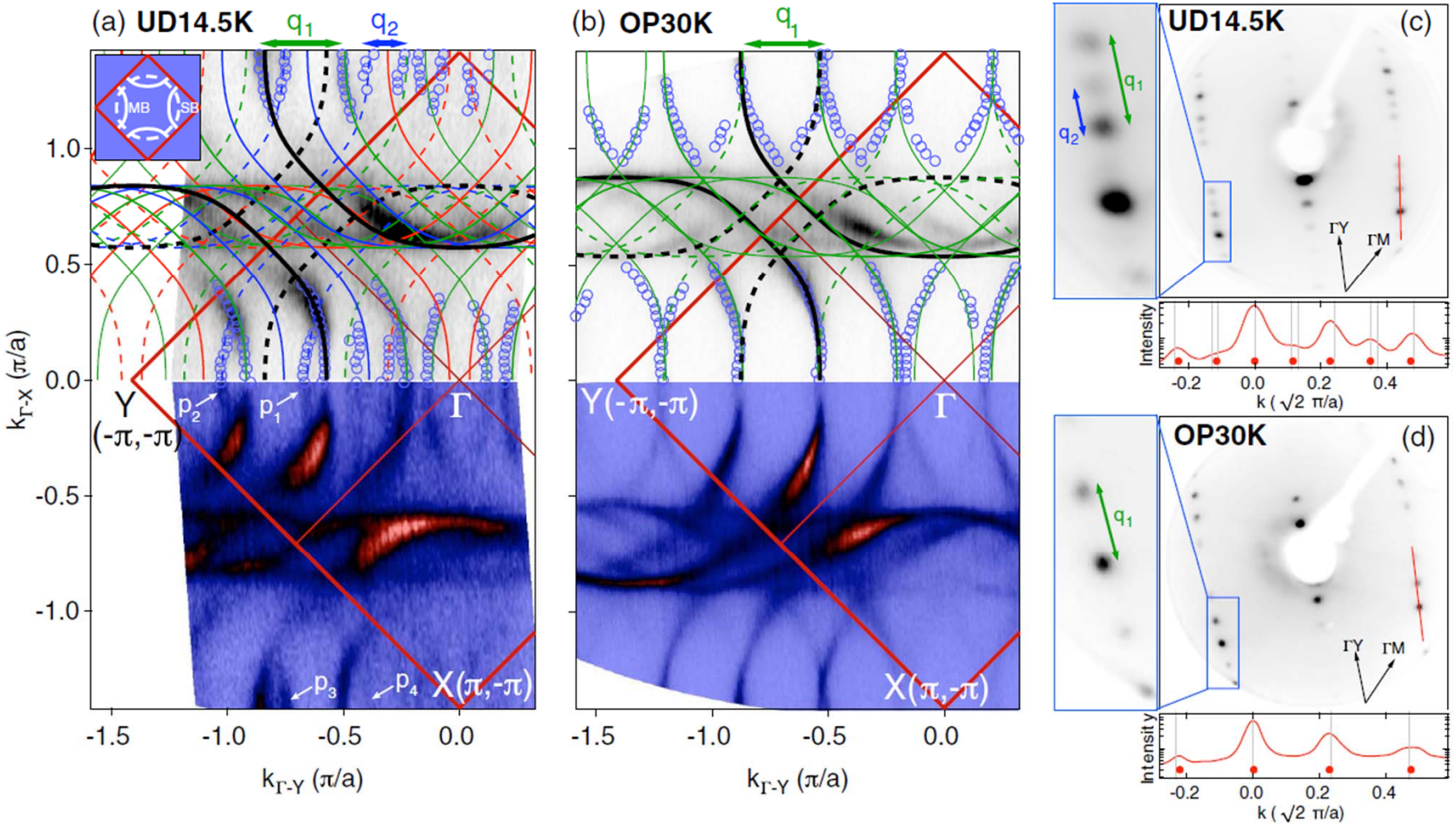

