The Fermi Surface of High-T_c Superconductors

Sudipfest 2019

Brad Ramshaw

Laboratory for Atomic and Solid State Physics

Cornell University

LASSP Laboratory of Atomic and Solid State Physics

Cornell University

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Collaborators

Ross McDonald
Neil Harrison
Mun Chan
Jon Betts
Zengwei Zhu
Arkady Shekhter

Kimberly Modic

Yawen Fang

Cornell University

James Day
Doug Bonn
Walter Hardy
Ruixing Liang

UBC

Paul Goddard
Saman
Ghannadzadeh

WARWICK
THE UNIVERSITY OF WARWICK

Suchitra
Sebastian
Beng Tam

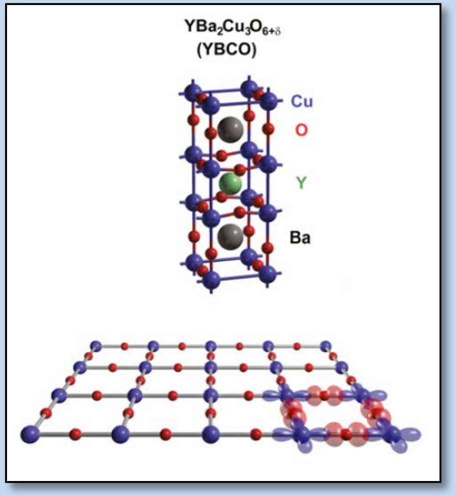
UNIVERSITY OF
CAMBRIDGE

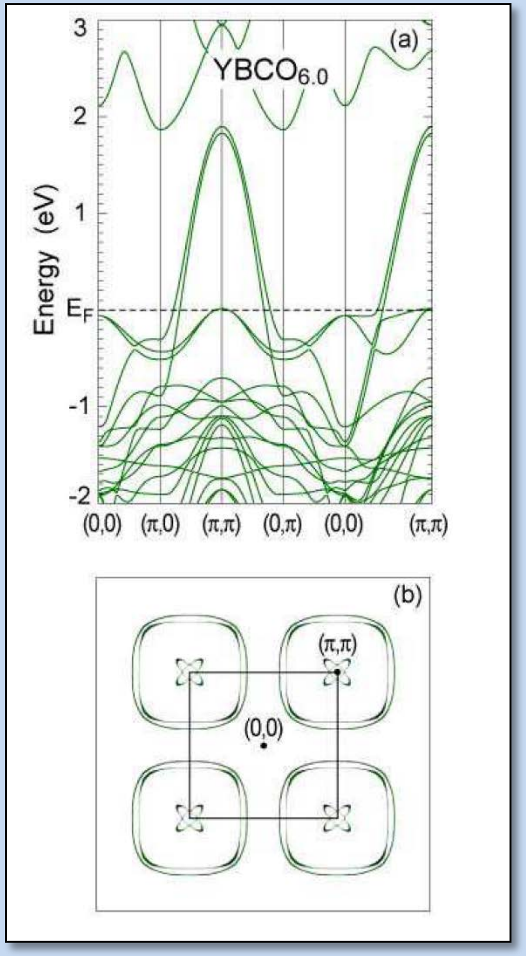
Louis Taillefer
Gael
Grissonnanche
Anaelle Legros
Francis Laliberte

UNIVERSITÉ DE
SHERBROOKE

NSF

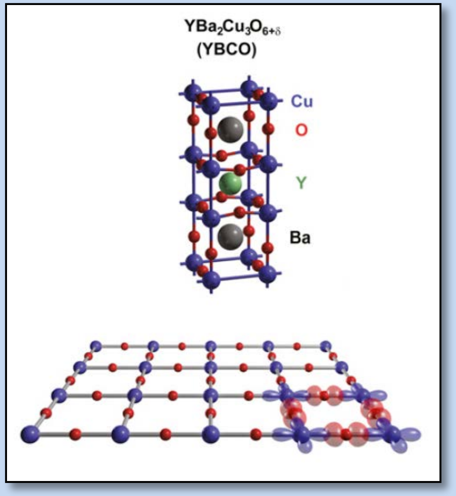
From Insulator to Superconductor

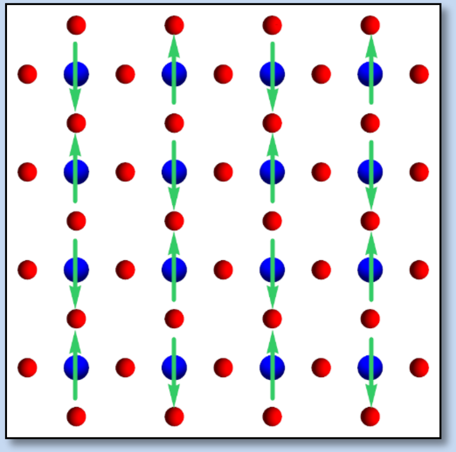


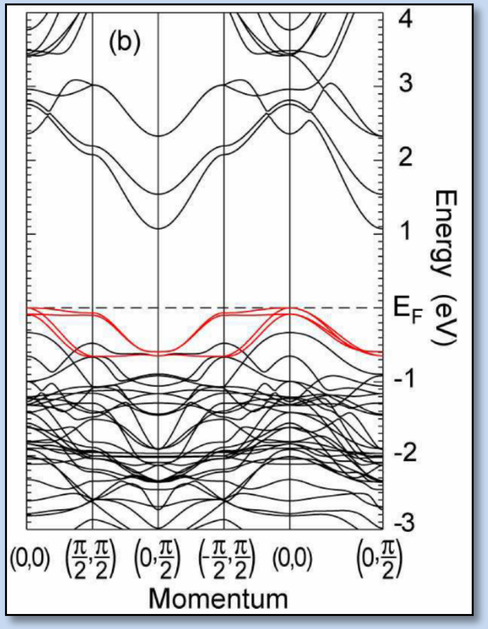


Barisic, N *et al.,* PNAS (2013), I.S. Elfimov *et al.* PRB 060504(R) 2008

From Insulator to Superconductor

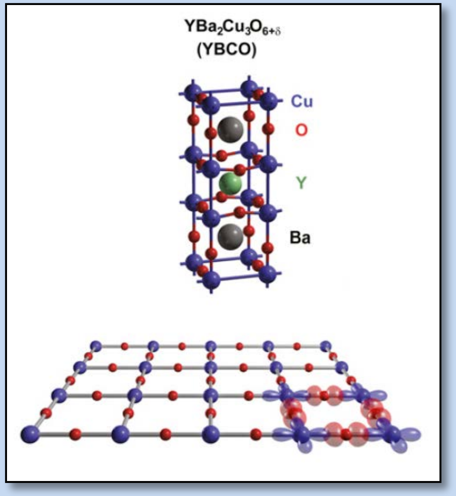


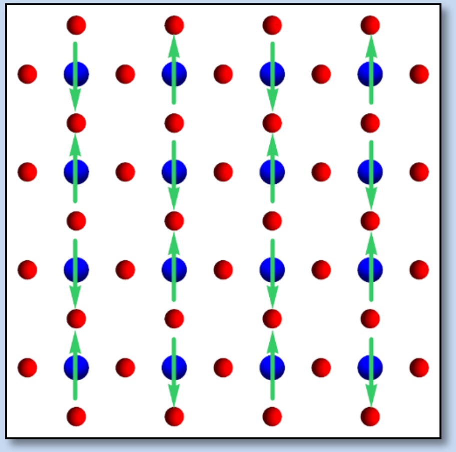


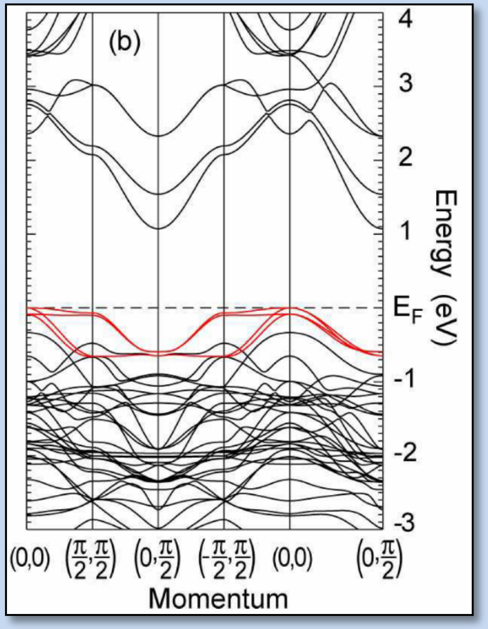


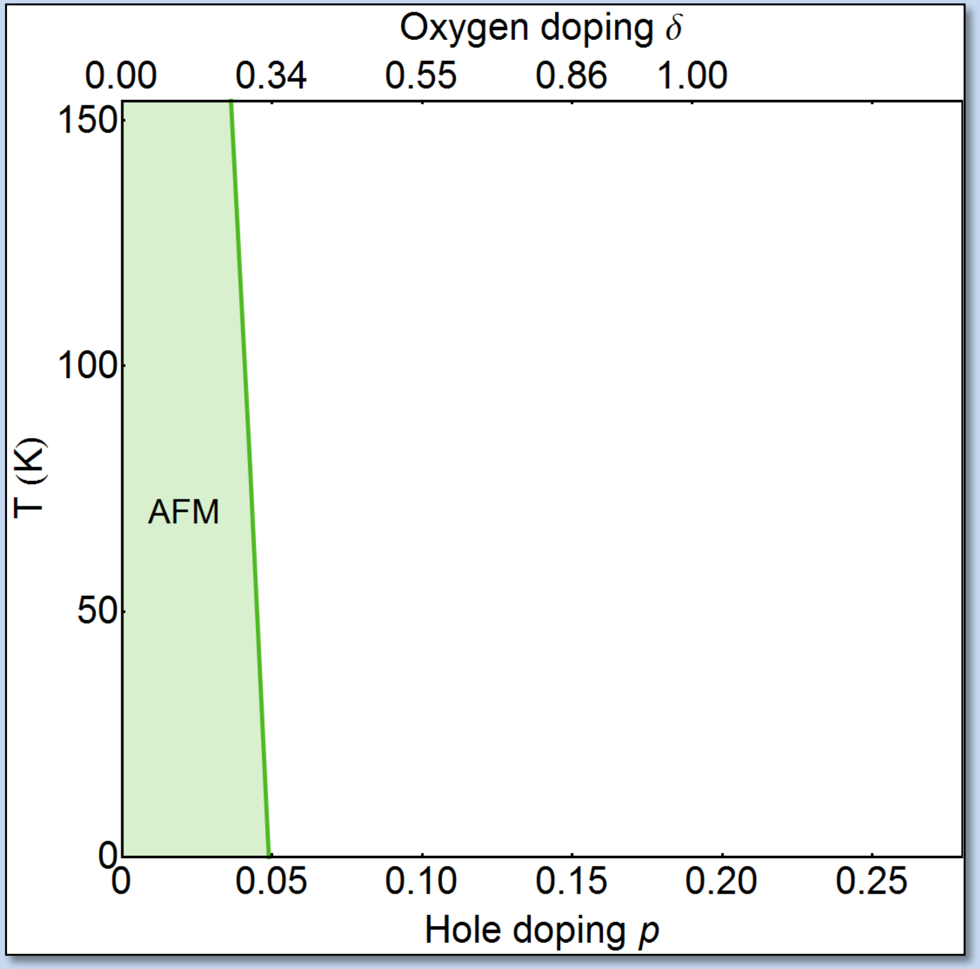
Barisic, N *et al.,* PNAS (2013), I.S. Elfimov *et al.* PRB 060504(R) 2008

From Insulator to Superconductor



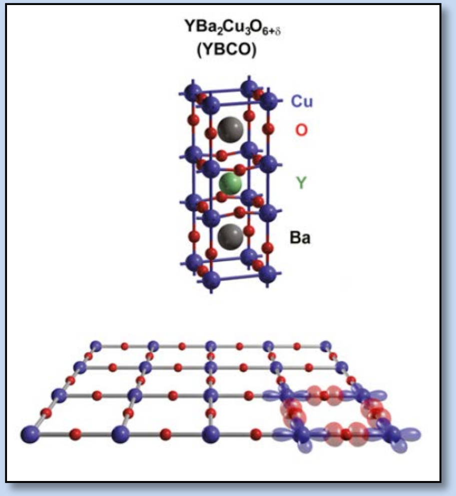


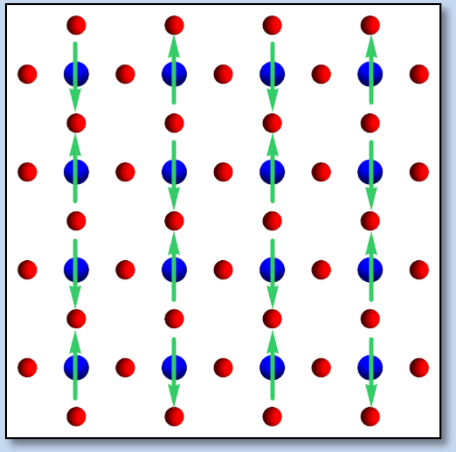




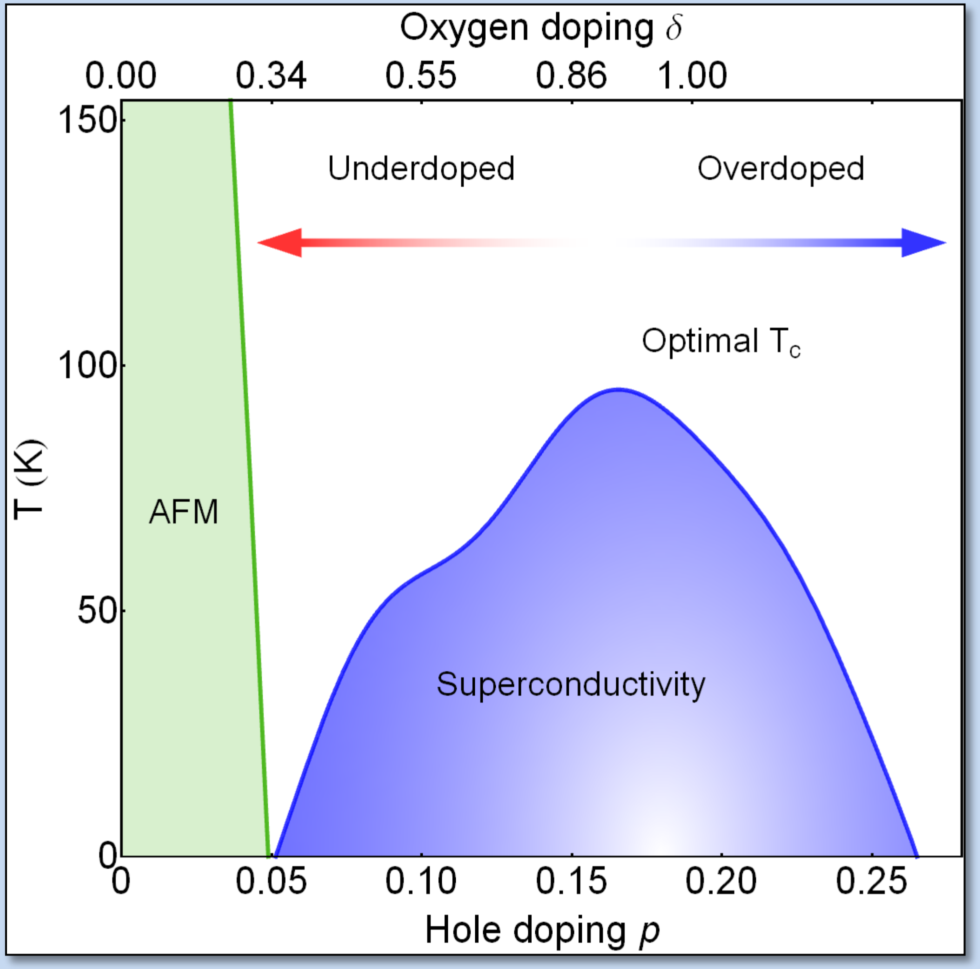
Barisic, N *et al.,* PNAS (2013), I.S. Elfimov *et al.* PRB 060504(R) 2008

From Insulator to Superconductor



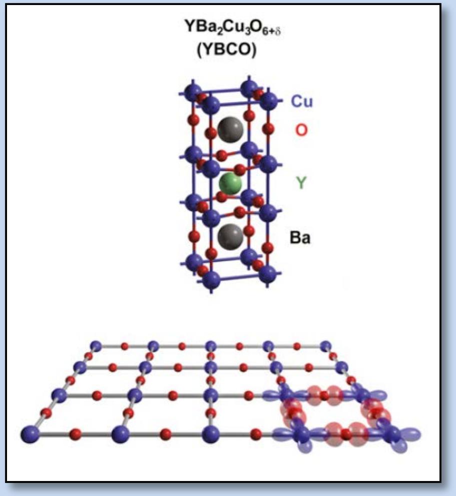


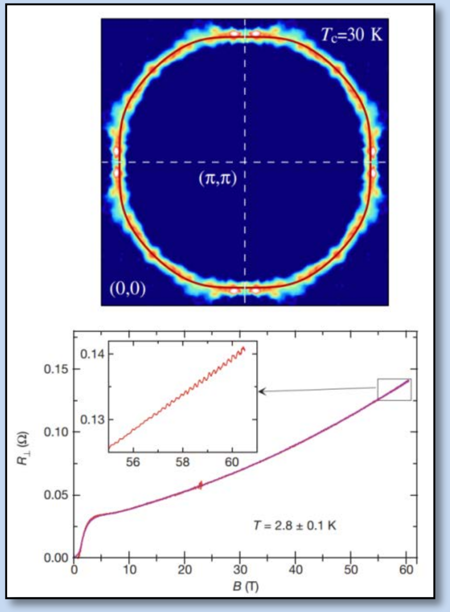
?



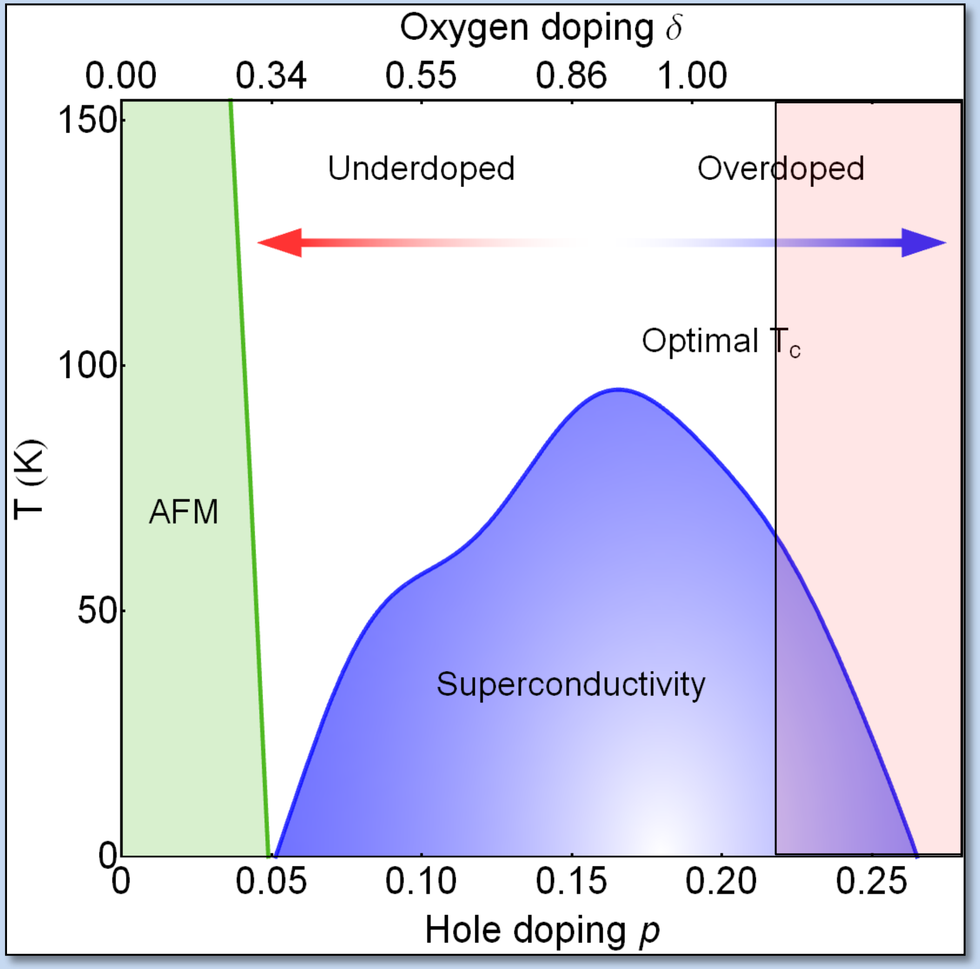
Barisic, N *et al.*, PNAS (2013),

From Insulator to Superconductor



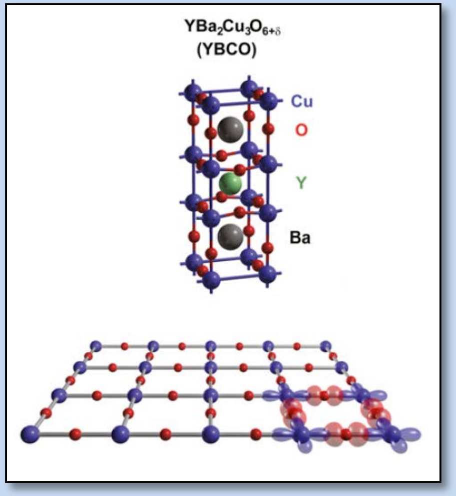


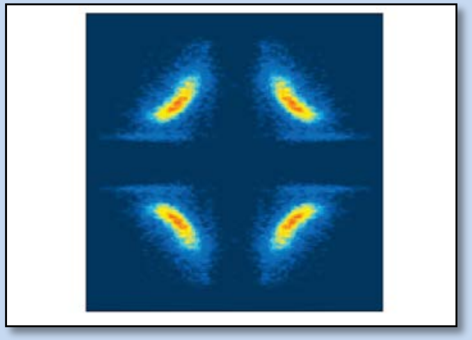
Fermi surface volume is 1+*p*



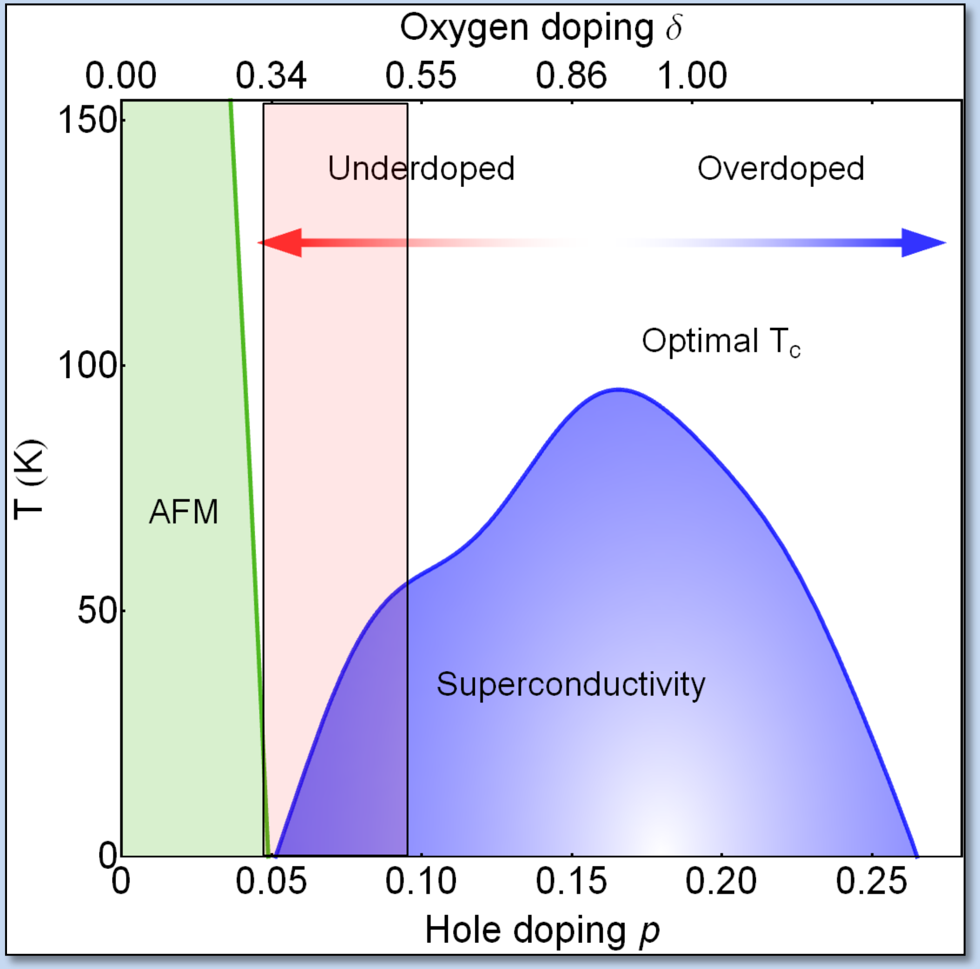
Barisic, N *et al.,* PNAS (2013), M. Platé *et al.*, PRL (2005); B. Vignolle *et al.*, Nature (2008); N.E. Hussey *et al.*, Nature (2003)
Ramshaw *et al.*, Nature Physics (2011); M. A. Hossain *et al.*, Nature (2008)

