The Current Experimental Status of the High-Tc Problem

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UNIVERSITY OF MARYLAND

Outline

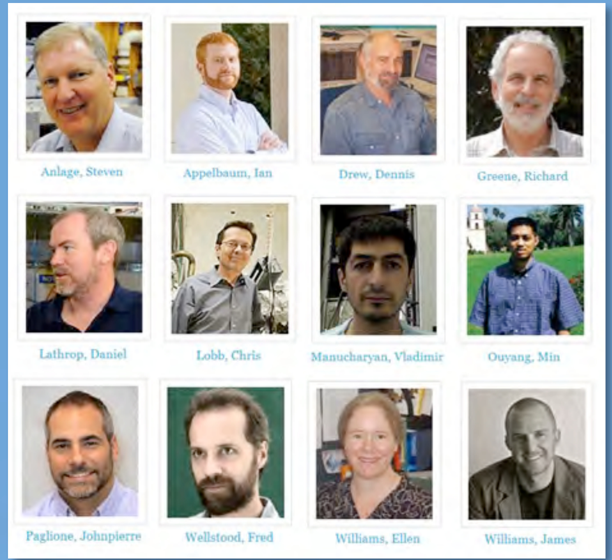
- A brief history of the search for high-Tc superconductivity
- What we know/understand at present
  [emphasis on doped copper oxides (cuprates)]
- What we do not understand
- My opinion of the current status of HTSC and the future

center for nanophysics and advanced materials

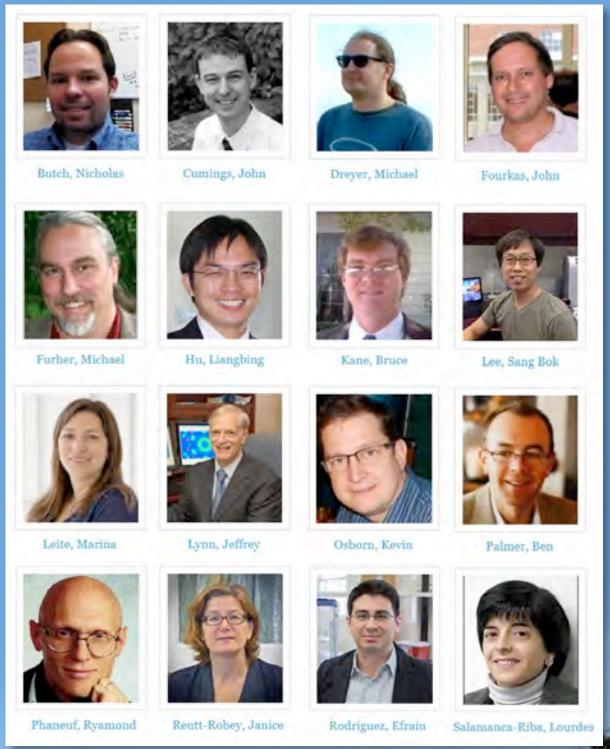
Membership

- 12 faculty (CMP)
- 16 affiliate members
- 8 research scientists
- 28 postdocs
- 55 grad students
- 20 undergrads
- 4 visitors
- 3 tech/admin staff

faculty



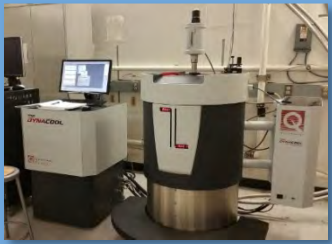
affiliates

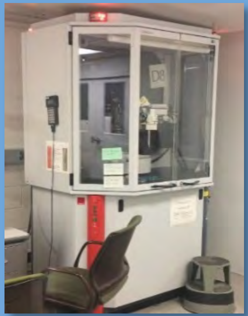


NAM center for nanophysics and advanced materials



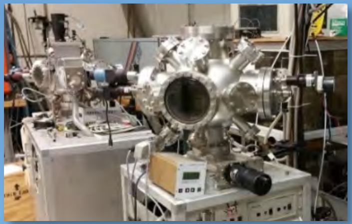




Research Facilities:

- 15 shared labs
- materials synthesis
- Thin-film synthesis (PLD)
- physical properties (100 mK, 14 T, 20 kbar)
- XRD facilities
- Ion mill, sputtering, evaporation
- AFM, STM, surface probes





How I got into superconductivity experimental research

My first day as a postdoc with Ted Geballe in 1967

Ted: I want to say one word to you. Just one word.

Rick: Yes, sir.

Ted: Are you listening?

Rick: Yes, I am.