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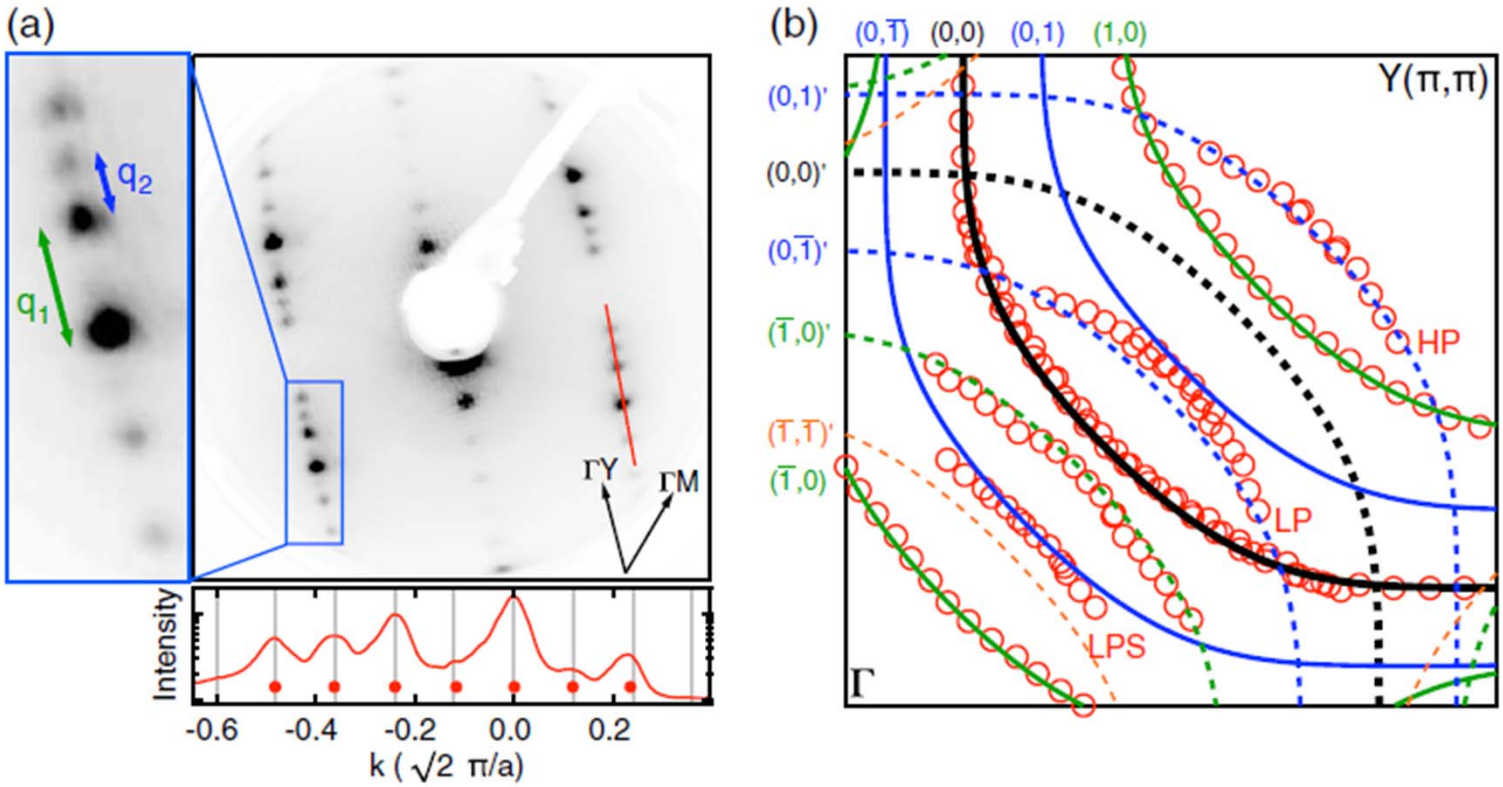