From Insulator to Superconductor



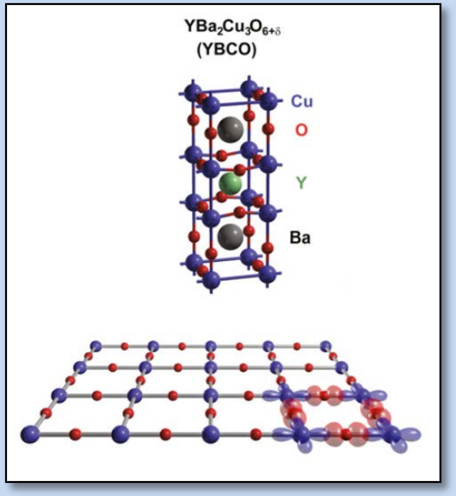


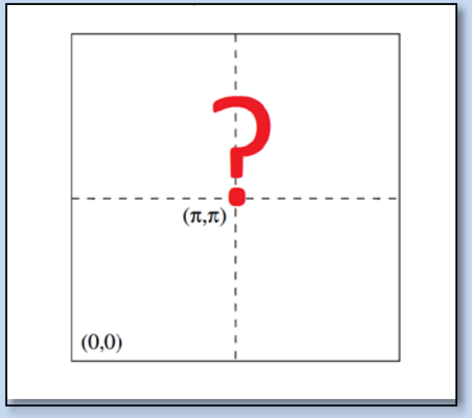
Hall effect indicates *p* holes at low doping



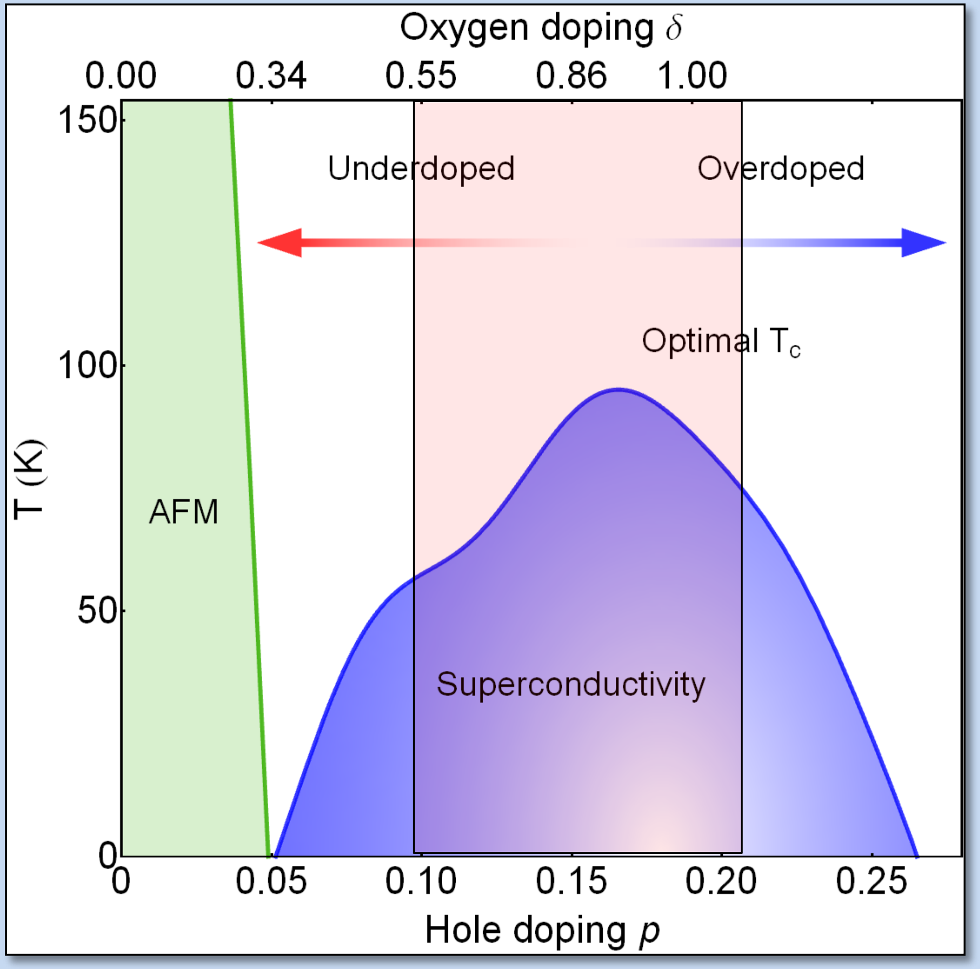
Barisic, N *et al.,* PNAS (2013), M. Platé *et al.*, PRL (2005); B. Vignolle *et al.*, Nature (2008); N.E. Hussey *et al.*, Nature (2003)
Ramshaw *et al.*, Nature Physics (2011); M. A. Hossain *et al.*, Nature (2008)

From Insulator to Superconductor



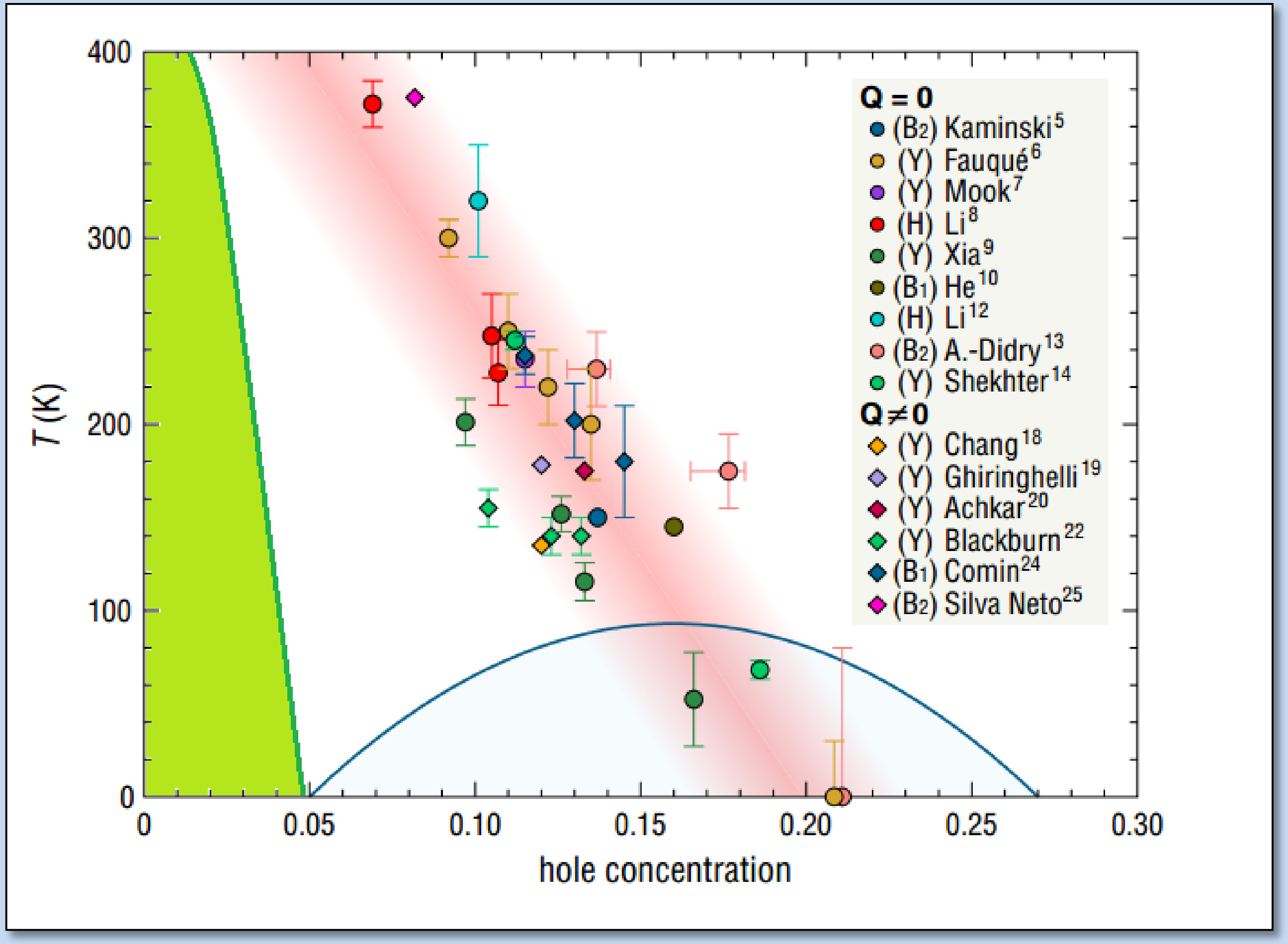


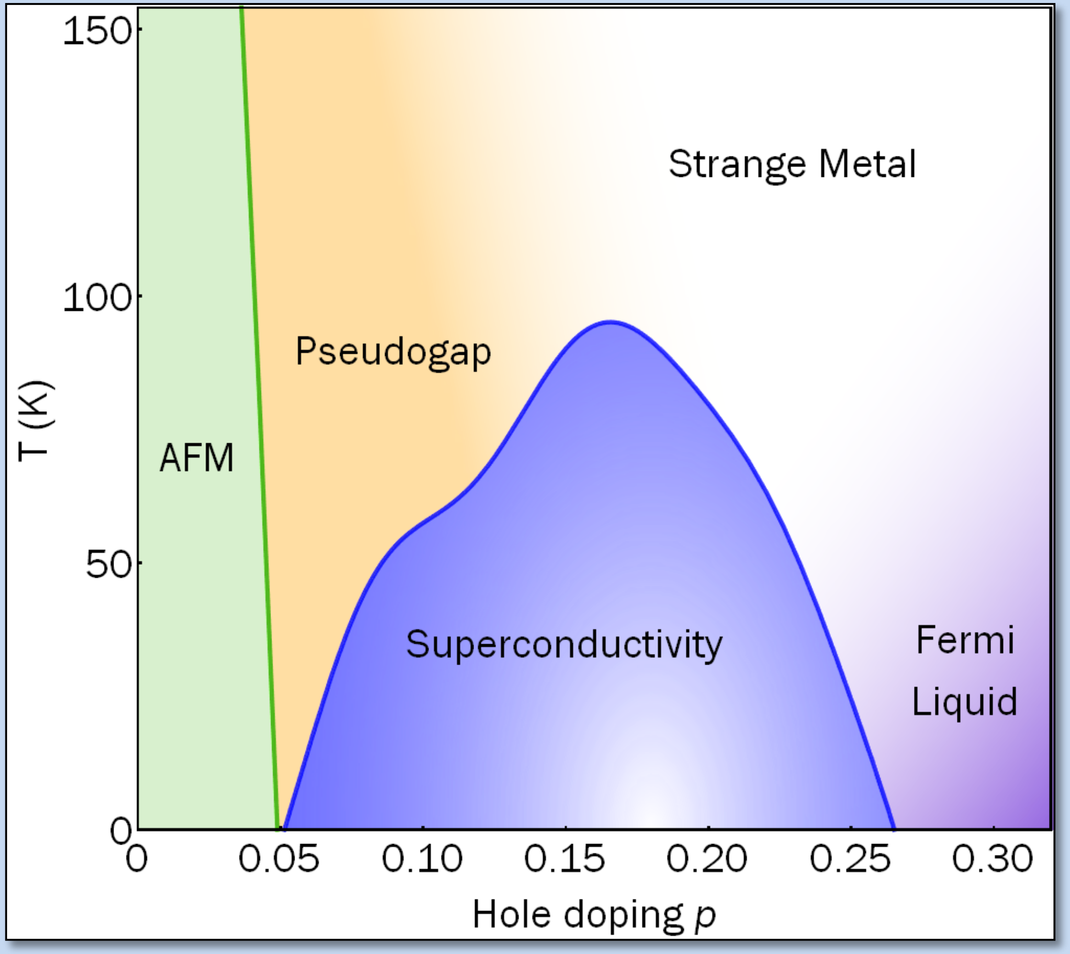
How to get from p to $1+p$?



Barisic, N *et al.*, PNAS (2013), M. Platé *et al.*, PRL (2005); B. Vignolle *et al.*, Nature (2008); N.E. Hussey *et al.*, Nature (2003)
Ramshaw *et al.*, Nature Physics (2011); M. A. Hossain *et al.*, Nature (2008)

Broken Symmetry in the Phase Diagram

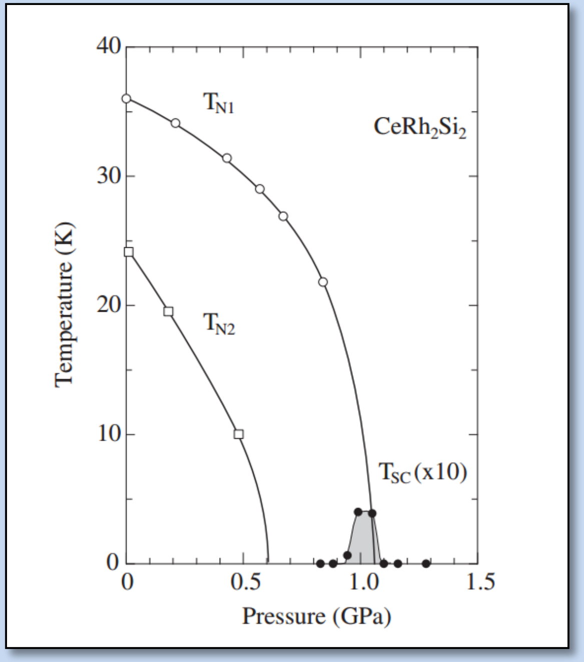




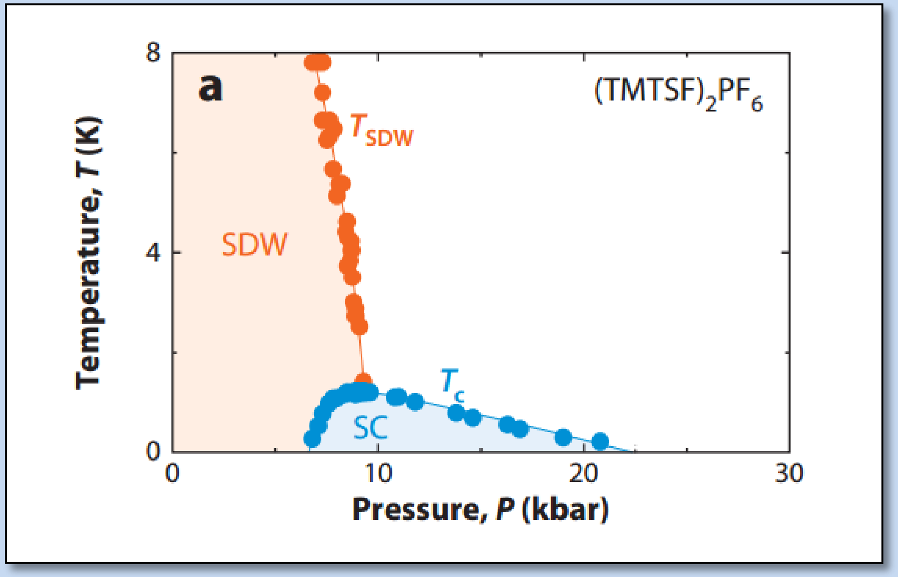
K. Fujita *et al.*, Science (2014)

Broken Symmetry and Unconventional Superconductivity

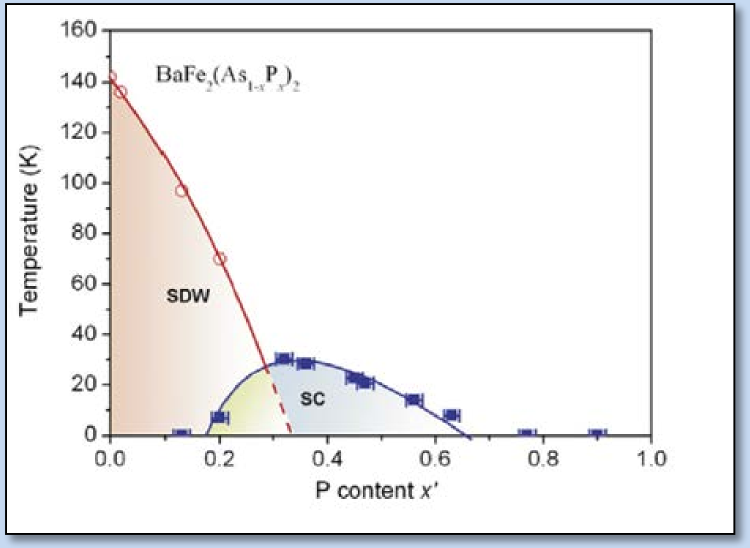
Heavy Fermions



Organics

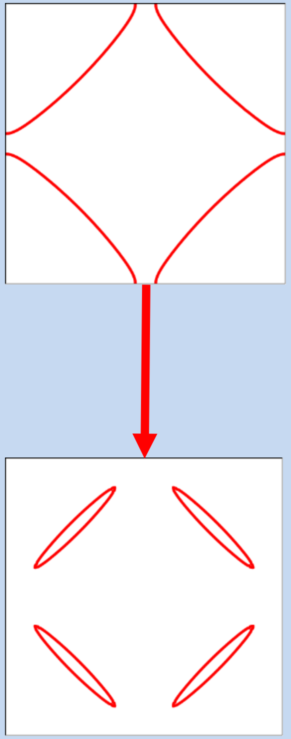


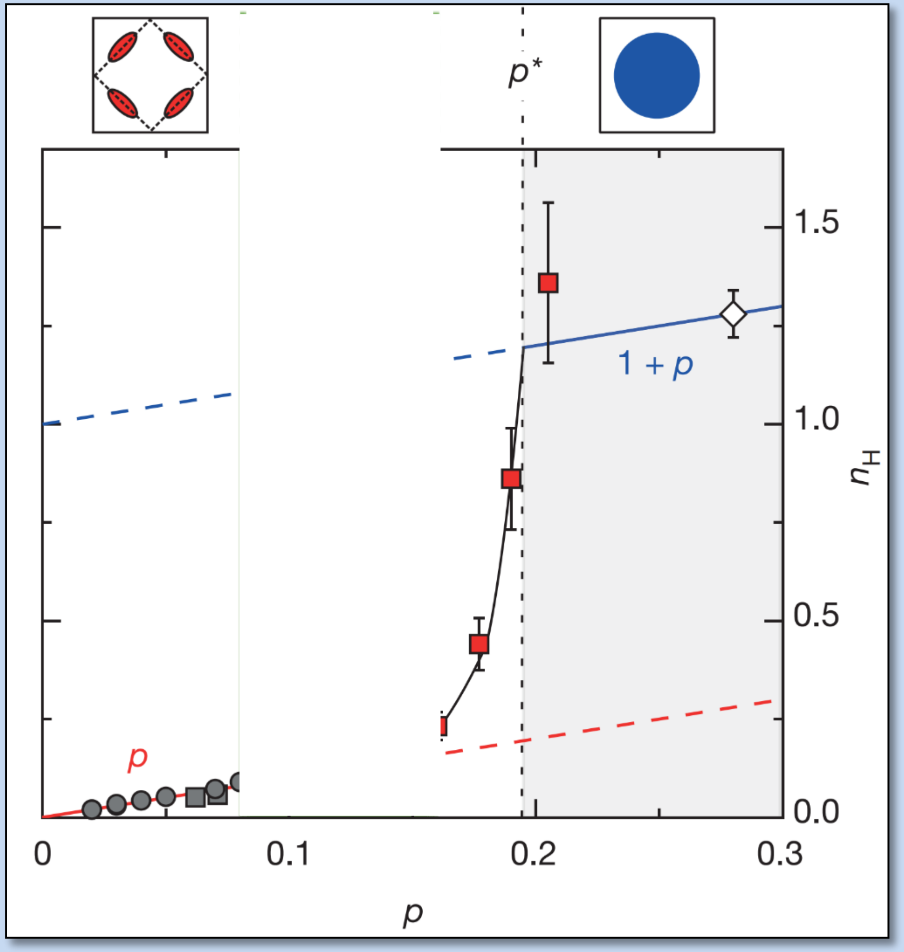
Iron Arsenides

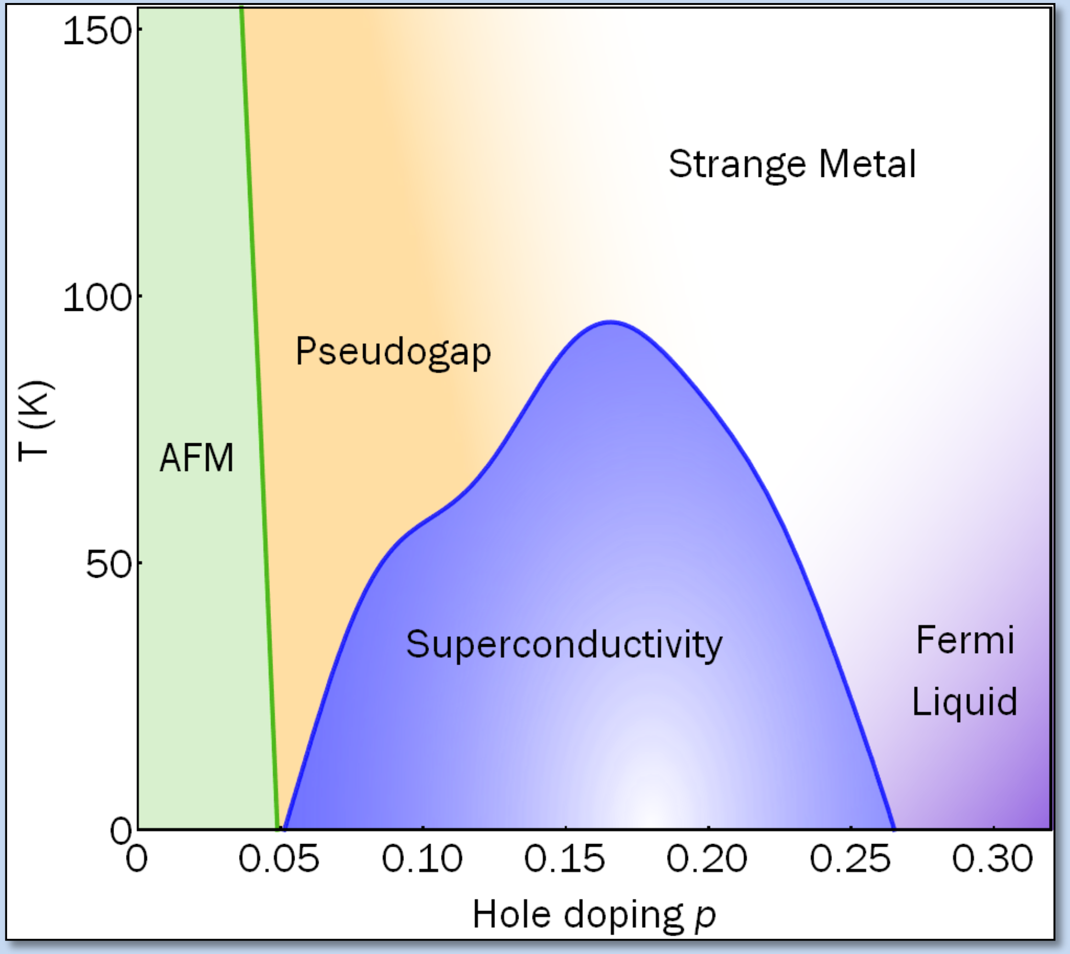


Onuki *et al.*, JPSJ. (2004), ,L. Taillefer, Annu. Rev. Condens. Matter Phys. (2010), Jiang *et al.*, J. Phys. C. (2009)