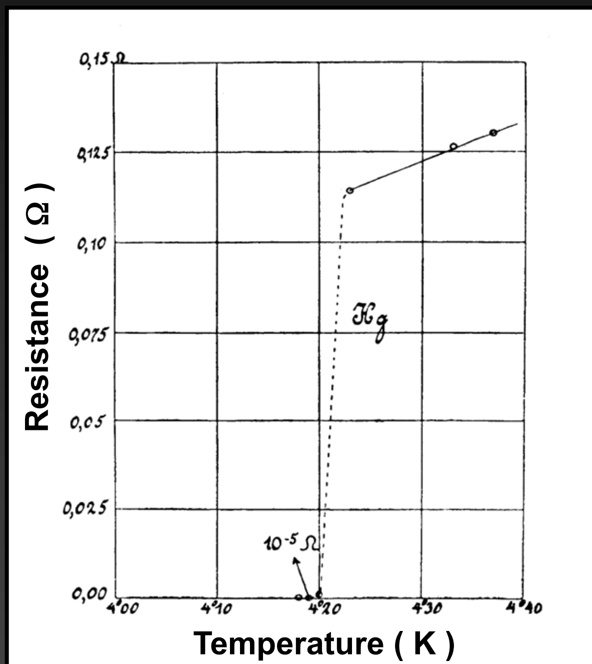
Ted: **SUPERCONDUCTORS.**

Rick: Exactly how do you mean?

Ted: **There's a great future in superconductors**. Think about it. Will you think about it?