Revealing the ortho-II Band Folding in $YBa_2Cu_3O_{7-\delta}$ Films

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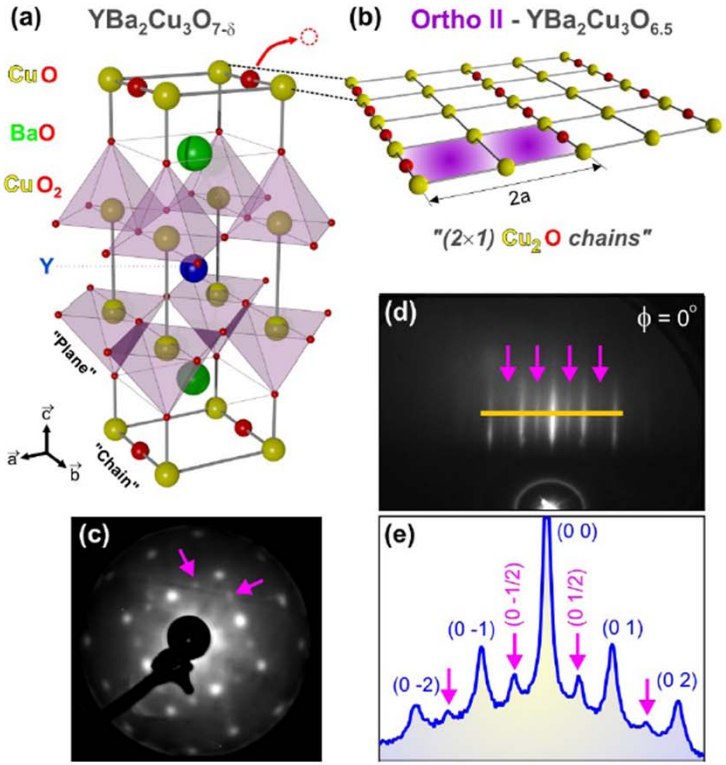
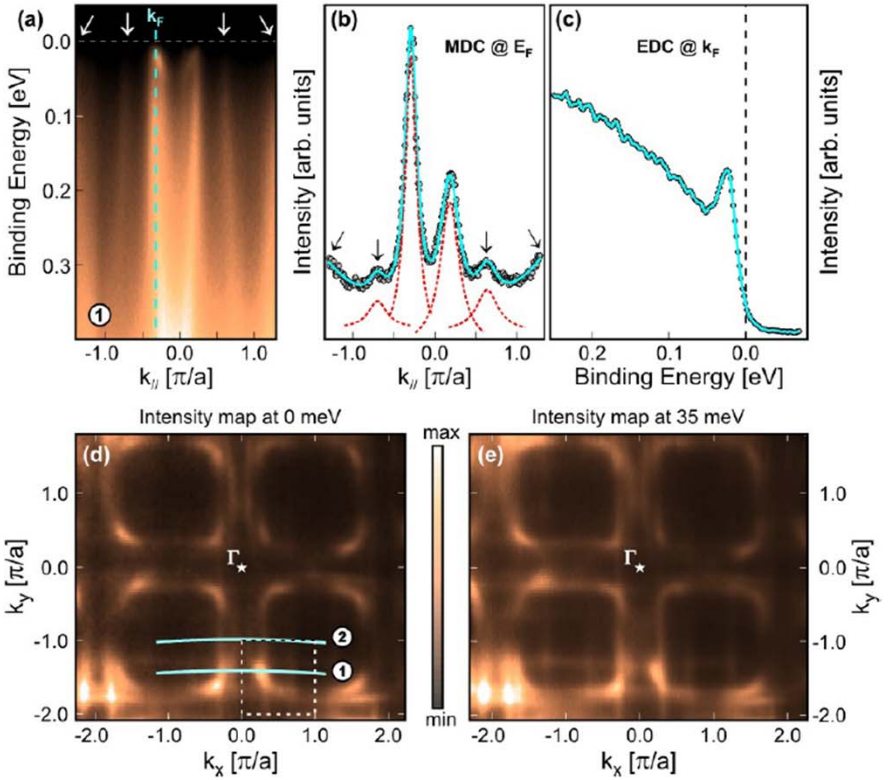
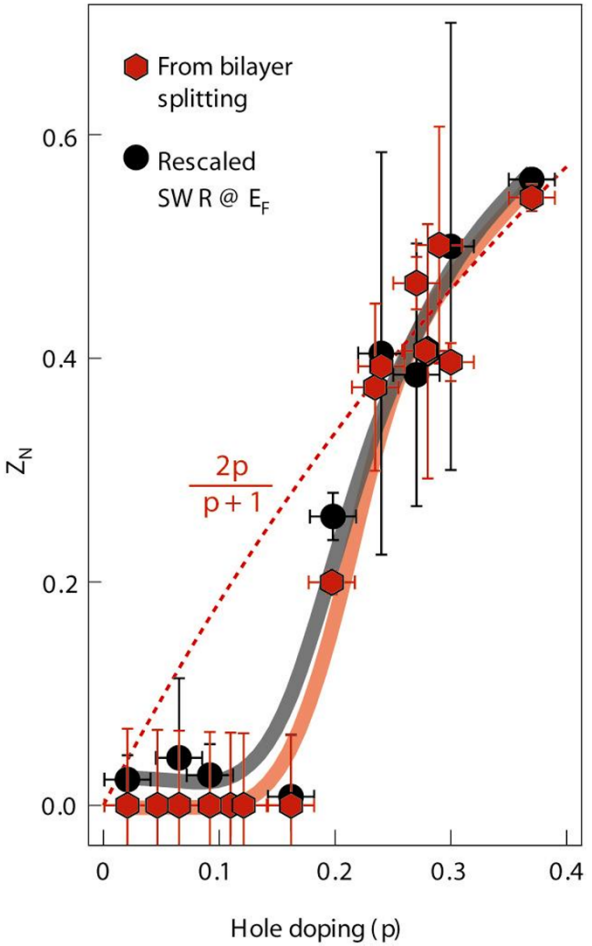




Bilayer band splitting and quasiparticle coherence

$$Z_N = \Delta\epsilon_N^{B,AB}/2t_\perp^{LDA}(N)$$

- Quantitative estimate of Z
- Agreement with 2p/(p+1) for x>0.23
- Isotropic Z_N~0.54 and Z_{AN}~0.50
- Vanishing Z_N below 15-10%
- $t_\perp$~10meV consistent with QO
- Z even smaller for pockets' "other side"
- Pseudogap? Loss of coherent SW
- Fermi surface? Luttinger's counting?



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