From Insulator to Superconductor

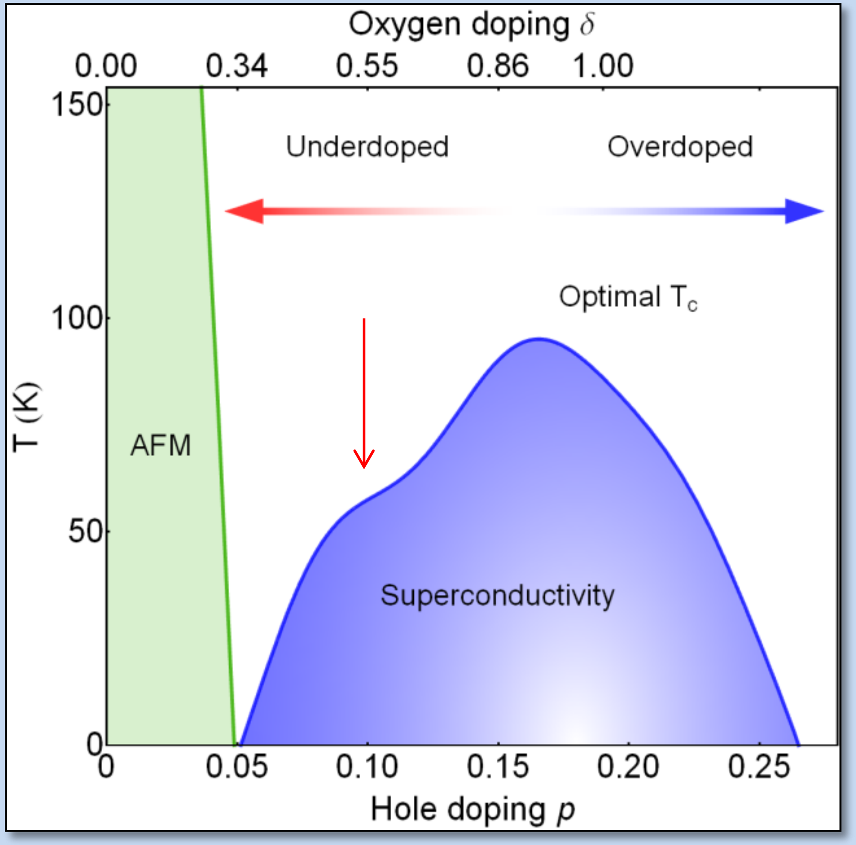


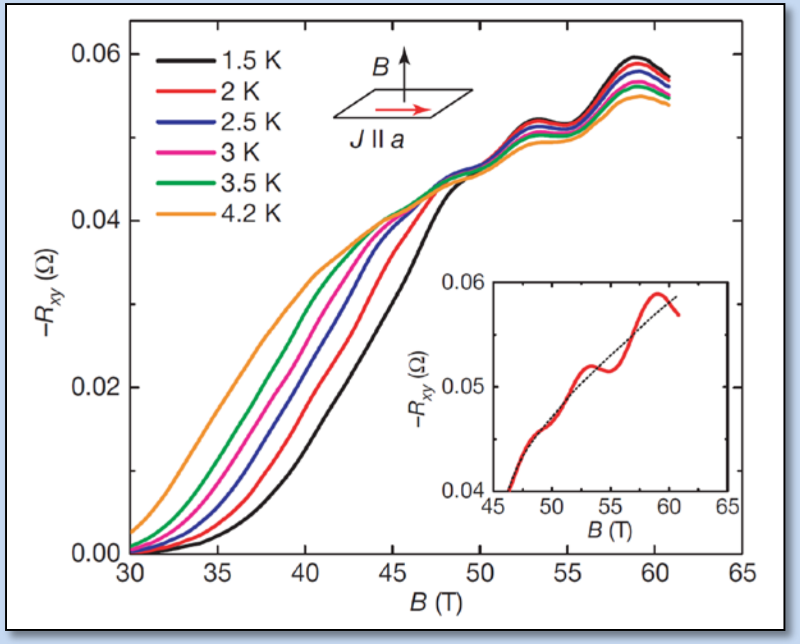


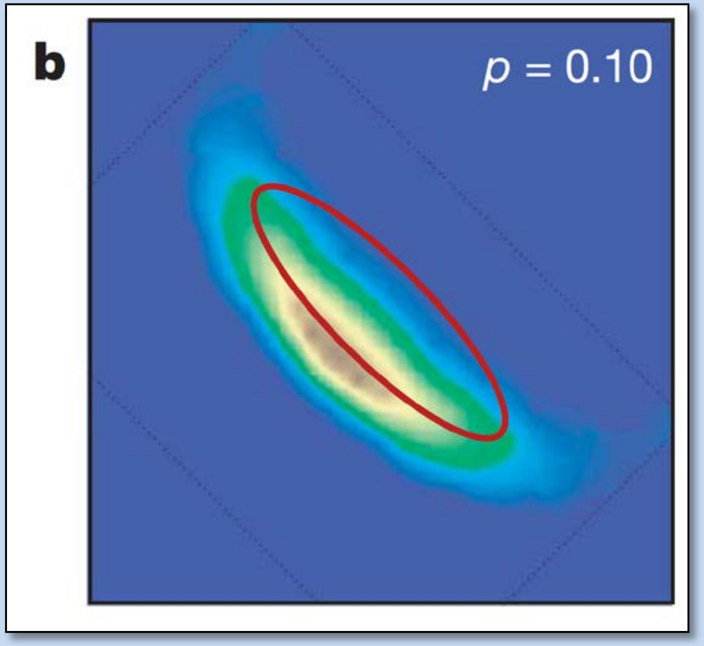


S. Badoux *et al.*, Nature (2017)

Small Fermi Surface in YBa$_2$Cu$_3$O$_{6.52}$

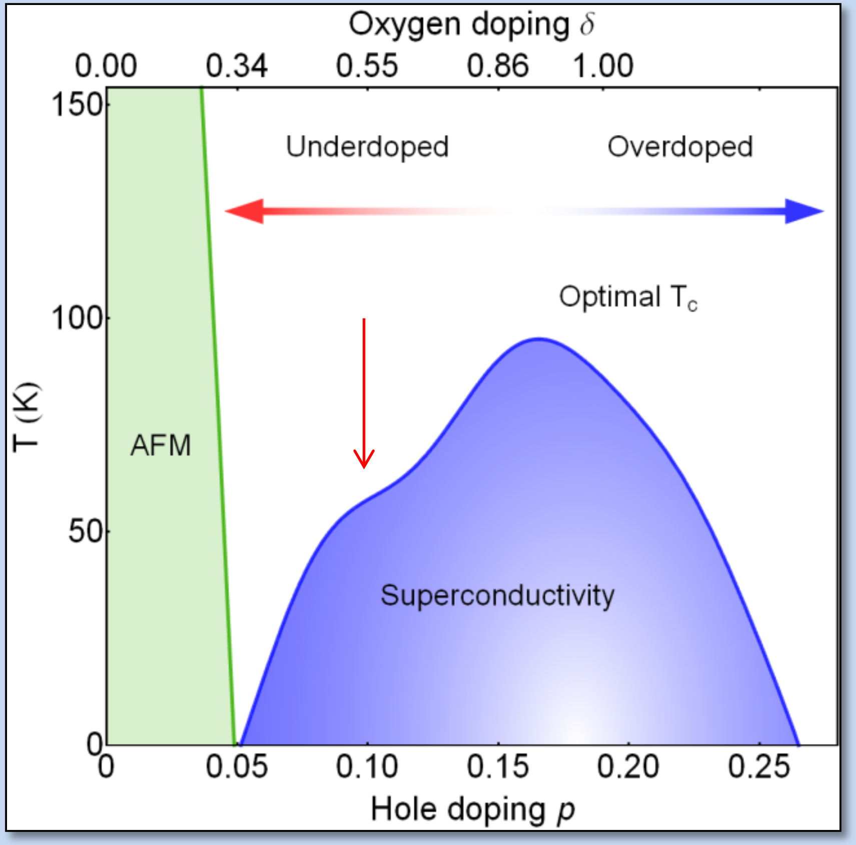


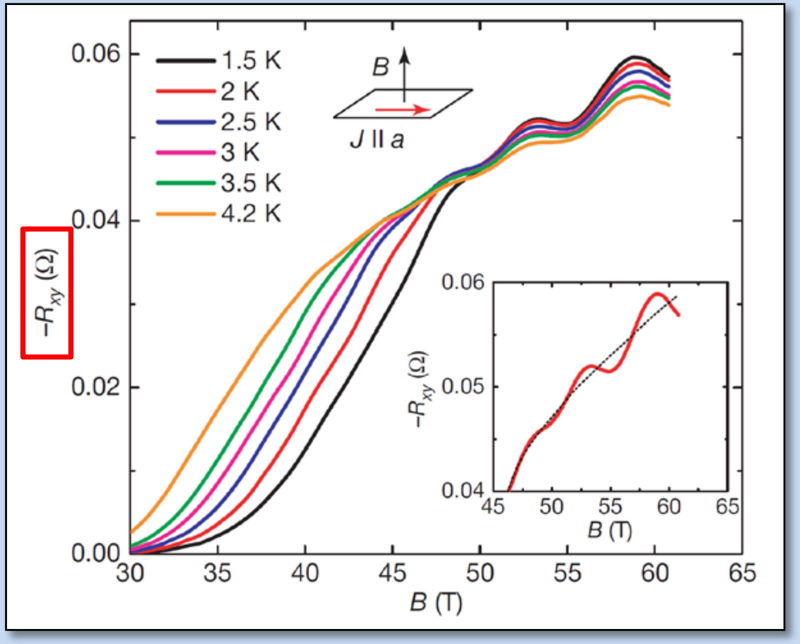


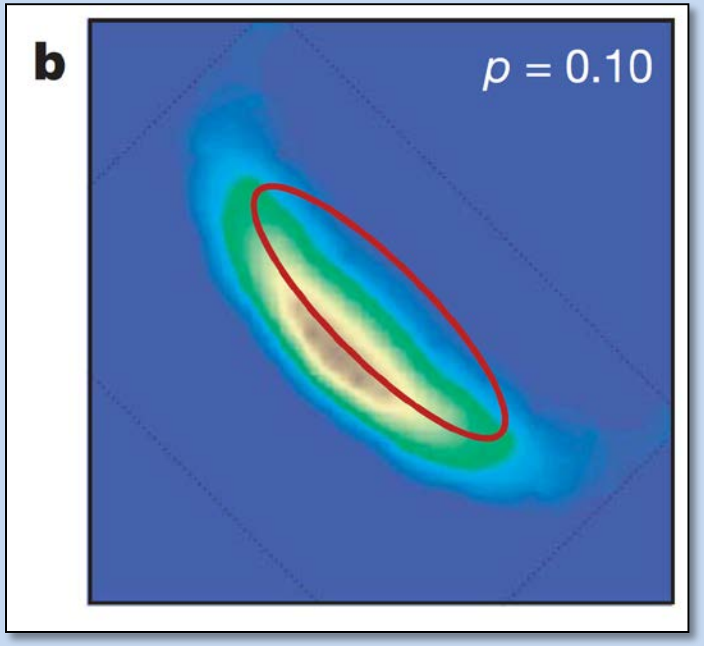


N. Doiron-Leyraud *et al.*, Nature (2007)

Small Fermi Surface in $YBa_2Cu_3O_{6.52}$

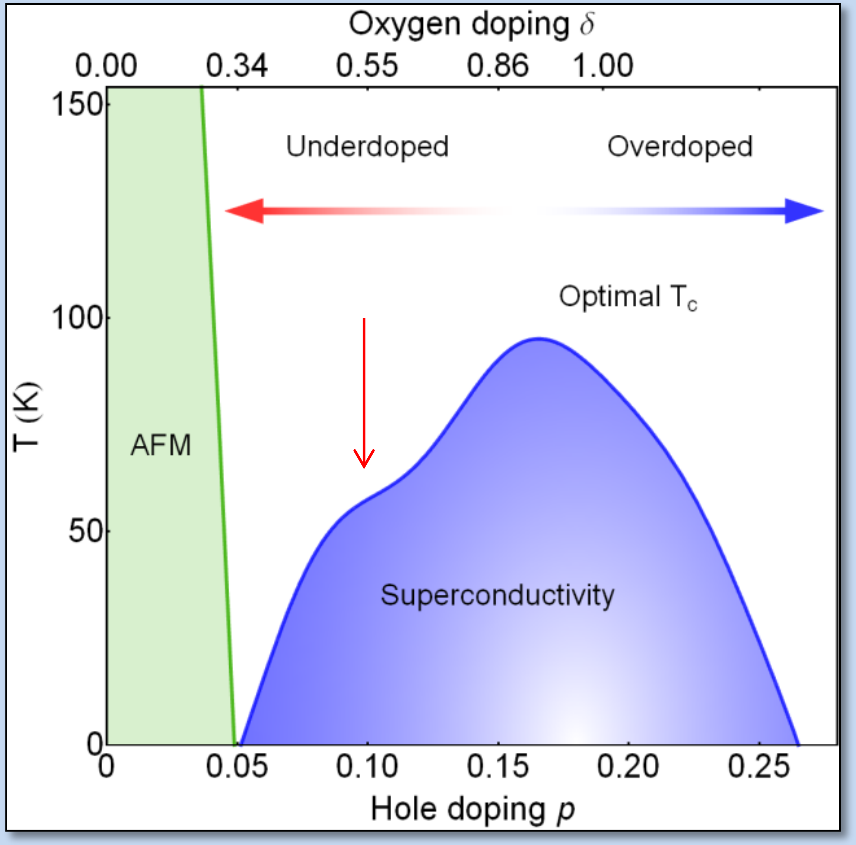


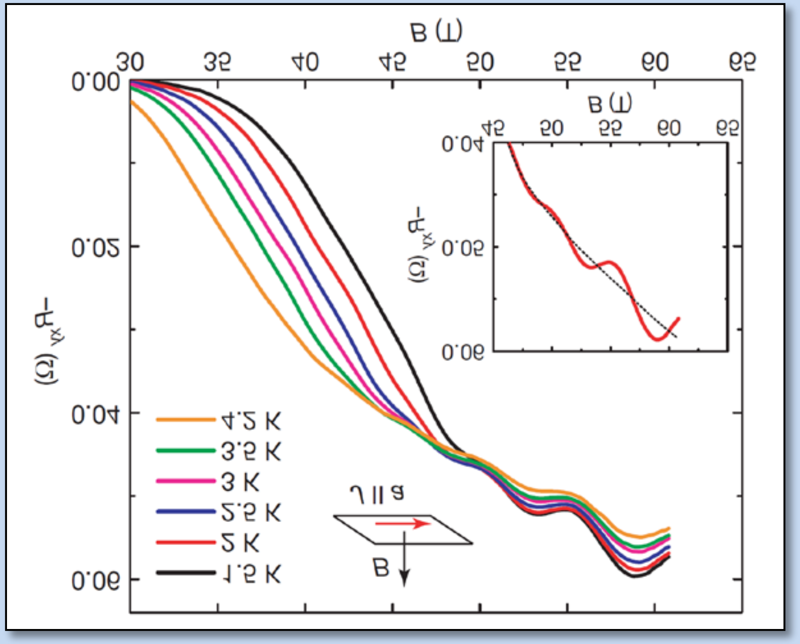


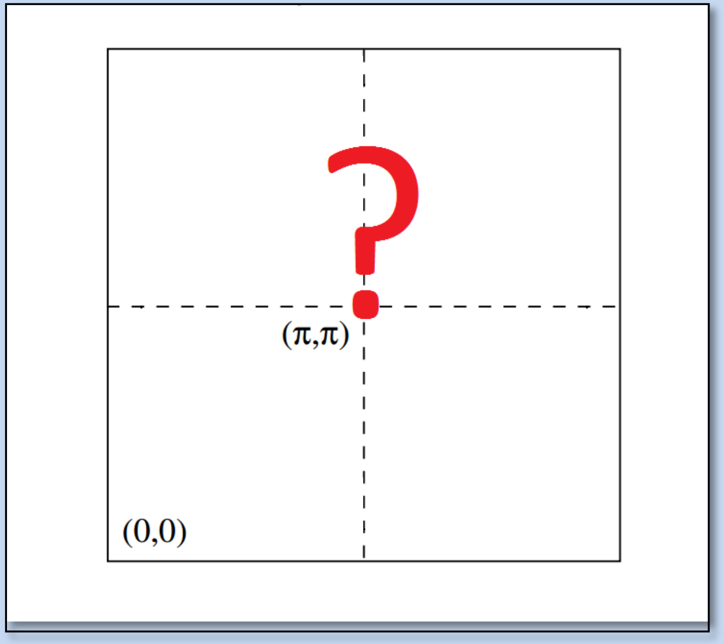


N. Doiron-Leyraud *et al.*, Nature (2007)

Electron Pocket in $YBa_2Cu_3O_{6.52}$

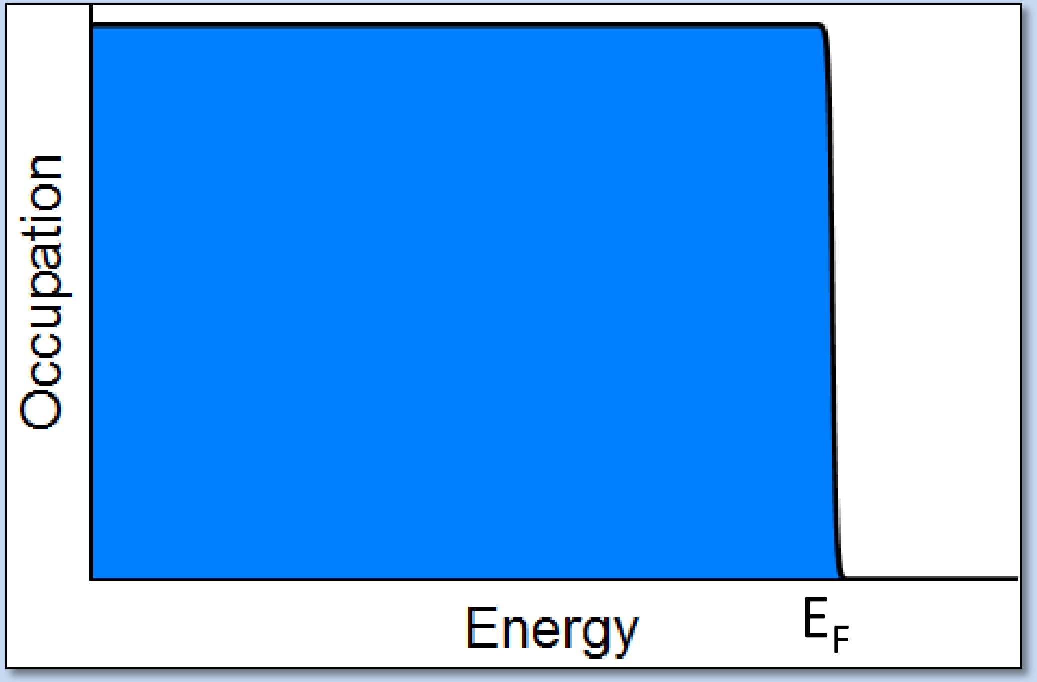


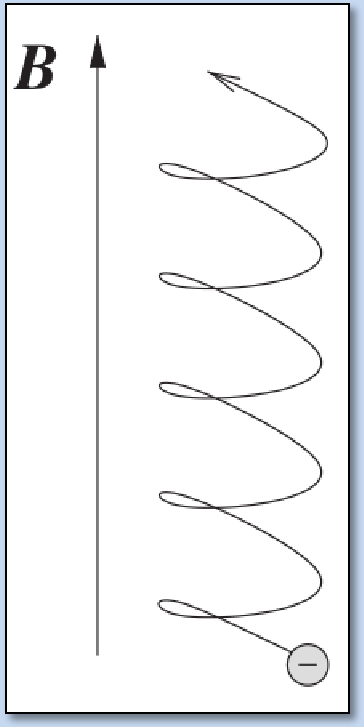




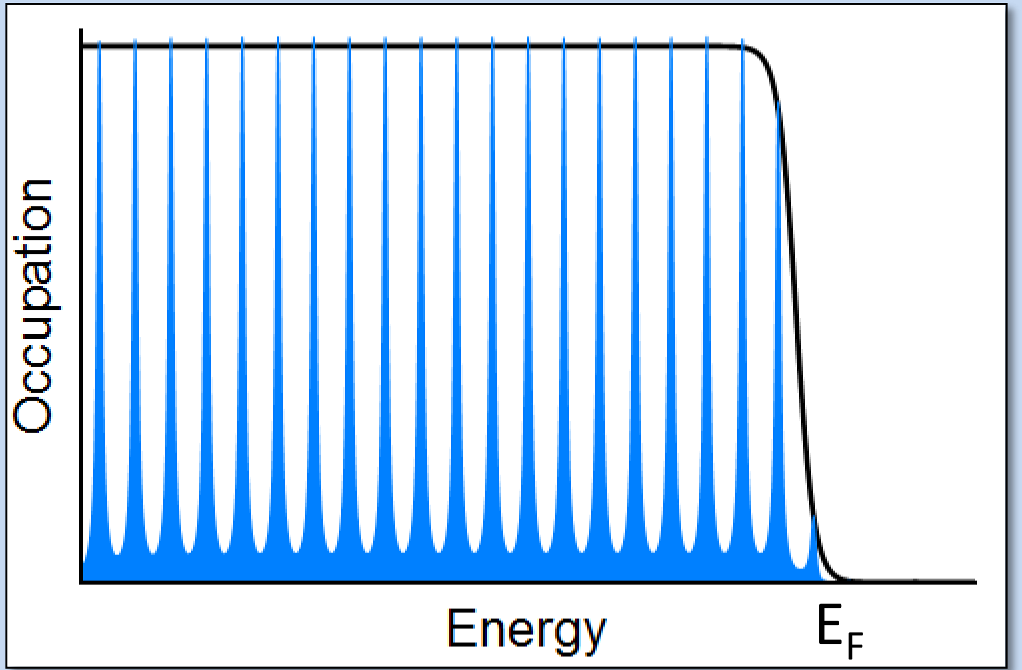
N. Doiron-Leyraud *et al.*, Nature (2007)

Introduction to Quantum Oscillations



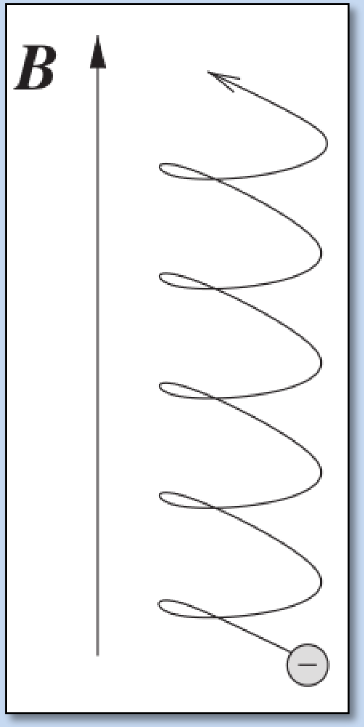


Introduction to Quantum Oscillations

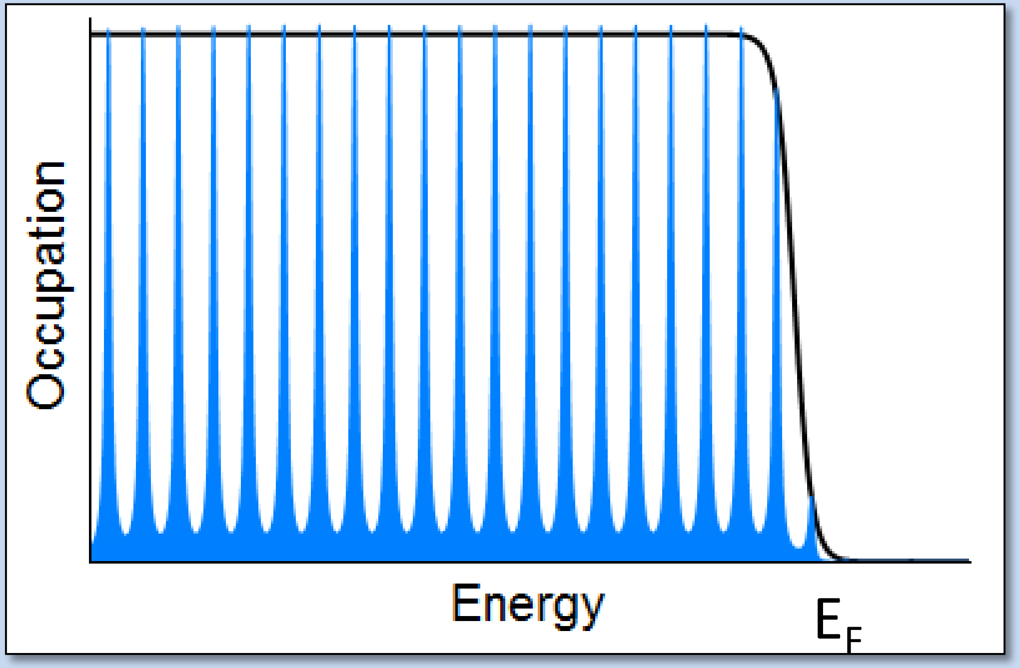


$$E_n = \hbar\omega_c\left(n+\frac{1}{2}\right)$$

$$\omega_c = \frac{eB}{m^*}$$

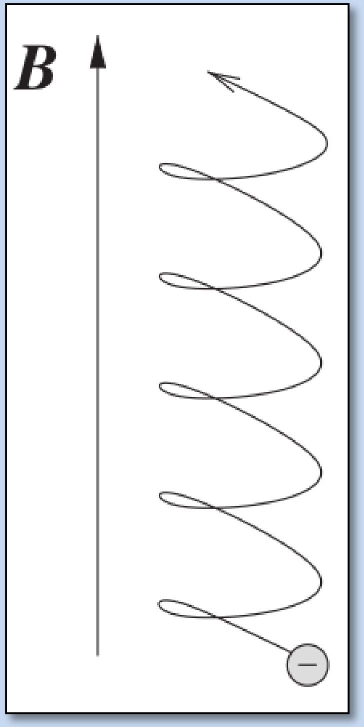


Introduction to Quantum Oscillations

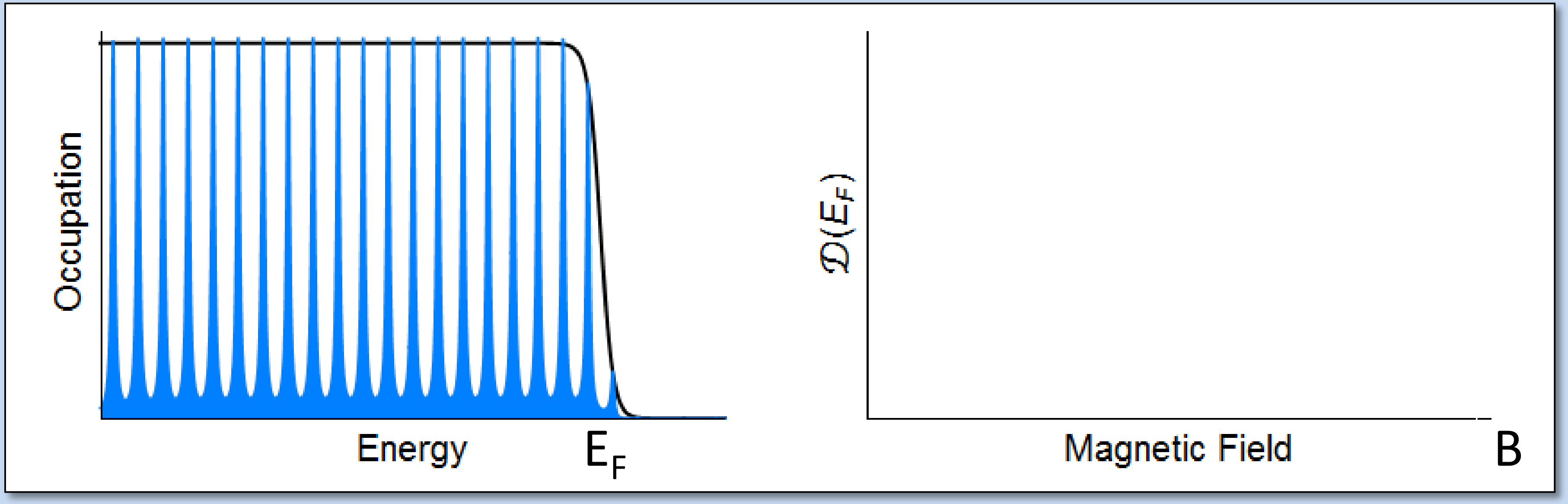


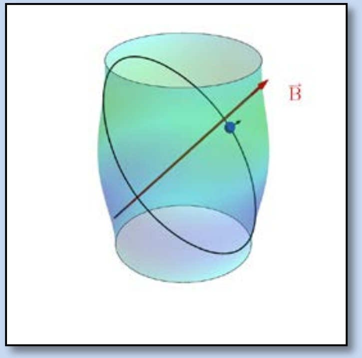
$$E_n = \hbar\omega_c\left(n + \frac{1}{2}\right)$$

$$\omega_c = \frac{eB}{m^*}$$



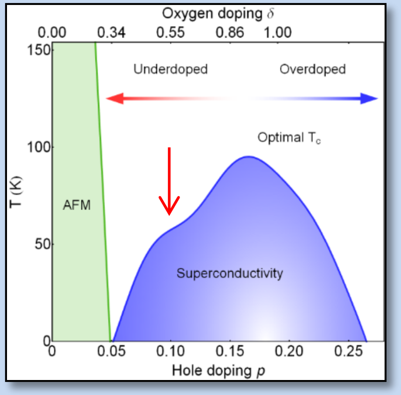
Introduction to Quantum Oscillations

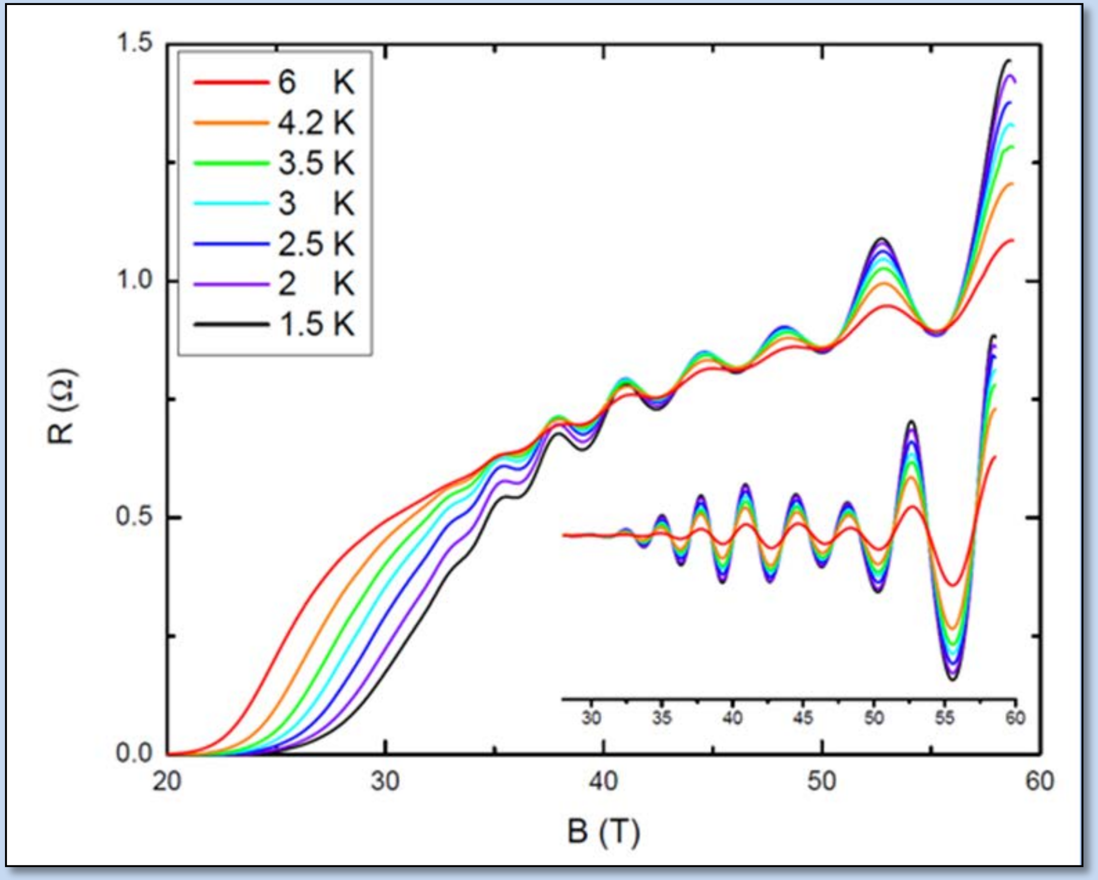


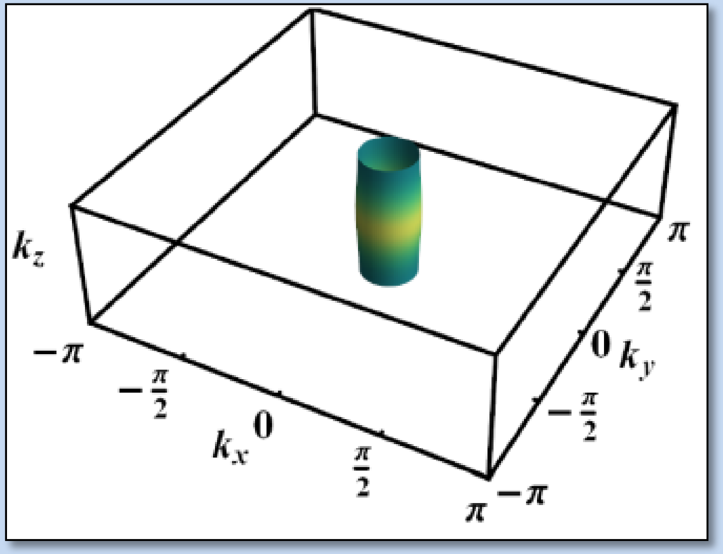


$$F = \frac{\hbar}{2\pi e} A_k$$

Quantum Oscillations in $YBa_2Cu_3O_{6.59}$



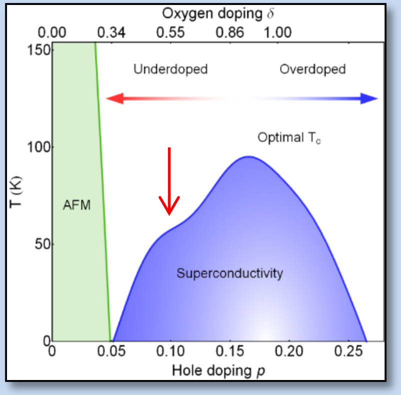


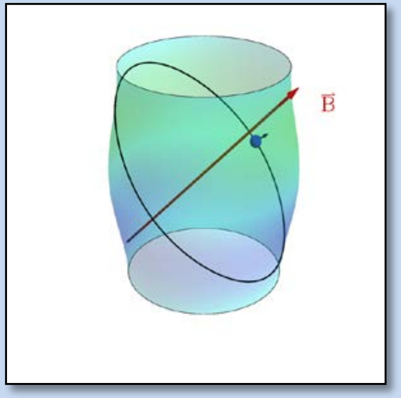


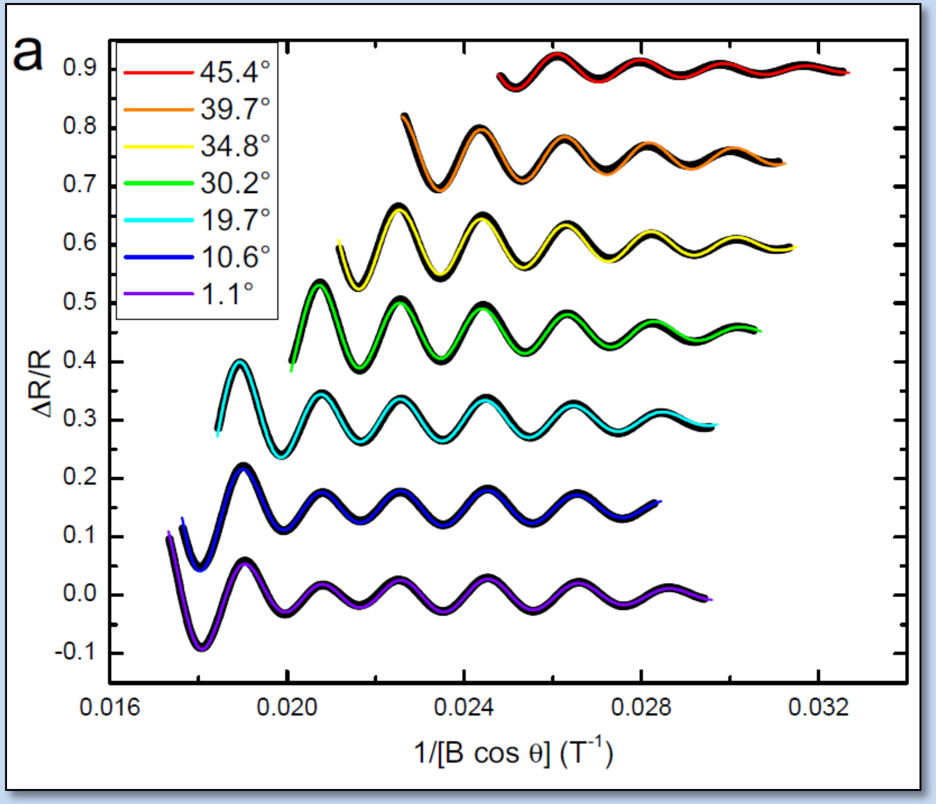
$$F = \frac{\hbar}{2\pi e} A_k$$

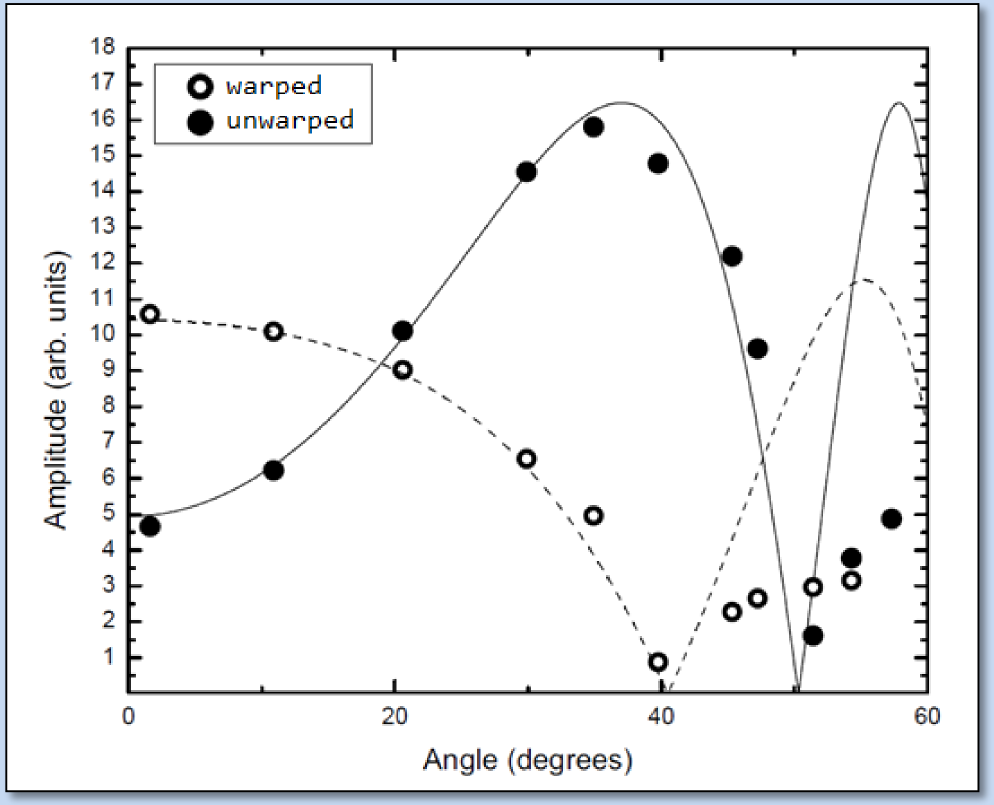
B.J. Ramshaw, *et al.* Nature Physics, 7:3 (2011)

Angle dependence of Quantum Oscillations



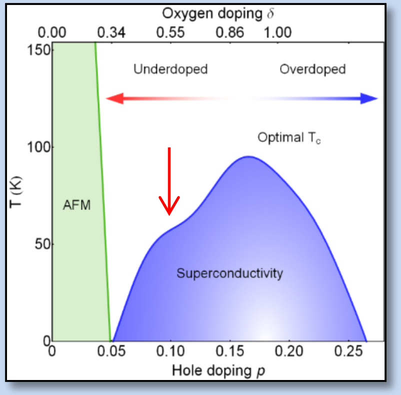


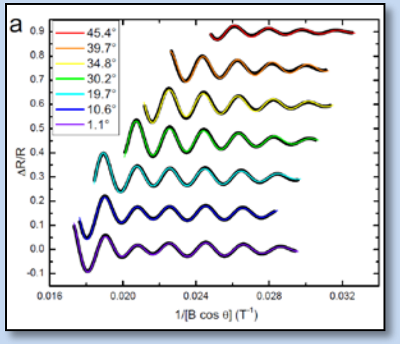


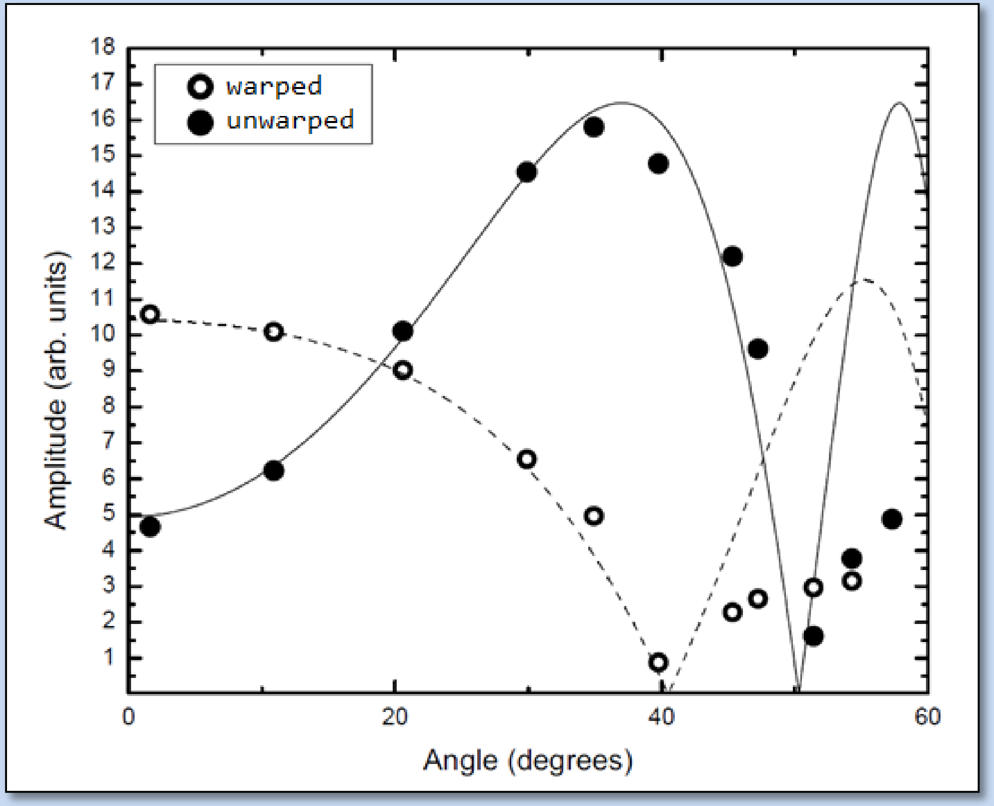


B.J. Ramshaw, *et al.* Nature Physics, 7:3 (2011)

Angle dependence of Quantum Oscillations



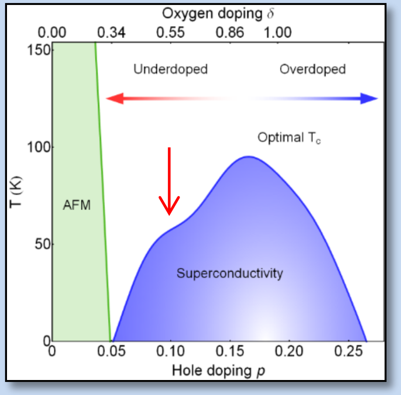


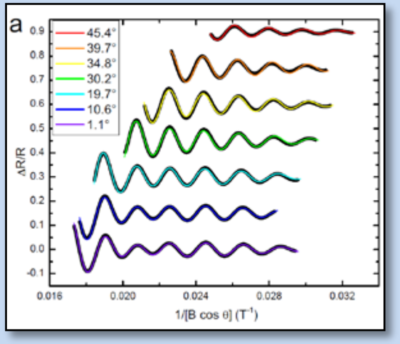


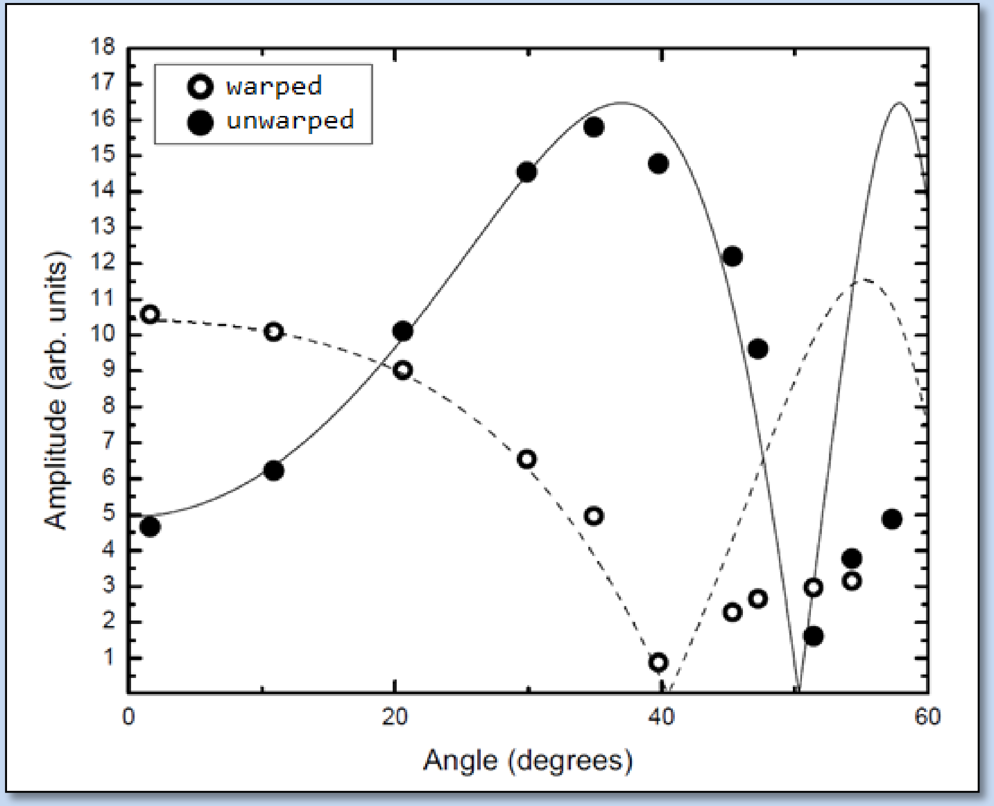
$$\widetilde{DOS} \propto \cos\left(\frac{2\pi F}{B} - \varphi\right) \times R_T R_D$$

B.J. Ramshaw, *et al.* Nature Physics, 7:3 (2011)

Angle dependence of Quantum Oscillations





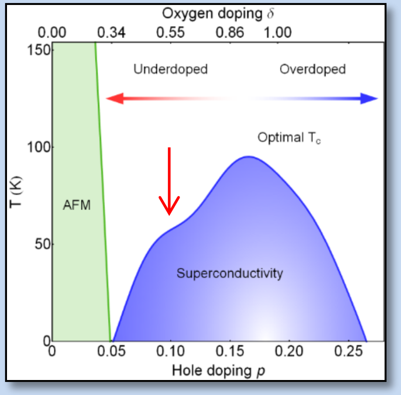


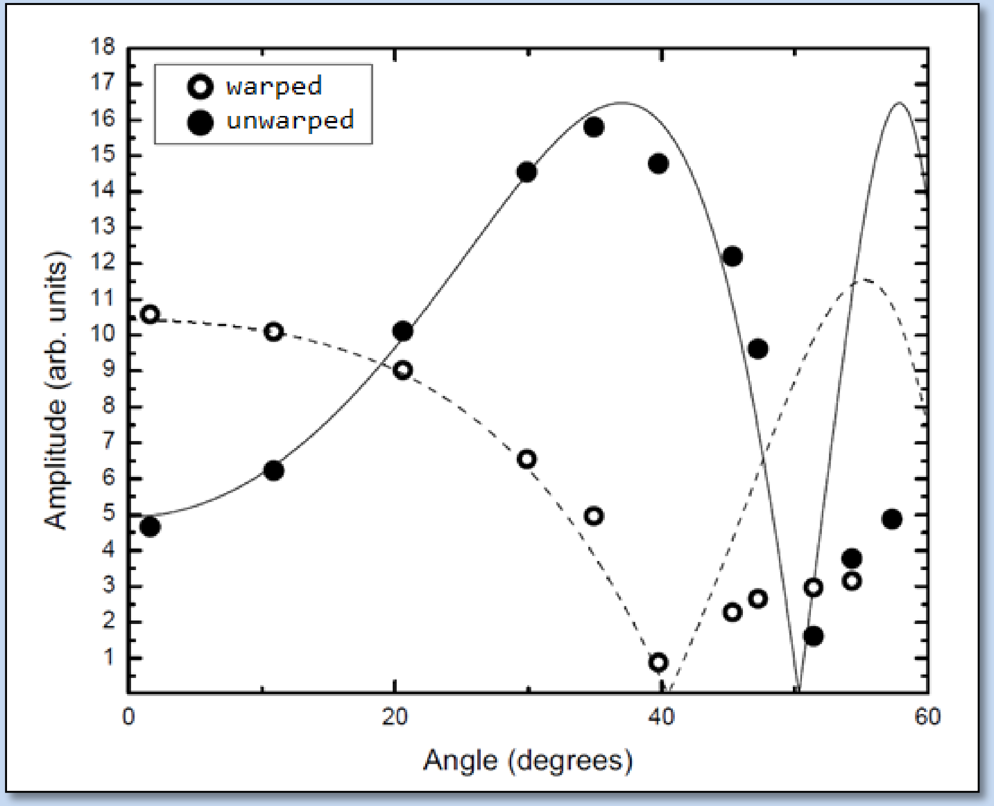
$$\widetilde{DOS} \propto \cos\left(\frac{2\pi\mu}{\hbar\frac{eB}{m^*}} - \varphi\right) \times R_T R_D$$

$$\mu_\pm = \mu_0 \pm g^* \frac{e}{2m_0}\frac{\hbar}{2}B$$

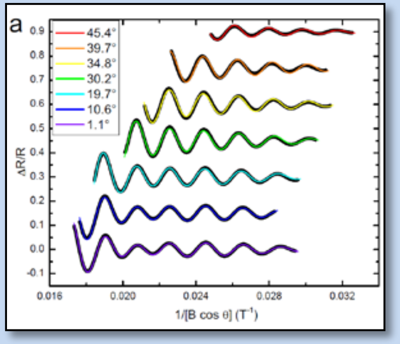
B.J. Ramshaw, *et al.* Nature Physics, 7:3 (2011)

Angle dependence of Quantum Oscillations



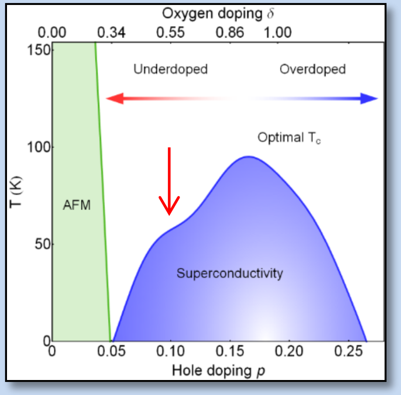


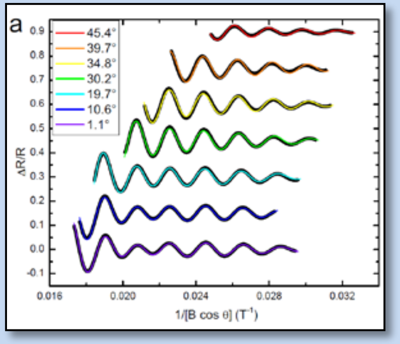
$$\widetilde{DOS} \propto \cos\left(\frac{2\pi\mu}{\hbar\frac{eB}{m^*}} - \varphi\right) \times \cos\left(\pi g^* \frac{m^*}{2m_0}\right)$$

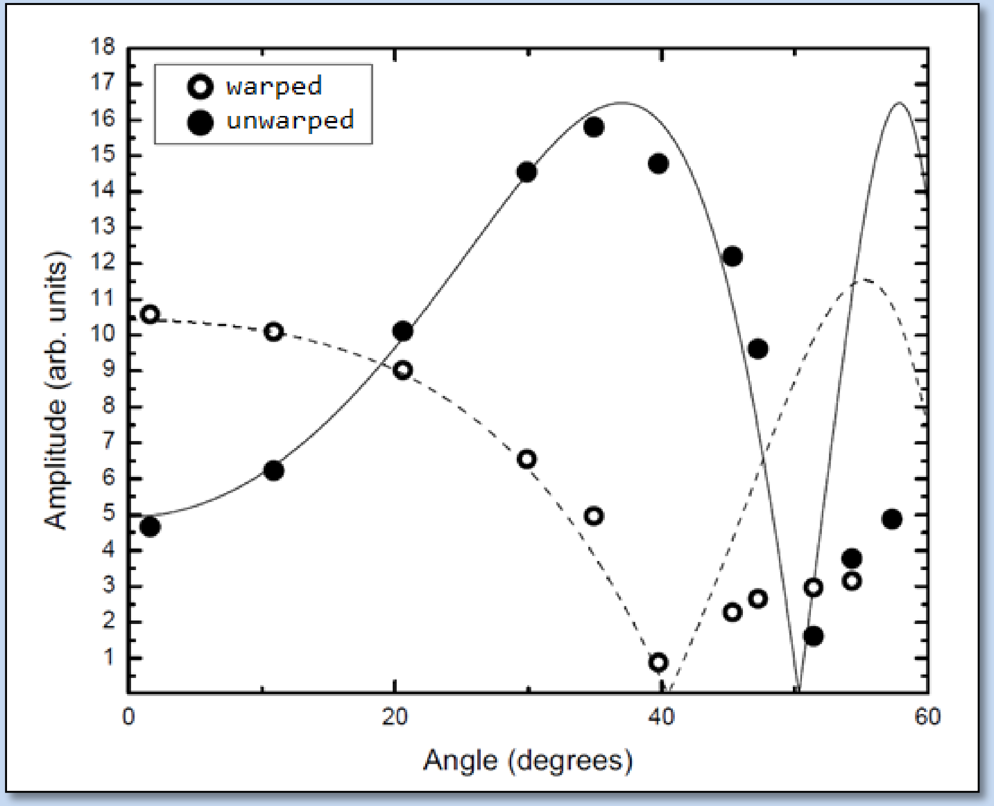


B.J. Ramshaw, *et al.* Nature Physics, 7:3 (2011)

Angle dependence of Quantum Oscillations







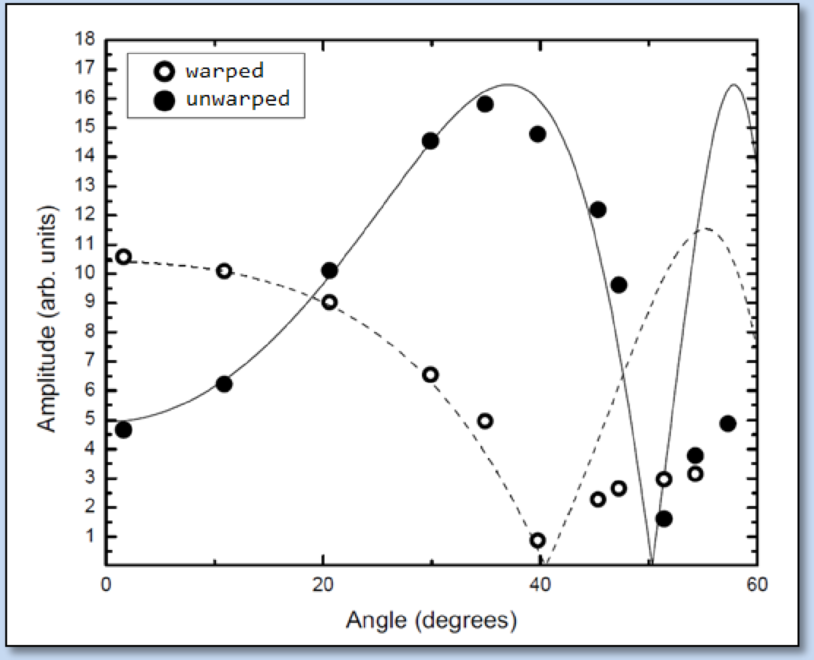
$$\widetilde{DOS} \propto \cos\left(\frac{2\pi\mu}{\hbar\frac{eB}{m^*}} - \varphi\right) \times cos\left(\pi g^* \frac{m^*}{2m_0}\right)$$

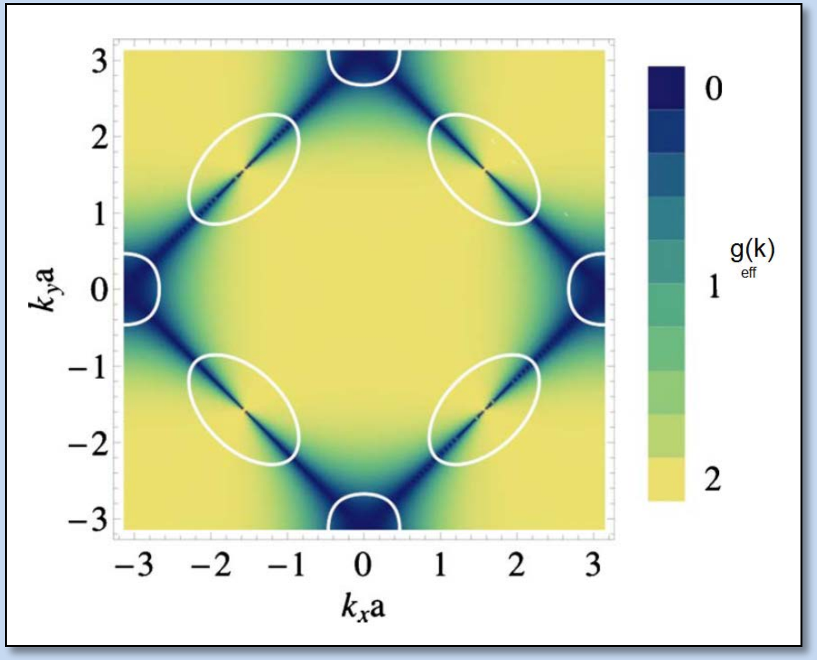
$$m^*(\theta) = \frac{m^*(\theta = 0)}{cos(\theta)}$$

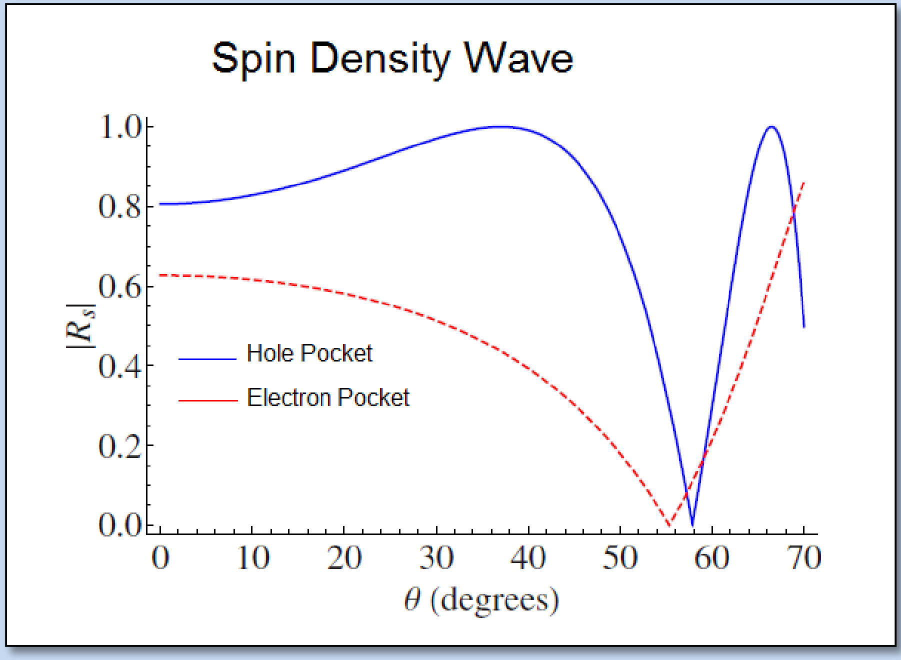
$$g^* \approx 2$$

B.J. Ramshaw, *et al.* Nature Physics, 7:3 (2011)

Fermi Surface Reconstruction, and the *g* Factor

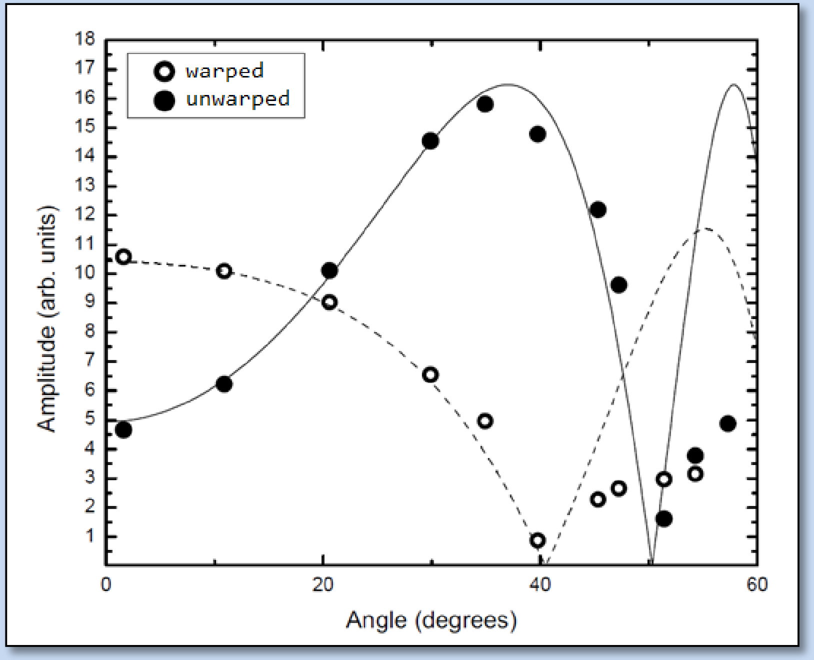


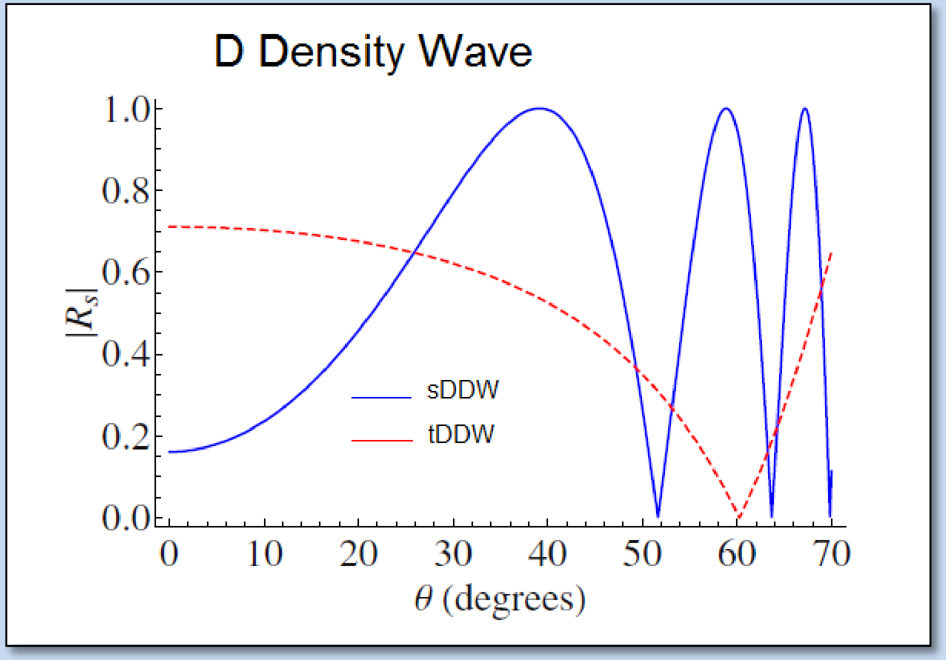


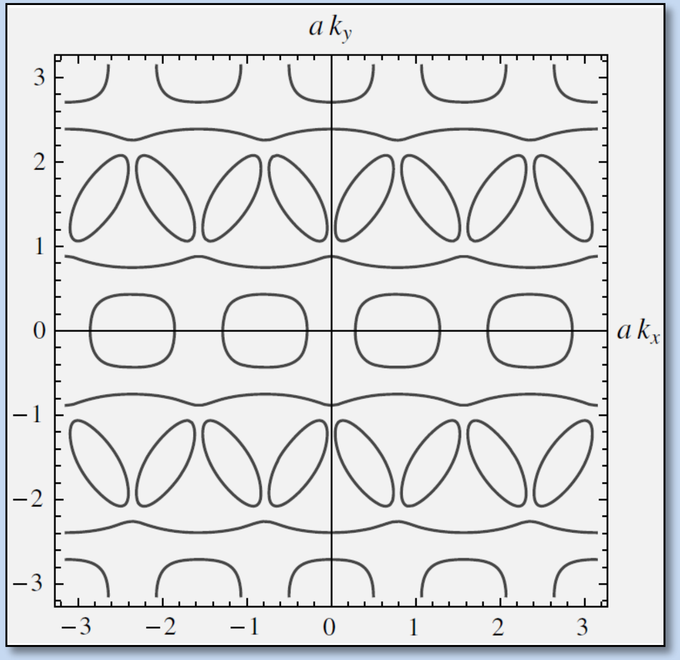


B.J. Ramshaw et al. (2011), D. Garcia-Aldea et. al. (2010)

Fermi Surface Reconstruction, and the *g* Factor



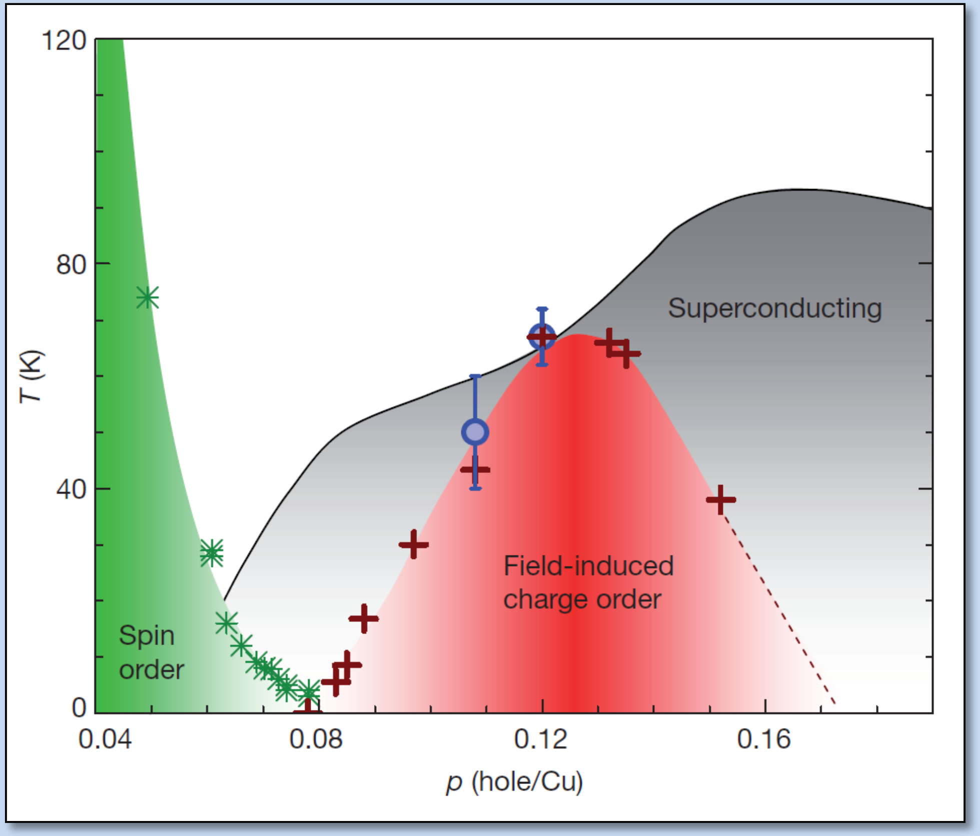




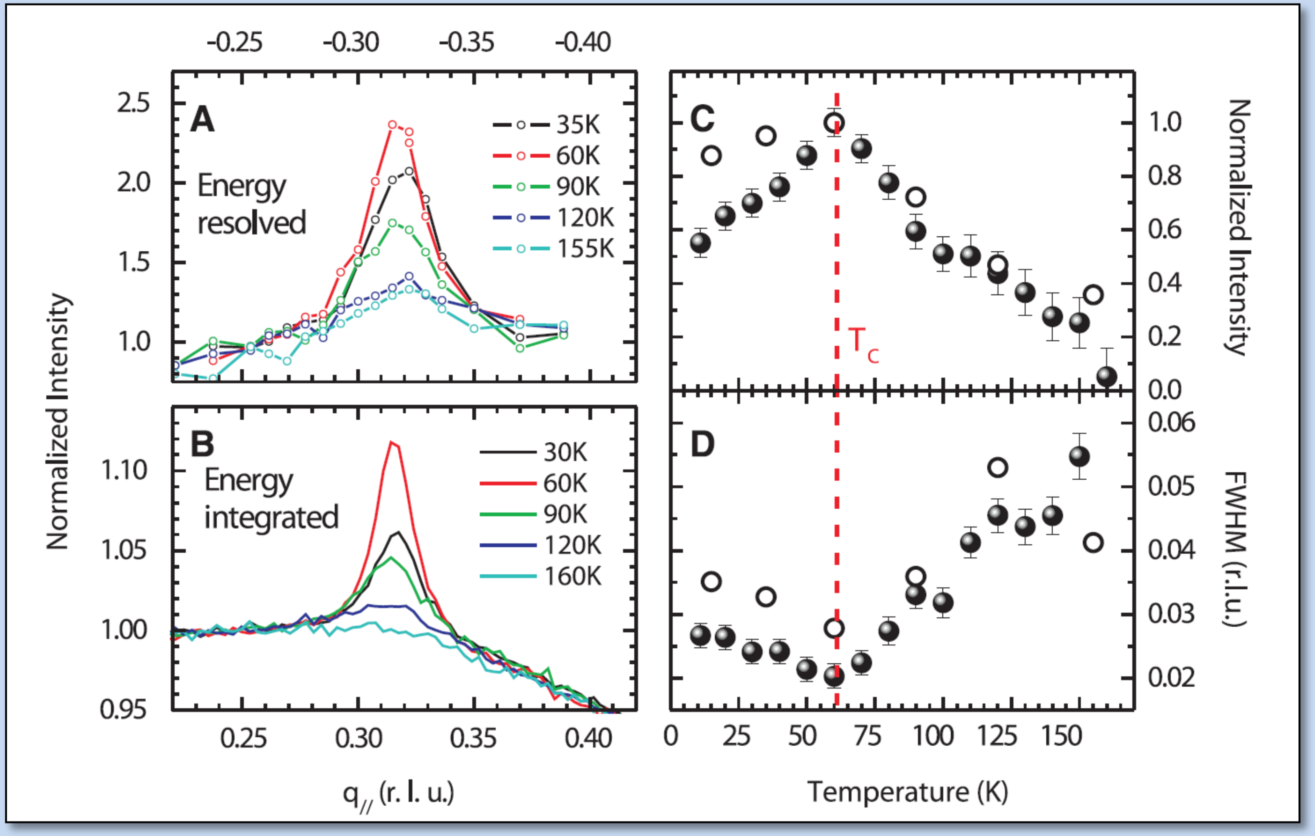
B.J. Ramshaw et al. (2011), D. Garcia-Aldea et. al. (2010), J. Eun et. al., PNAS (2012)

Charge Density Wave Order

NMR

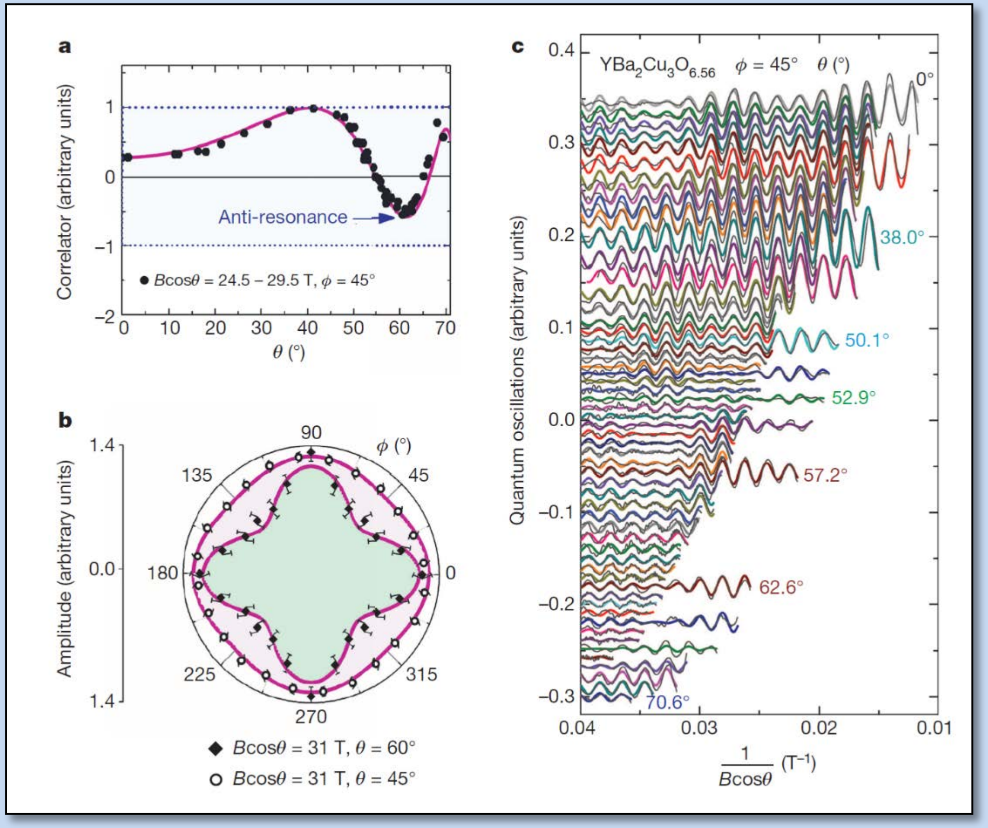


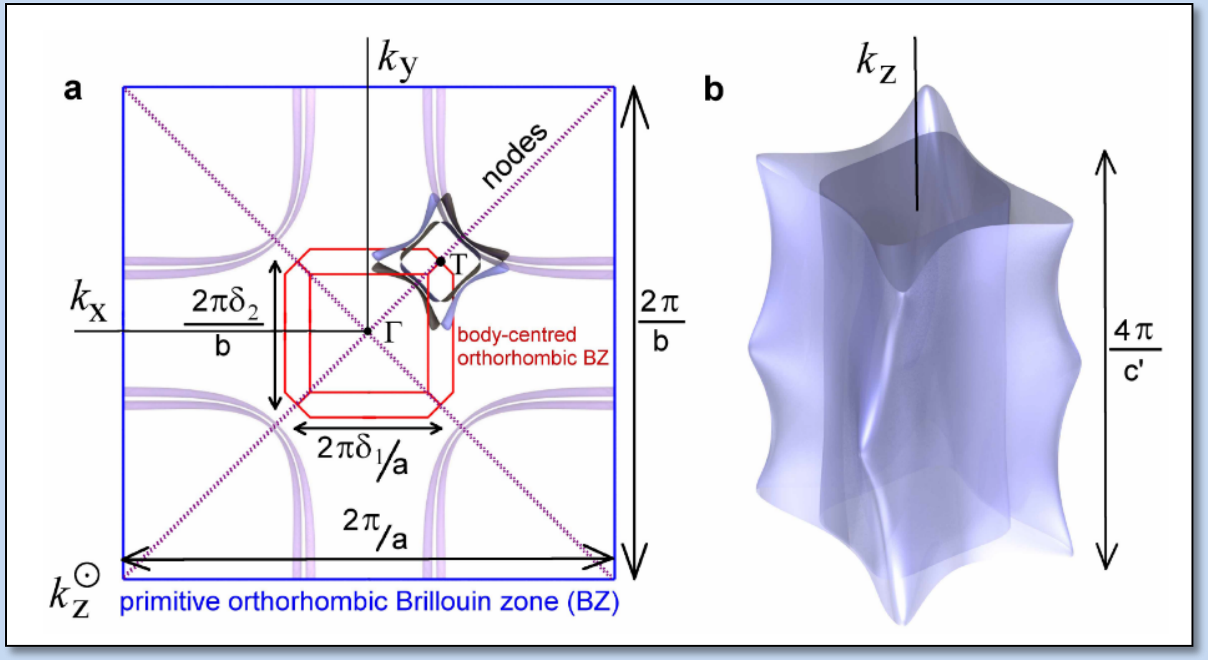
X-rays



T. Wu *et al.,* Nature 2011, G. Ghiringhelli *et al.,* Nature 2012

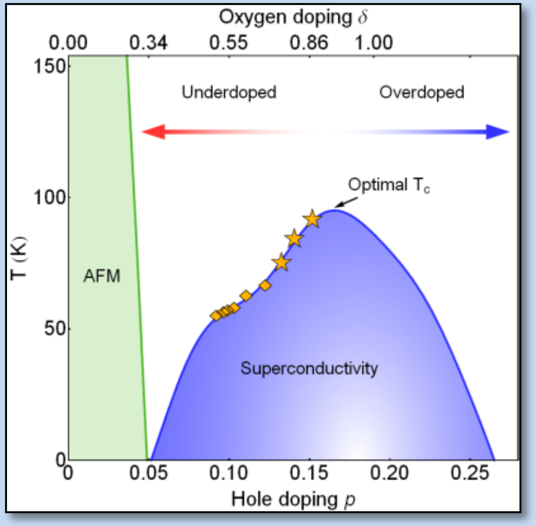
Charge Density Wave Reconstruction (?)

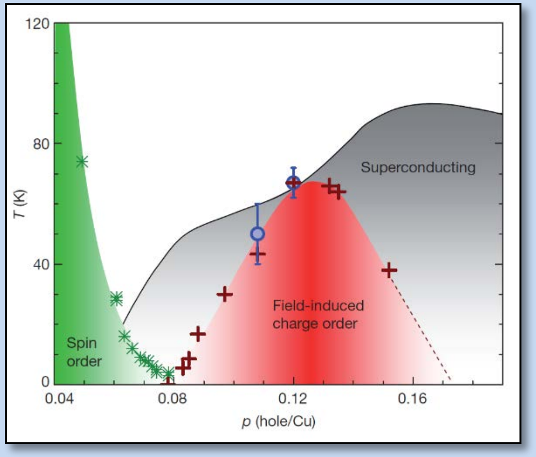




S. E. Sebastian, *et al.* Nature, (2014)

Small Electron Pocket Ubiquitous to the CDW Region

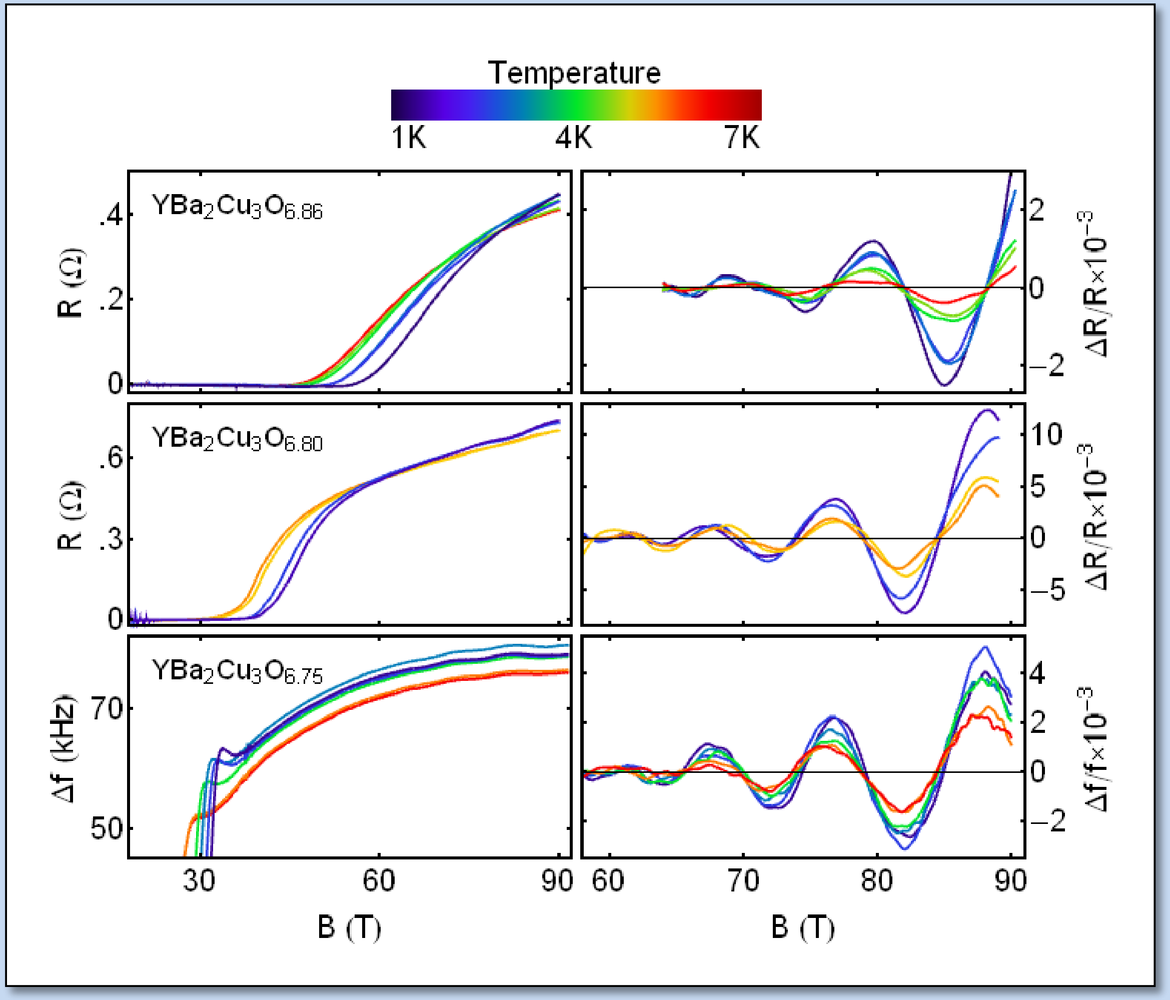




Tc ~ 91K

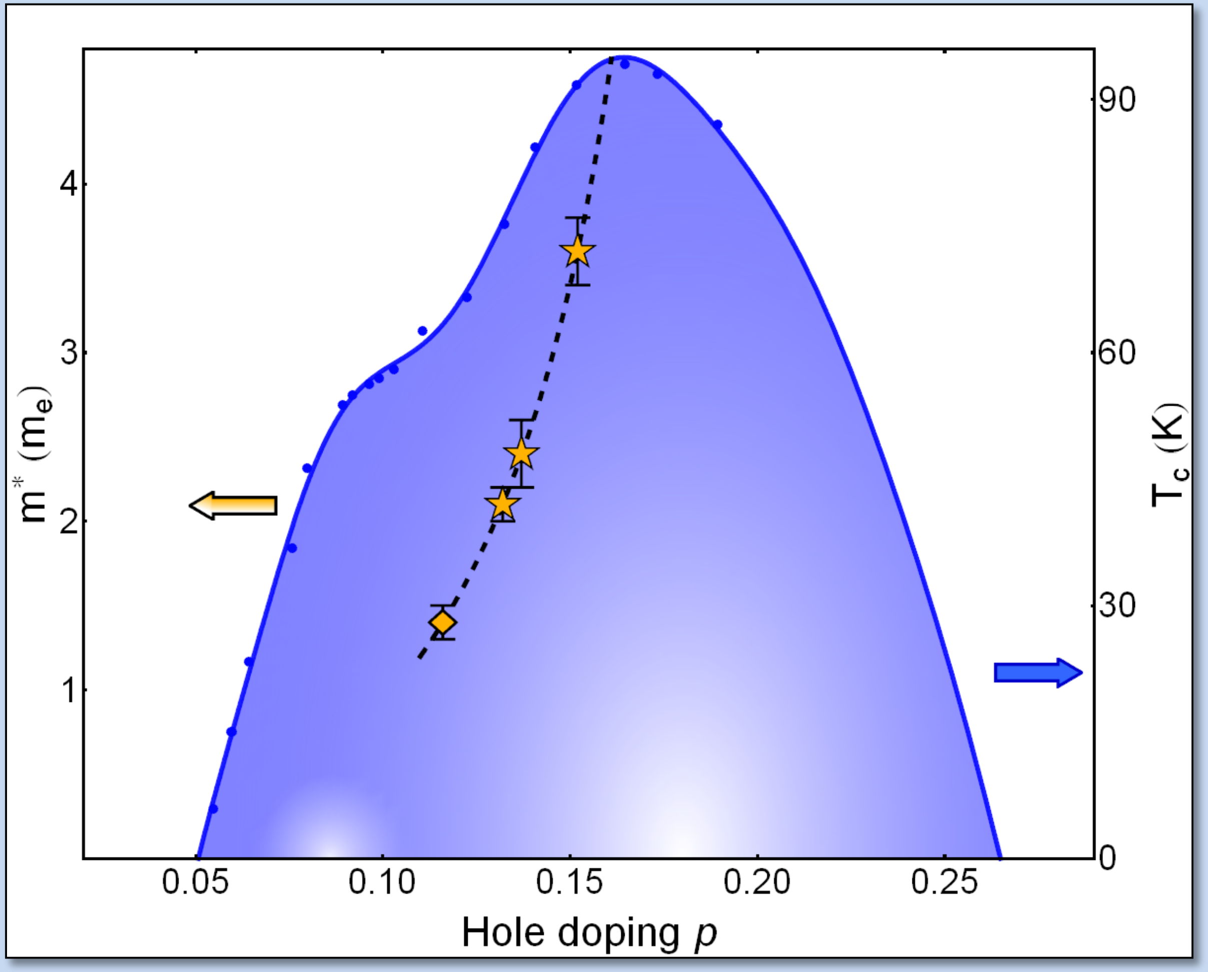
Tc ~ 81K

Tc ~ 75K



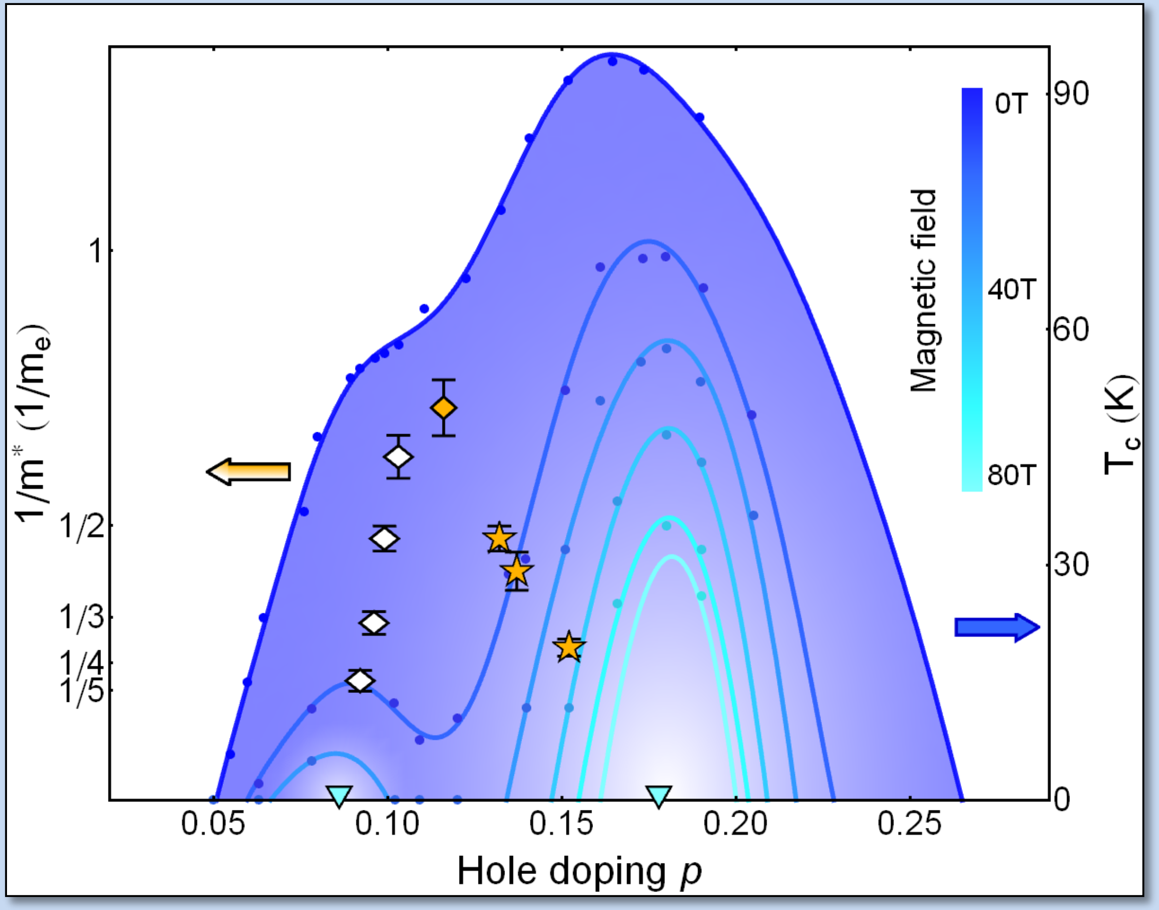
B.J. Ramshaw *et al.* Science 438 (2015), T. Wu et al., Nature 2011

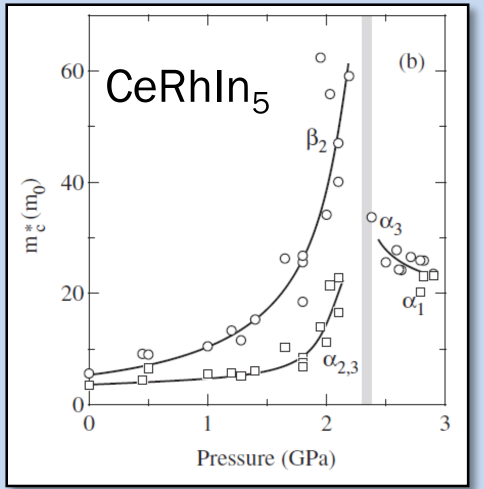
Diverging Effective Mass

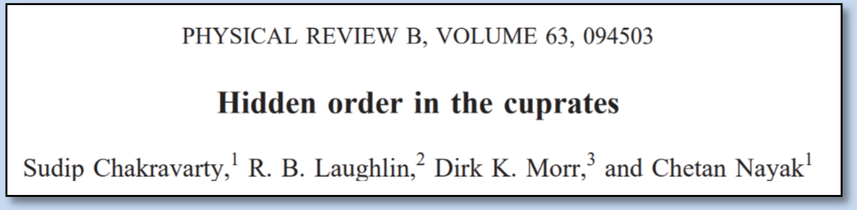


B.J. Ramshaw *et al.* Science 438 (2015)

Thermodynamic evidence for a Quantum Critical Point

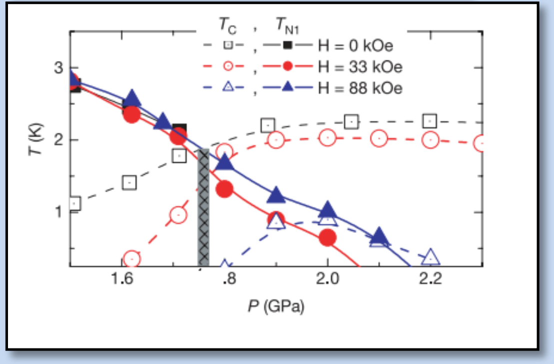





PHYSICAL REVIEW B, VOLUME 63, 094503

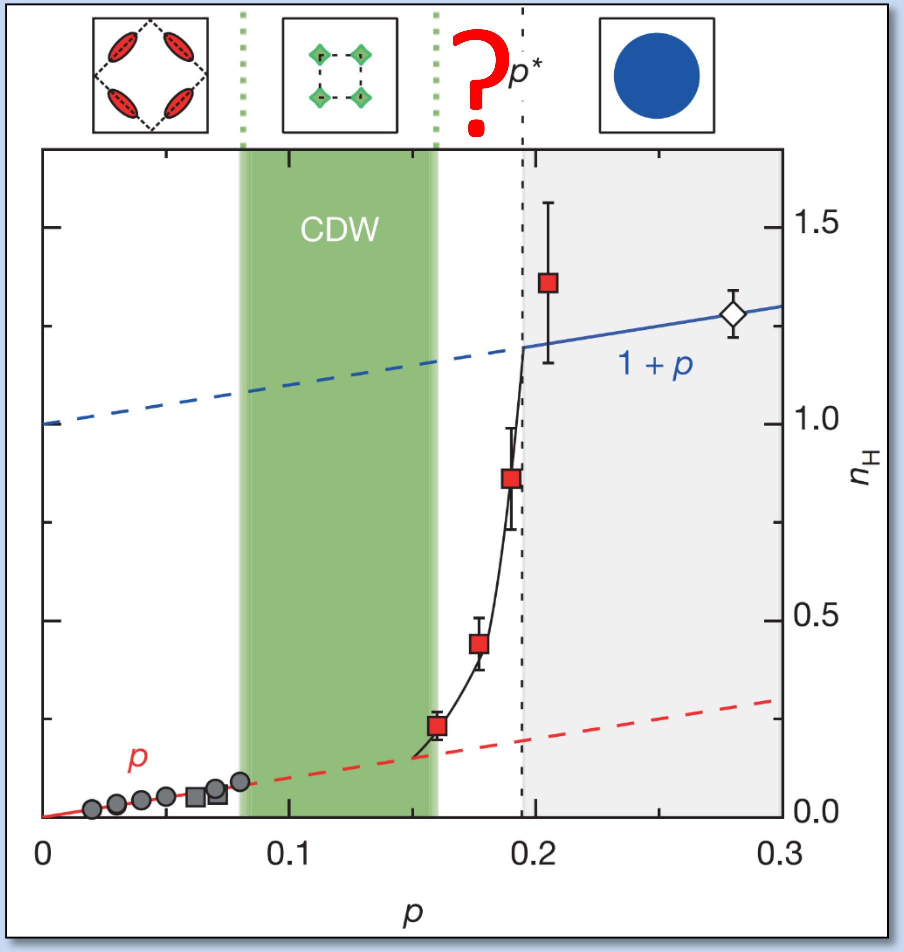
Hidden order in the cuprates

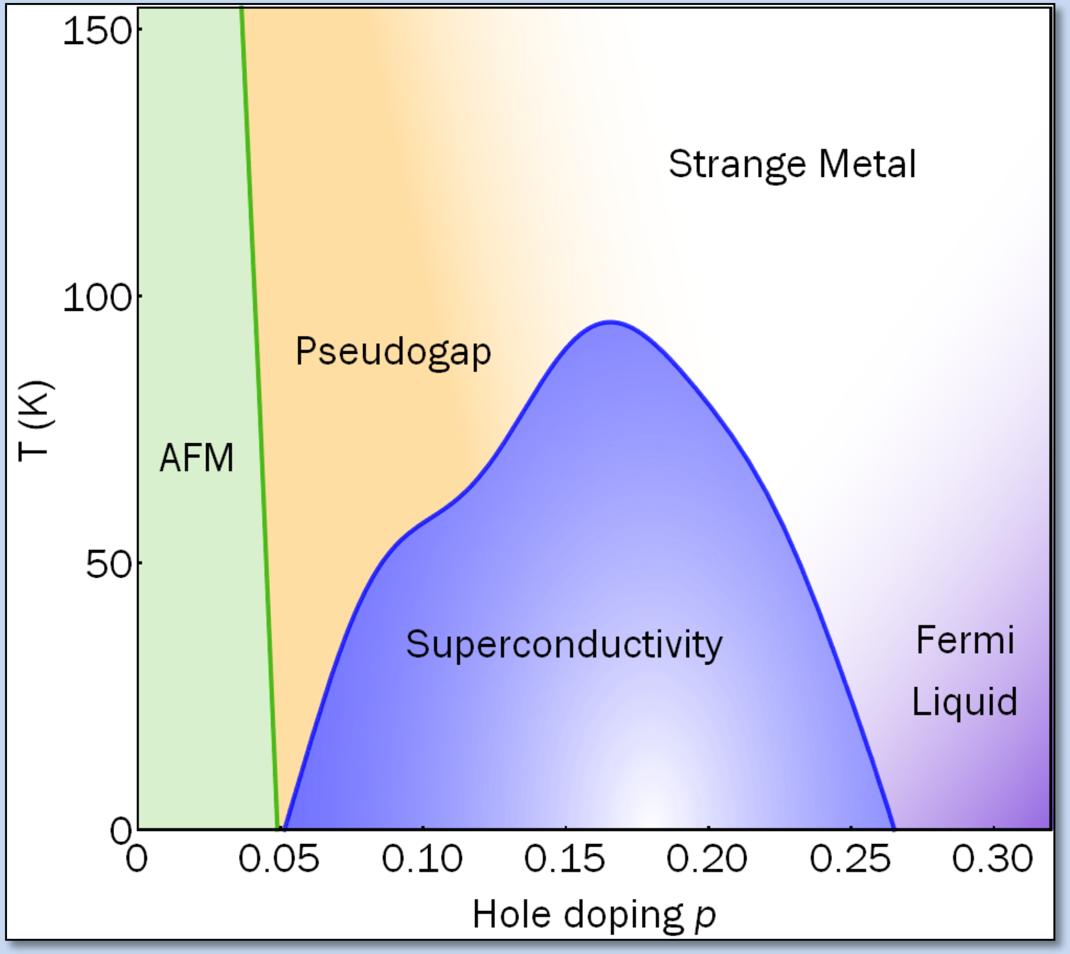
Sudip Chakravarty,[1] R. B. Laughlin,[2] Dirk K. Morr,[3] and Chetan Nayak[1]



B.J. Ramshaw *et al.* Science 438 (2015), Shishido et al., JPSJ. (2005), Tuson Park et al., Nature. (2006)

From Insulator to Superconductor

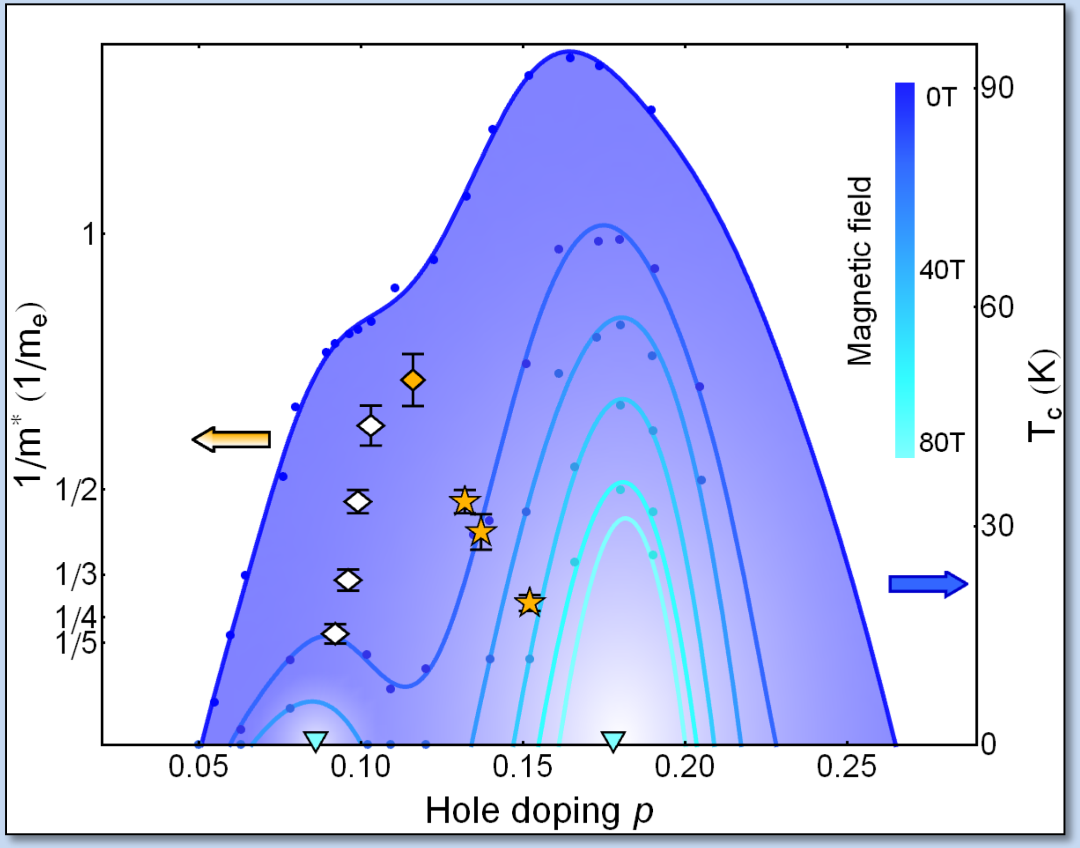




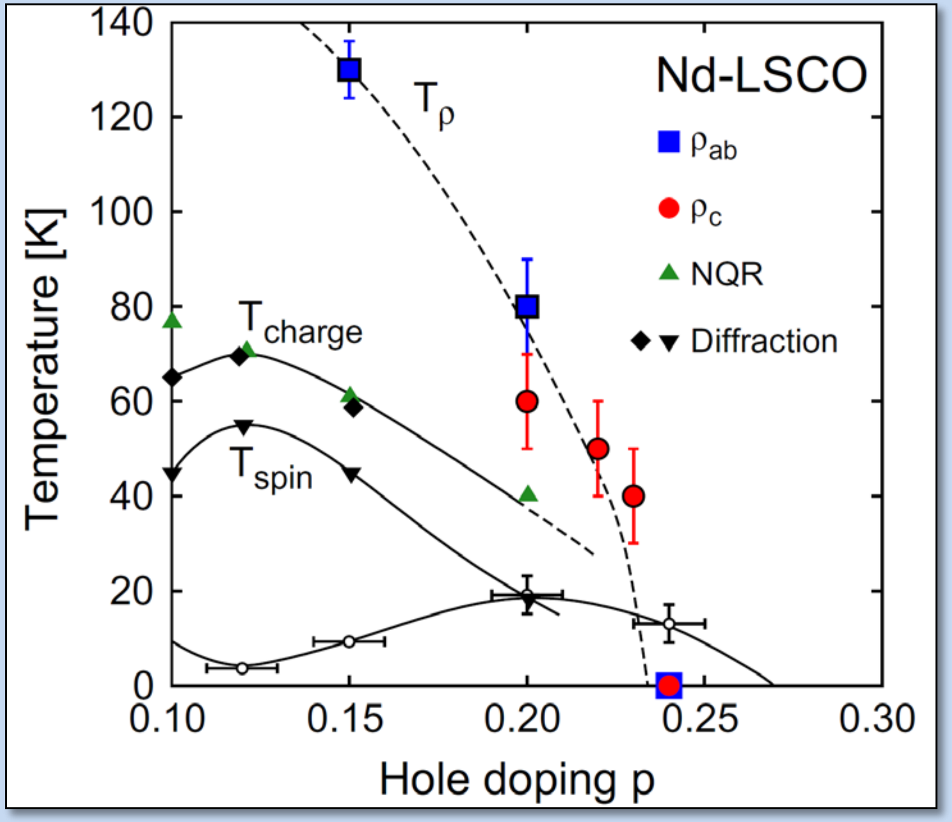
S. Badoux *et al.*, Nature (2017)

End of the Line for YBCO

$YBa_2Cu_3O_{6+x}$

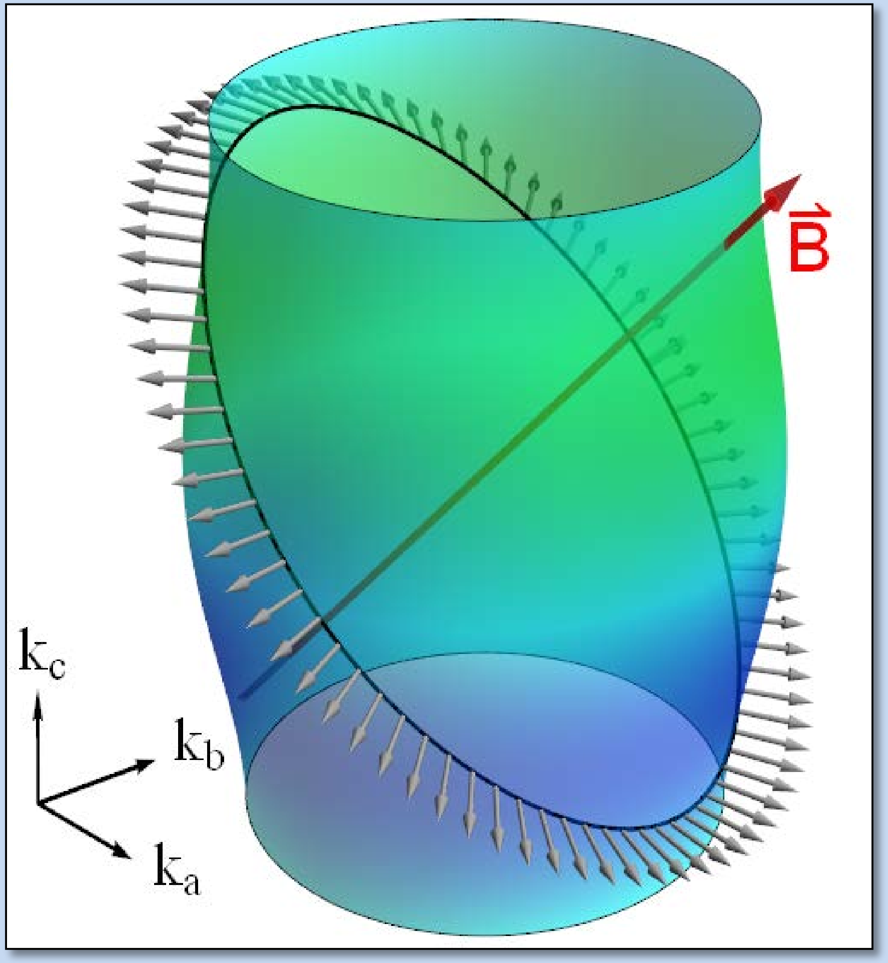


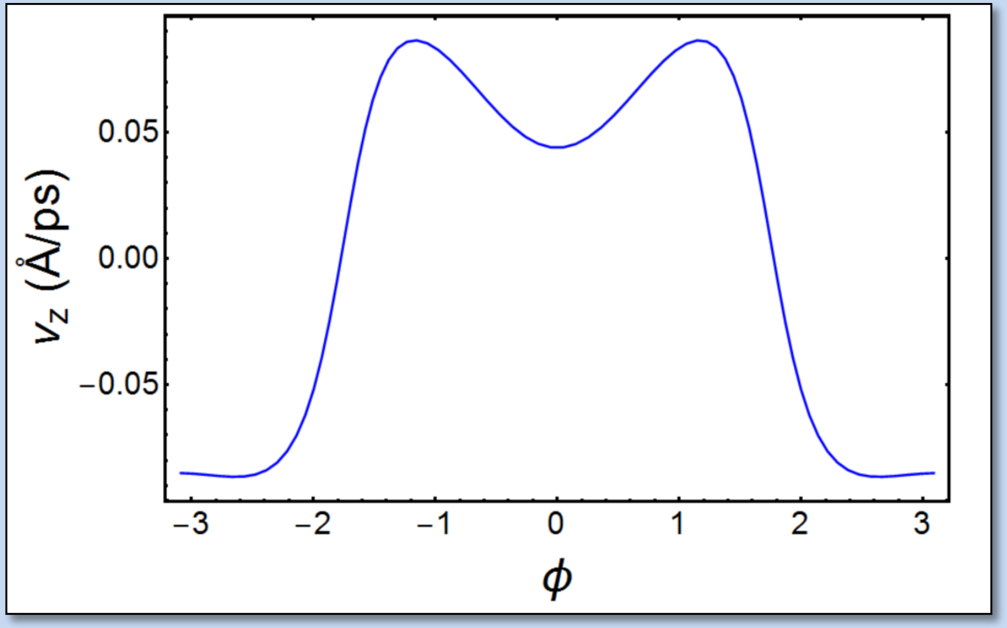
$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$



B.J. Ramshaw *et al.* Science 438 (2015)

Angle-Dependent Magnetoresistance (ADMR)





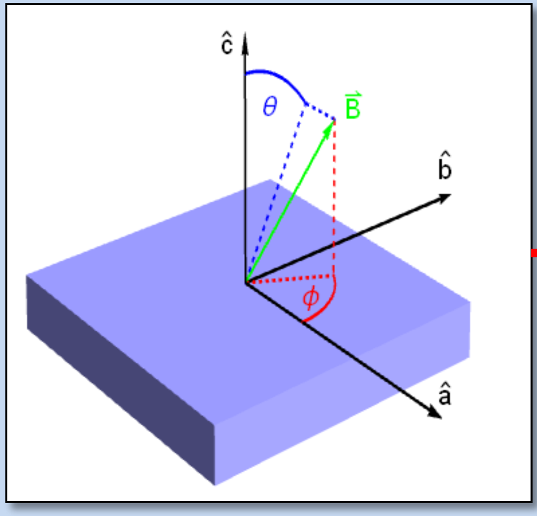
$$\sigma_{ij} = \frac{e^2}{4\pi^3}\int d^3k\left(-\frac{df_0}{d\epsilon}\right) v_i(t=0)\int_{-\infty}^{0} dt\, v_j(t)\, e^{t/\tau}$$

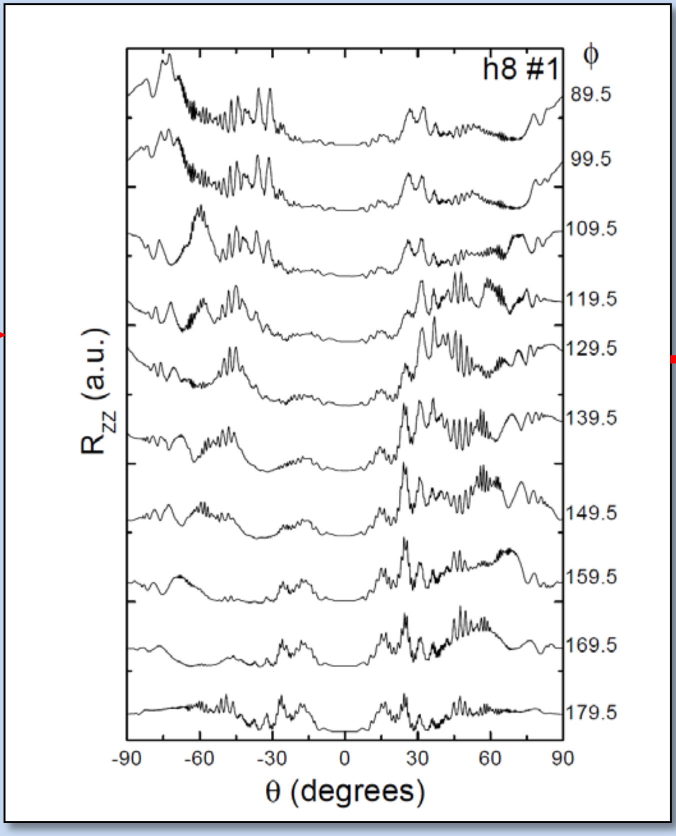
$$v(k) = \frac{1}{\hbar}\nabla_k \epsilon(k)$$

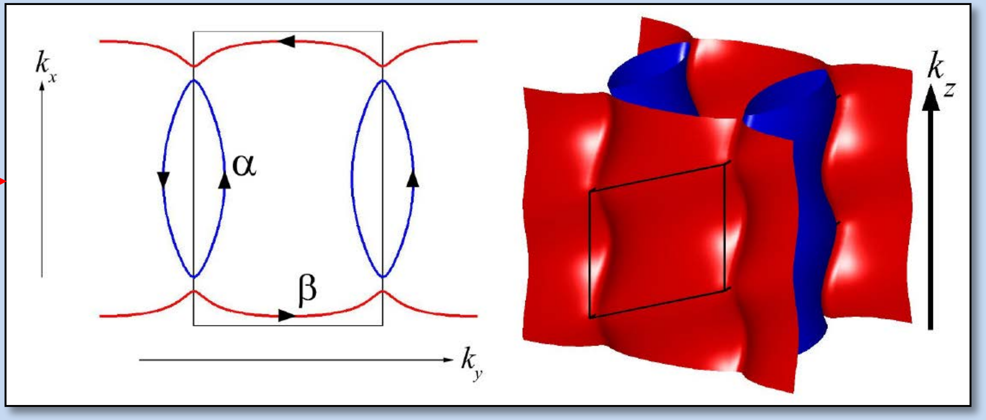
Can measure $\epsilon(k)$

Angle-Dependent Magnetoresistance (ADMR)

κ-$(ET)_2Cu(NCS)_2$



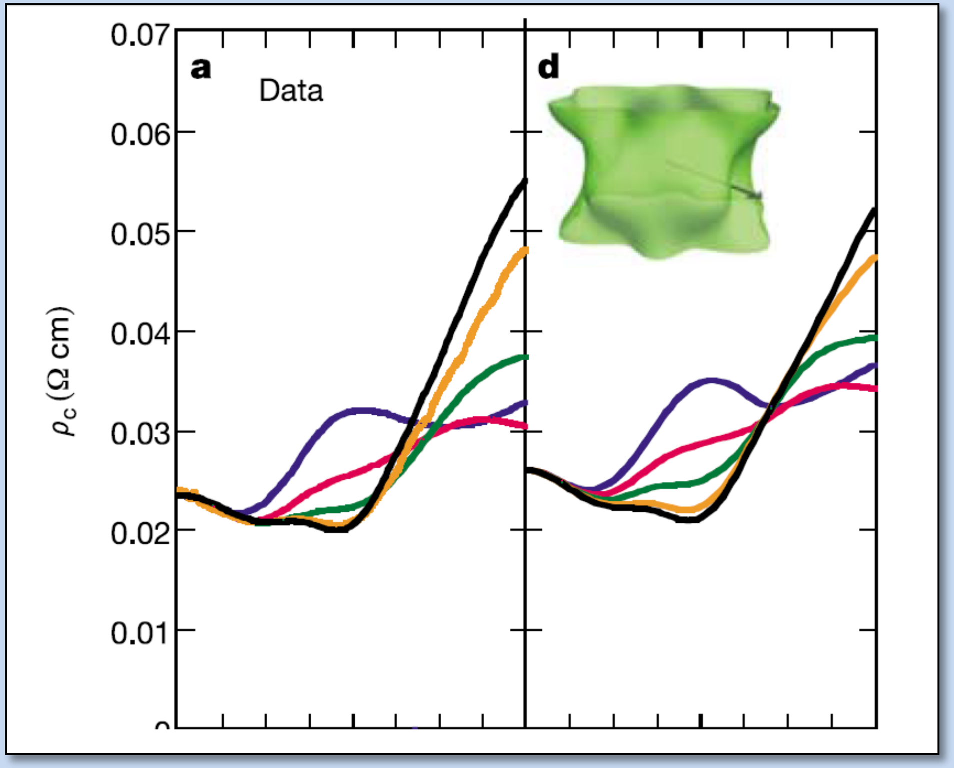


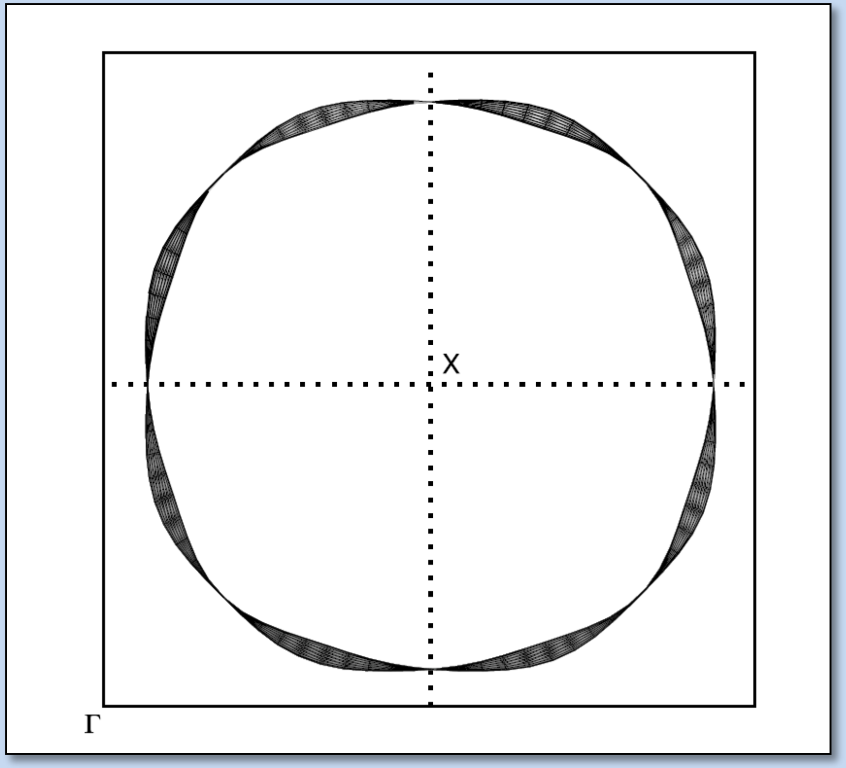


P. Goddard, PhD Thesis, Oxford (2003)

Angle-Dependent Magnetoresistance (ADMR)

Tl-2201

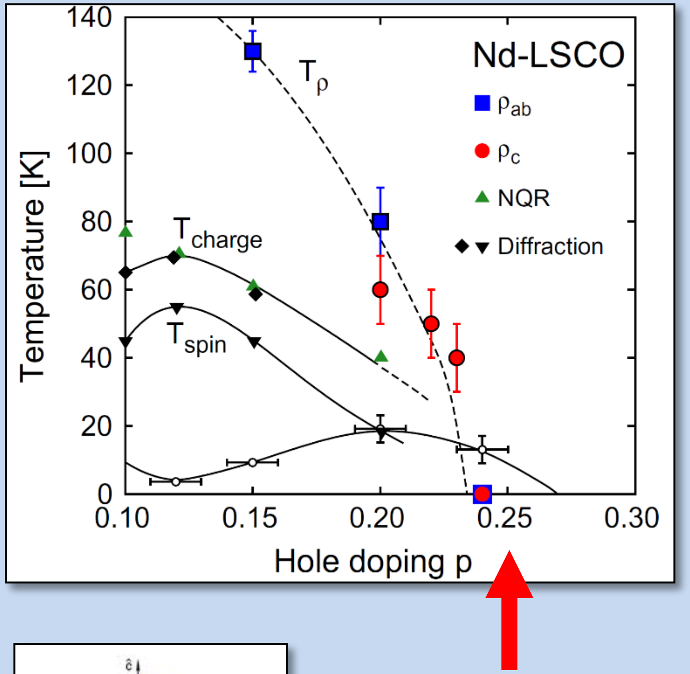


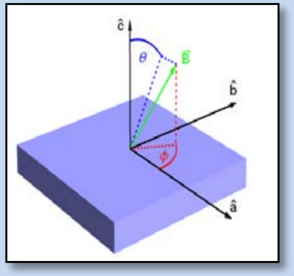


N. Hussey *et al.,* Nature, (2003)

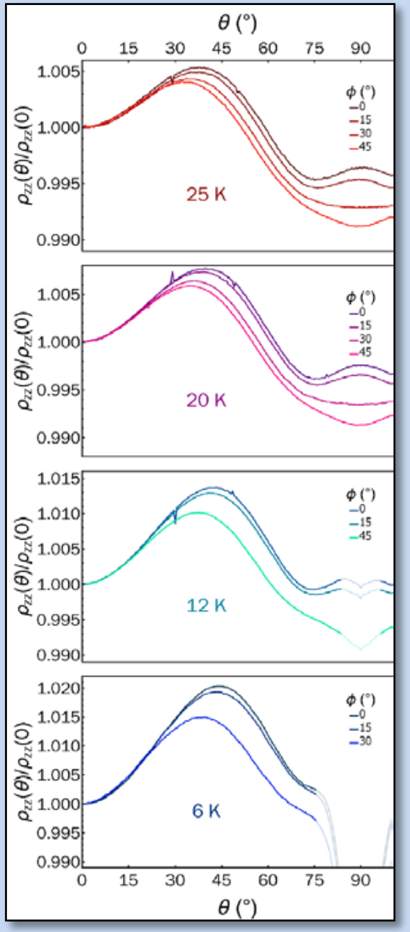
ADMR of $La_{1.6-0.25}Nd_{0.4}Sr_{0.25}CuO_4$

$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$



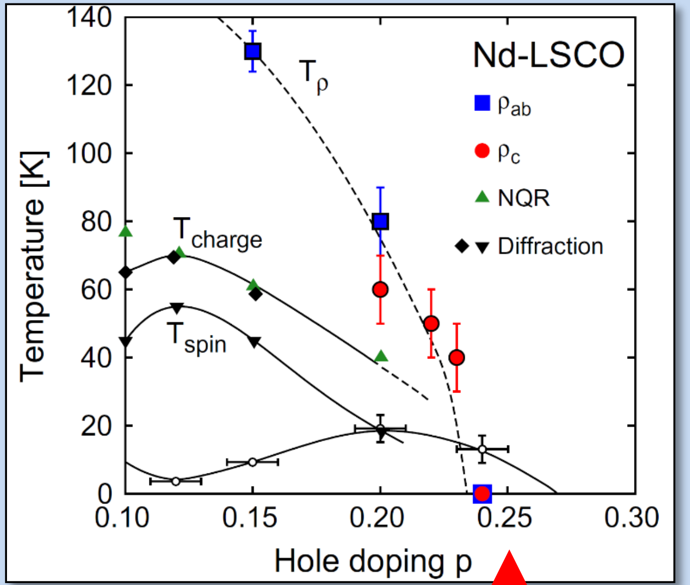


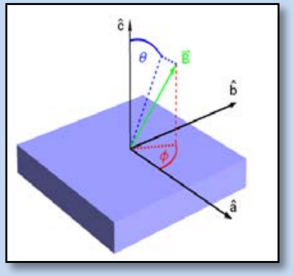
Data



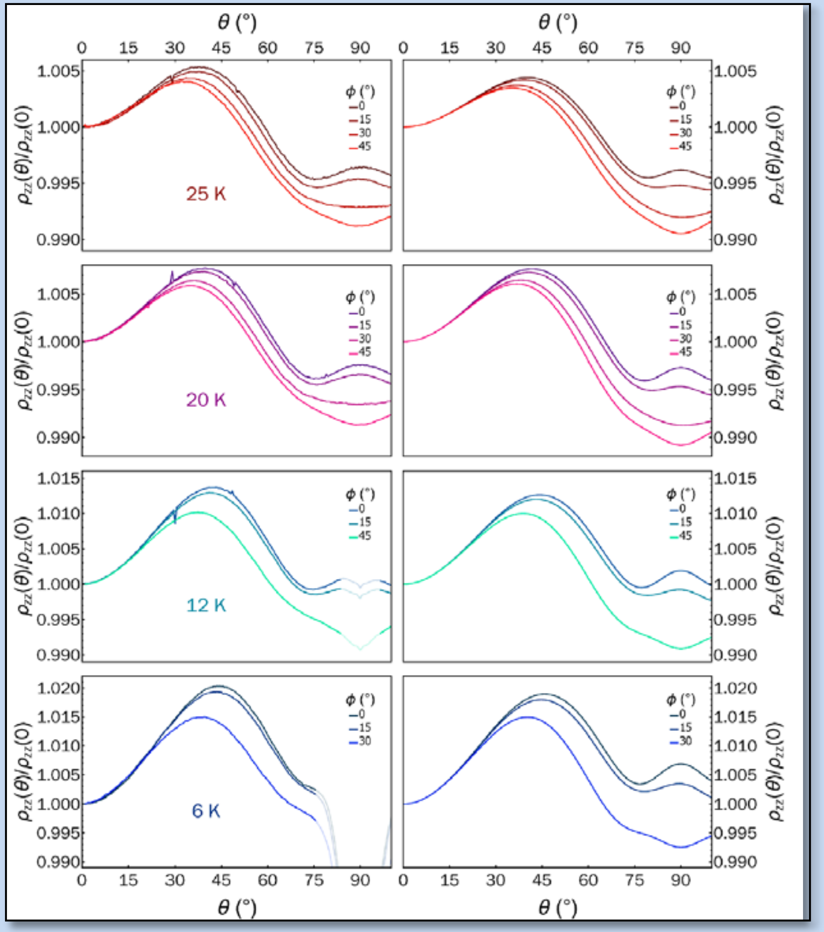
ADMR of $La_{1.6-0.25}Nd_{0.4}Sr_{0.25}CuO_4$

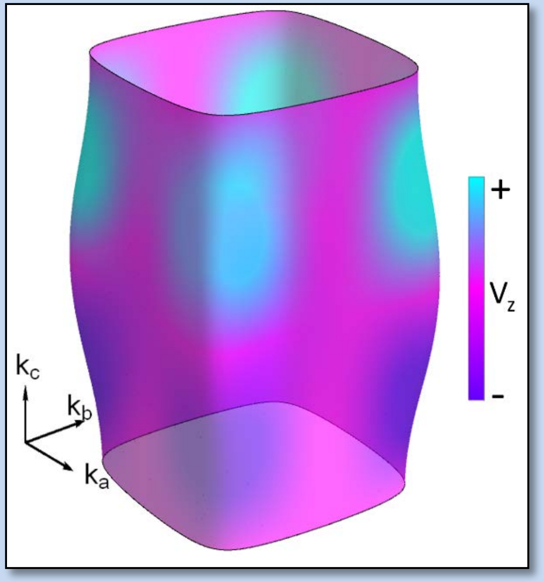
$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$

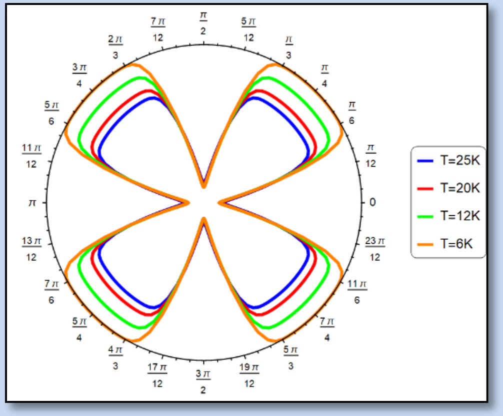




Data **Simulation**

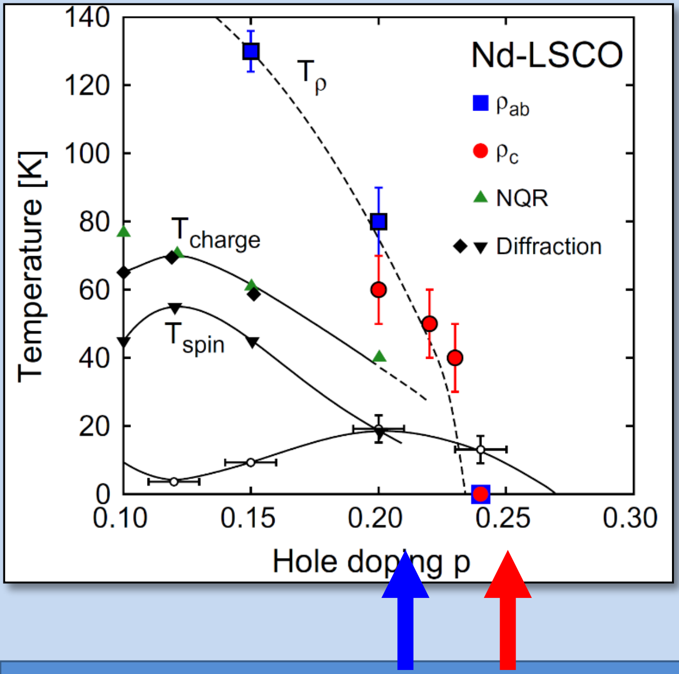


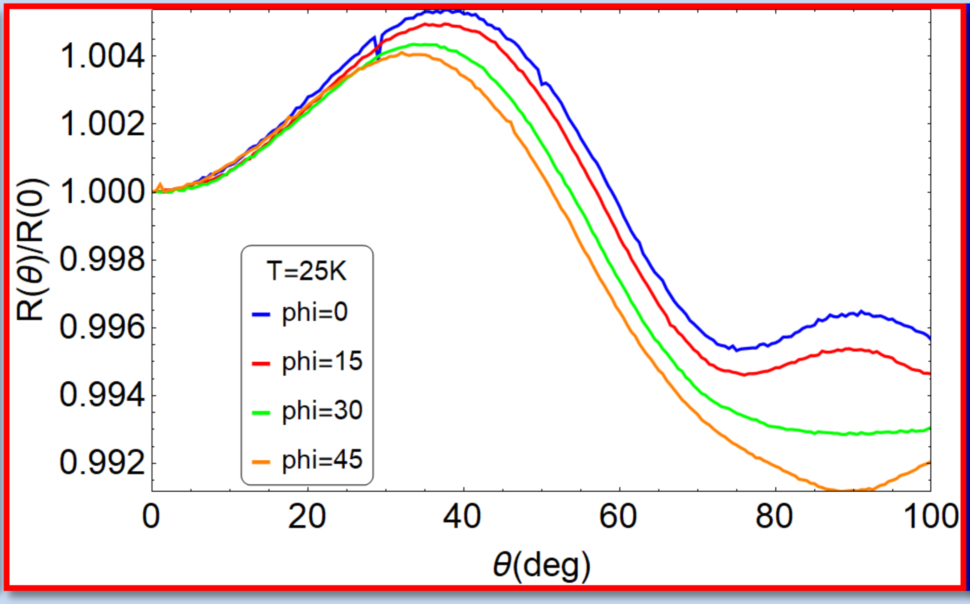




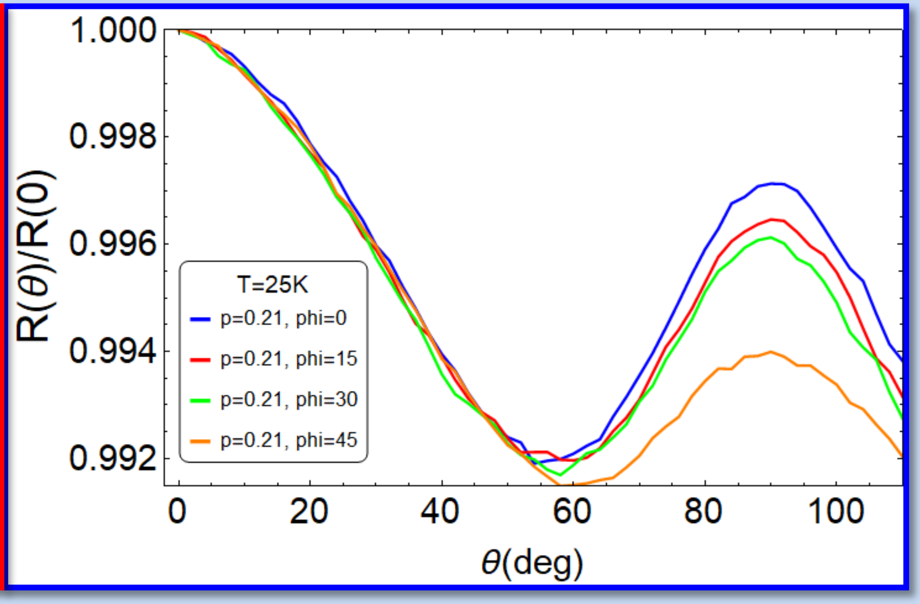
ADMR of $La_{1.6-0.21}Nd_{0.4}Sr_{0.21}CuO_4$

$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$





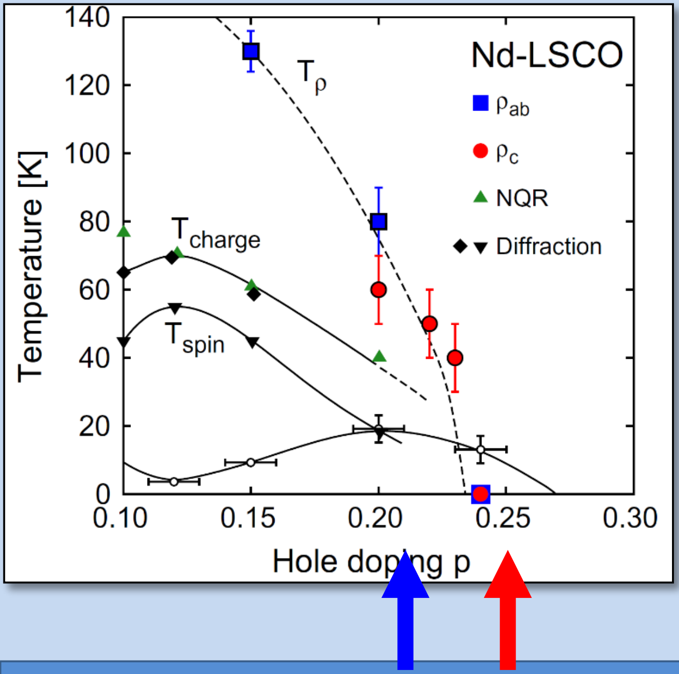
p = 0.25

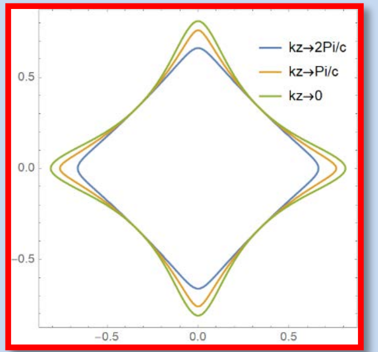


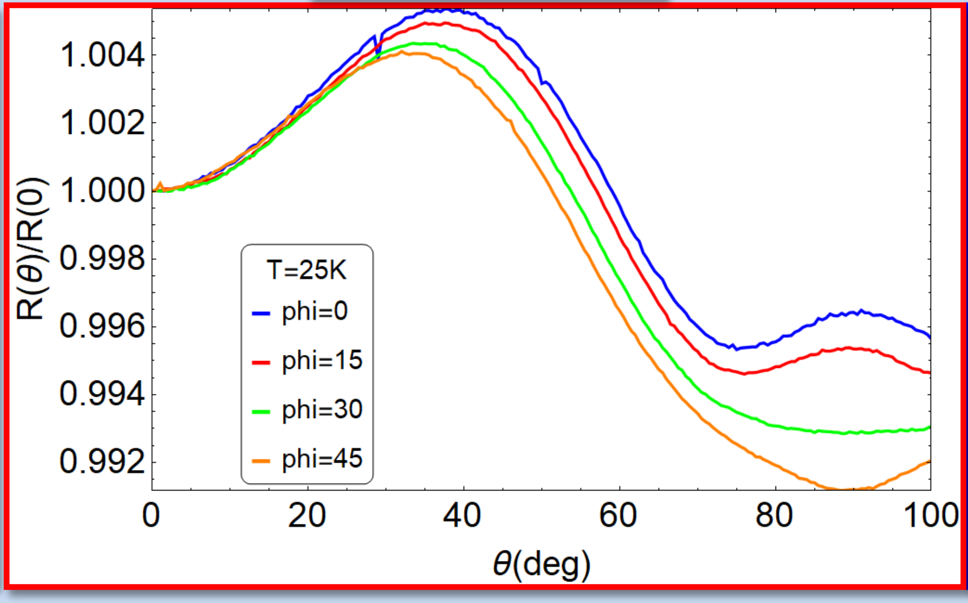
p = 0.21

ADMR of $La_{1.6-0.21}Nd_{0.4}Sr_{0.21}CuO_4$

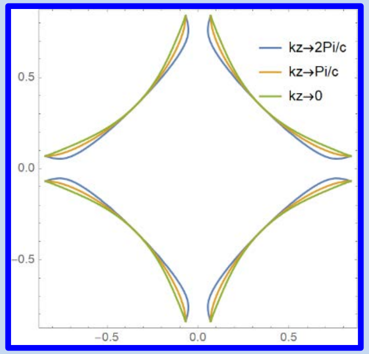
$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$

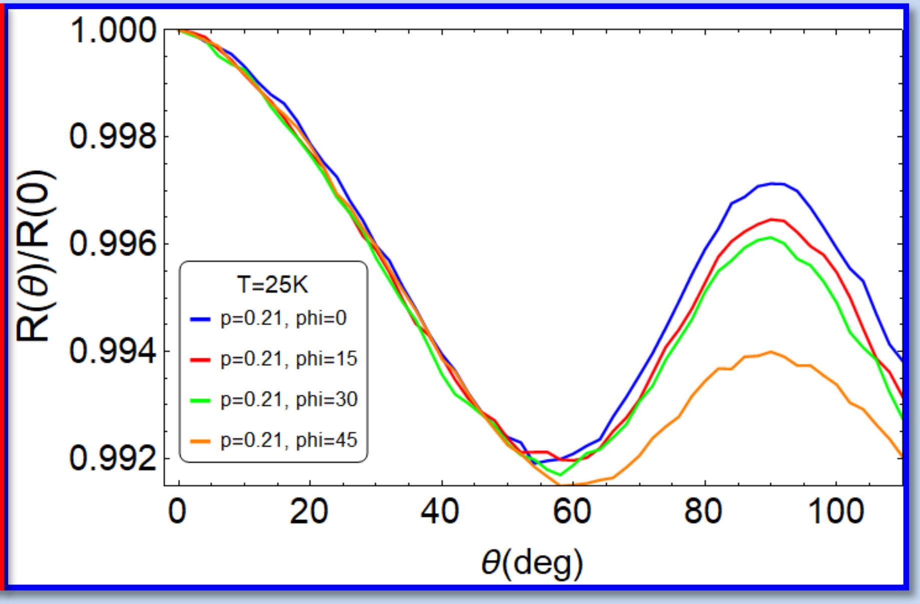






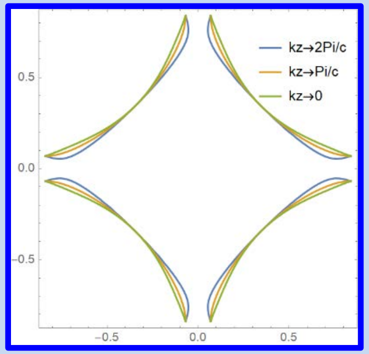
p = 0.25



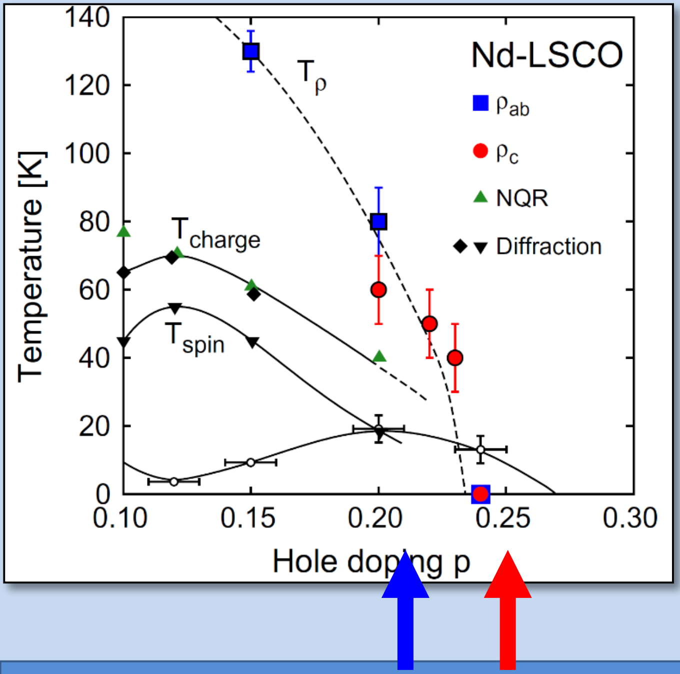


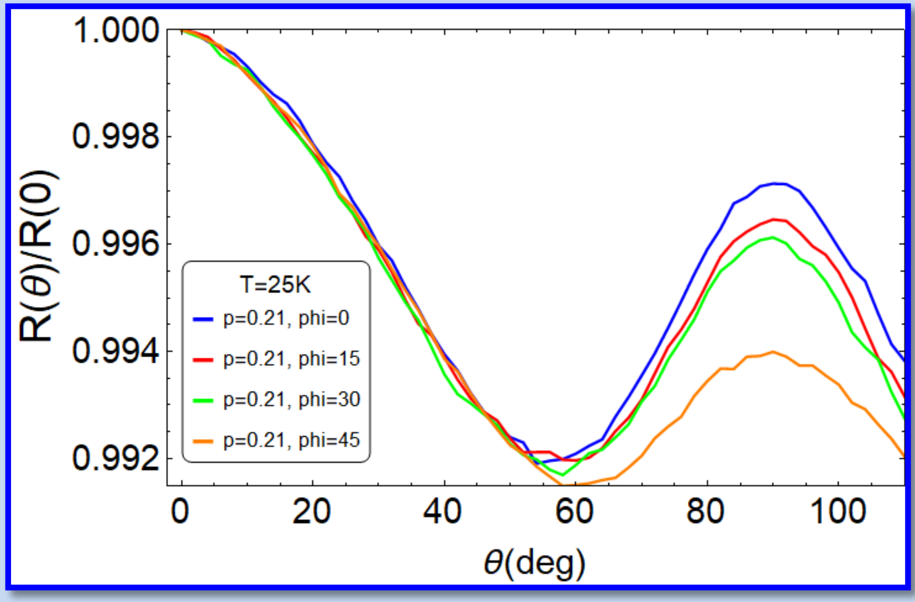
p = 0.21

ADMR of $La_{1.6-0.21}Nd_{0.4}Sr_{0.21}CuO_4$

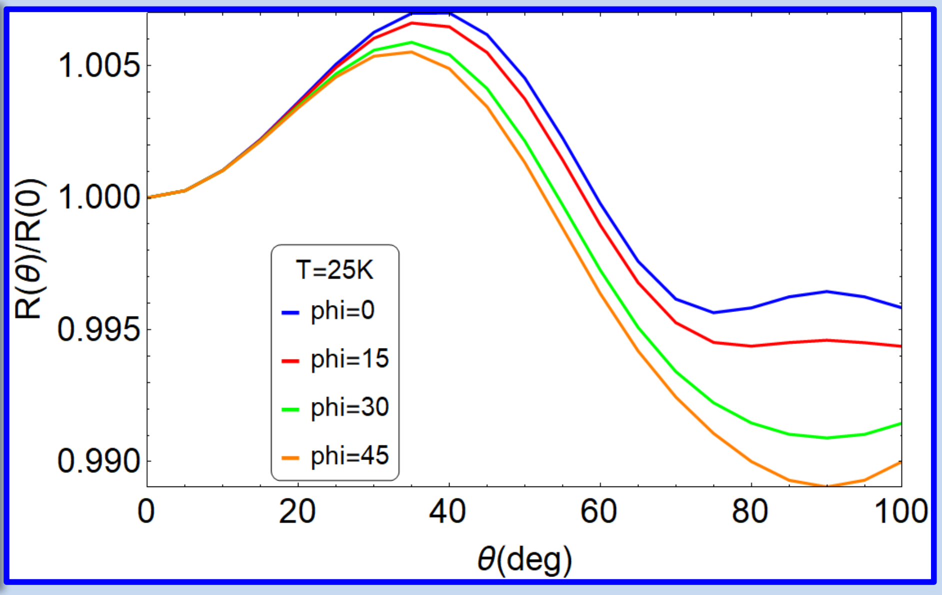


$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$



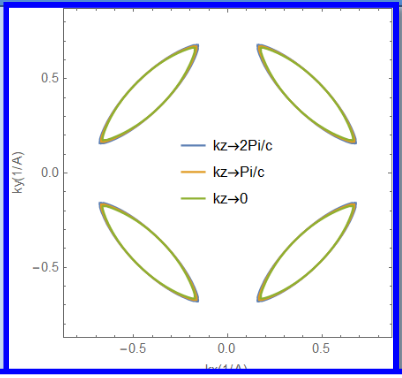


***p* = 0.21 - Data**

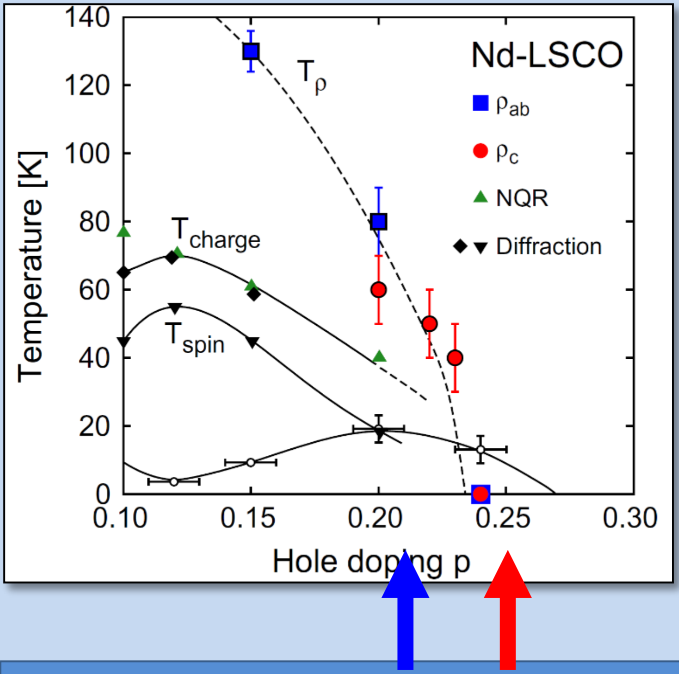


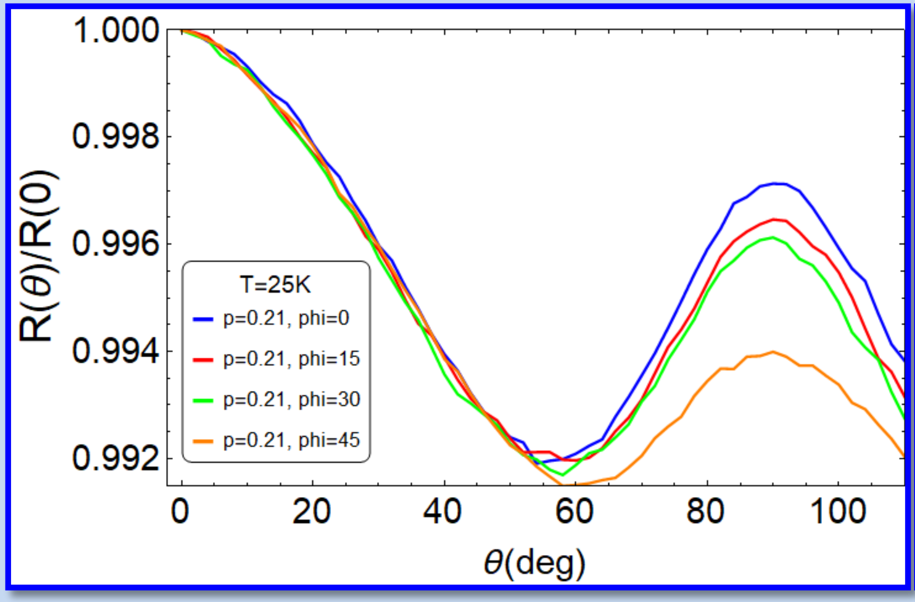
Simulation

ADMR of $La_{1.6-0.21}Nd_{0.4}Sr_{0.21}CuO_4$

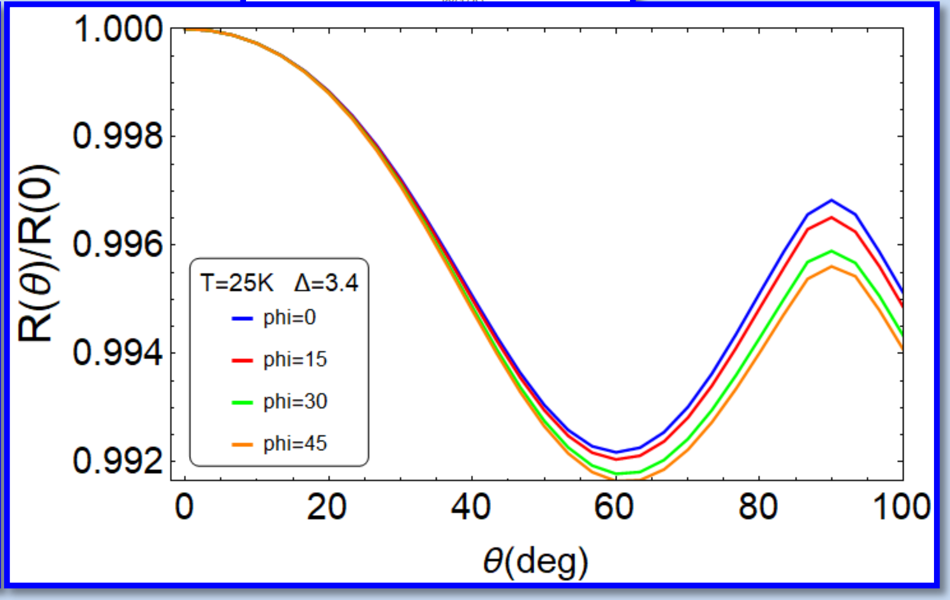


$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$





***p* = 0.21 - Data**



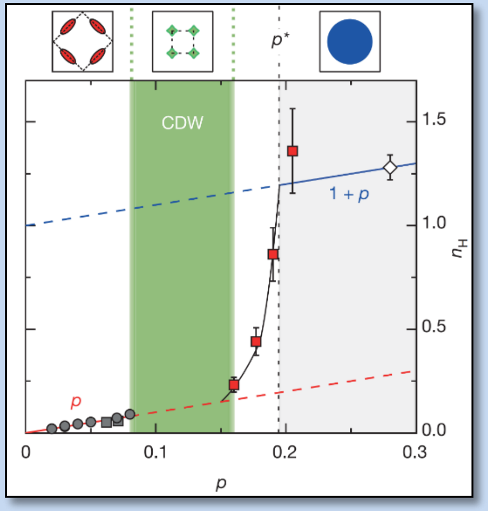
Simulation

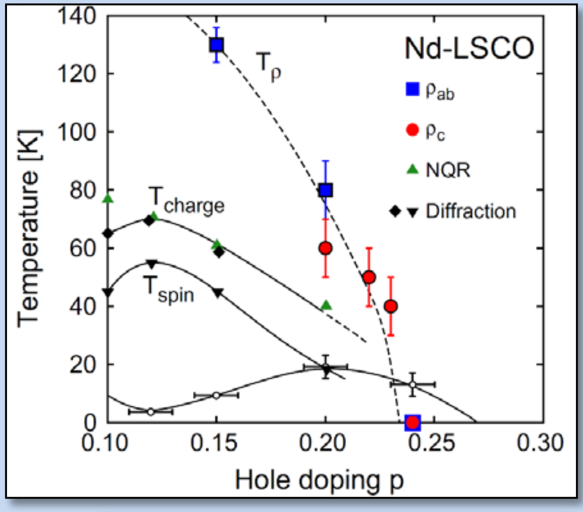
Conclusions

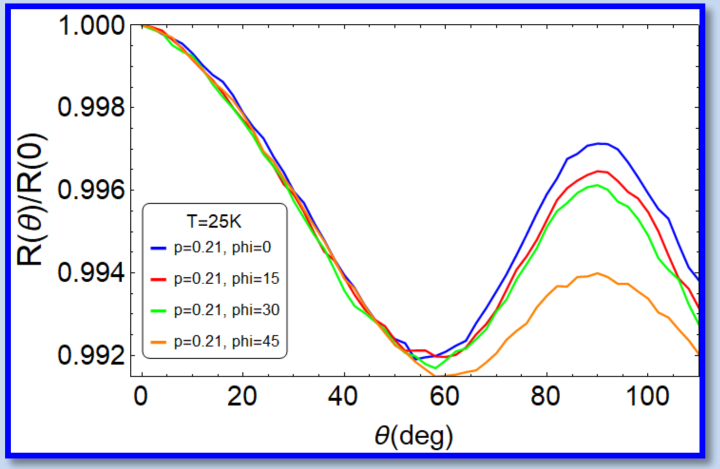
- ‘New’ technique to measure the Fermi surface for $p < p^*$.
- Doesn’t look like arcs or charge order.

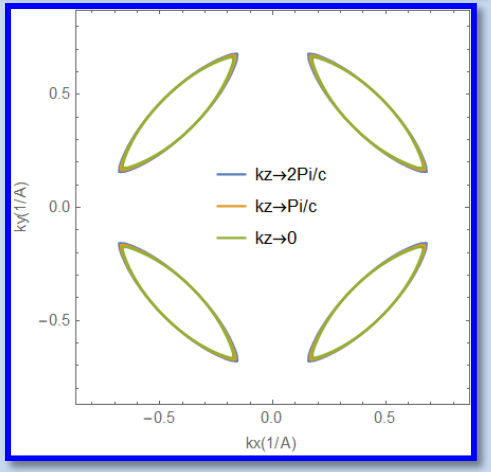
- ADMR may give us access to the normal-state fermi surface across the phase diagram.
- Doesn’t need a Fermi liquid, just Fermi surface.
- Can extract the k-dependent lifetime.

- High T in YBCO? Low doping “metal”?









S. Badoux *et al.*, Nature (2017)