From **"The Graduate",** a 1967 classic movie

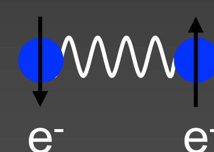
Superconductivity



T_c = 4.2 K in elemental Hg

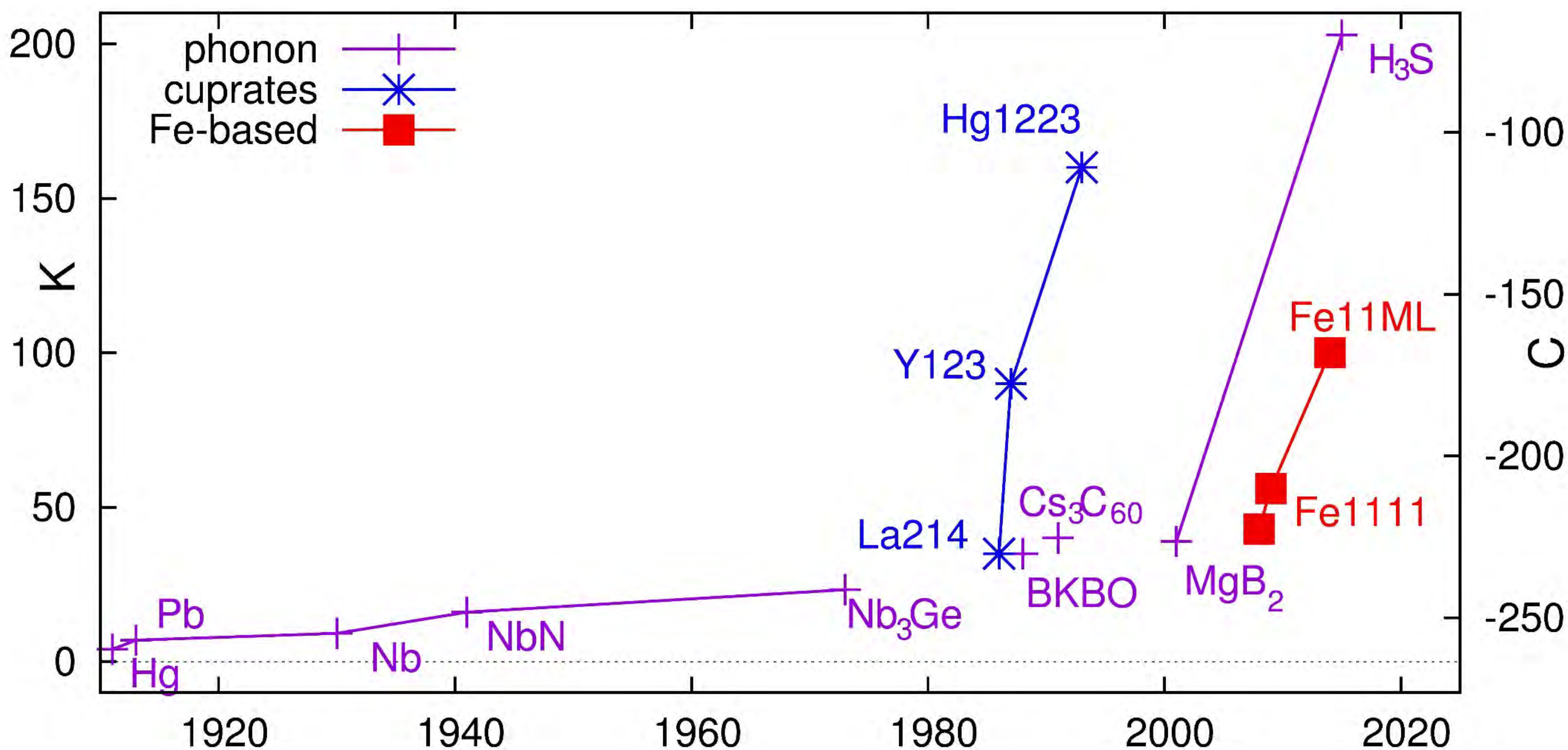
Gerrit Flim

H. Kammerlingh Onnes



electrons "pair up"

Superconductivity Tc versus year of discovery



A few pre-1987 theoretical proposals for HTSC

PHYSICAL REVIEW VOLUME 134, NUMBER 6A 15 JUNE 1964

Possibility of Synthesizing an Organic Superconductor*

W. A. LITTLE
Department of Physics, Stanford University, Stanford, California
(Received 13 November 1963; revised manuscript received 27 January 1964)

VOLUME 21, NUMBER 26 PHYSICAL REVIEW LETTERS 23 DECEMBER 1968

METALLIC HYDROGEN: A HIGH-TEMPERATURE SUPERCONDUCTOR?

N. W. Ashcroft
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 3 May 1968)

VOLUME 92, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 7 MAY 2004

Hydrogen Dominant Metallic Alloys: High Temperature Superconductors?

N.W. Ashcroft

PHYSICAL REVIEW B VOLUME 7, NUMBER 3 1 FEBRUARY 1973

Model for an Exciton Mechanism of Superconductivity*

David Allender,† James Bray, and John Bardeen

First 2D Organic Superconductor---IBM Almaden---PRL 50, 270 (1983)

$(BEDT\text{-}TTF)_2ReO_4$

Tc ~ 2K

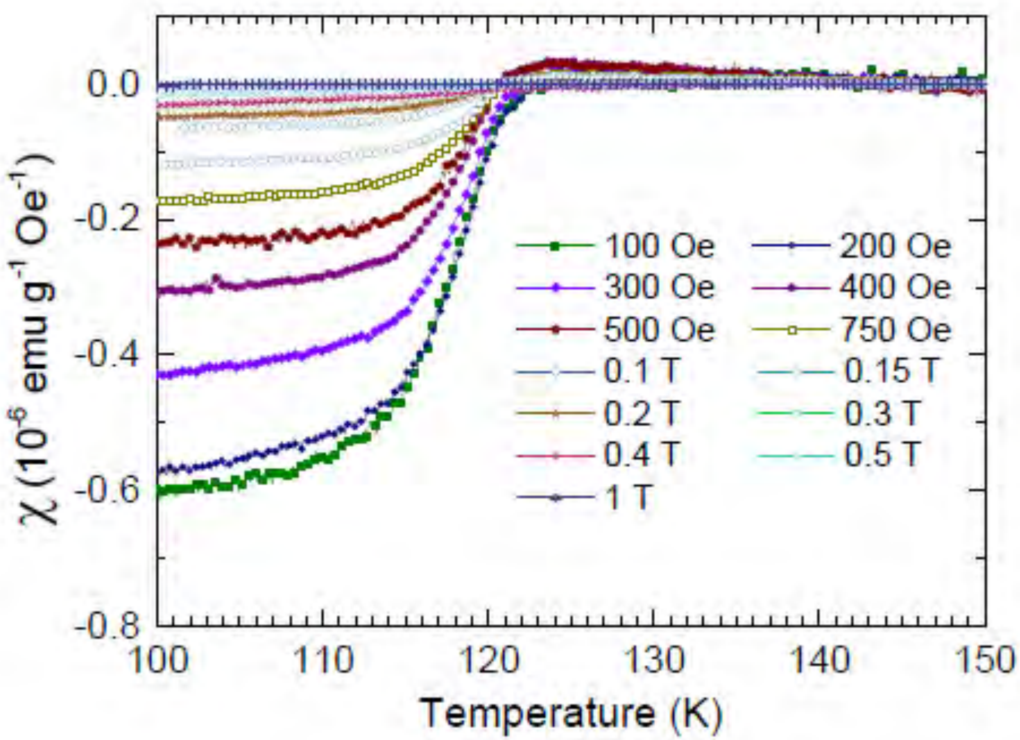
Stuart Parkin, Rick Greene, Paul Grant

New high-Tc Organic SC?

potassium doped p-terphenyl arXiv: 1703.06641

Superconductivity above 120 kelvin in a chain link molecule

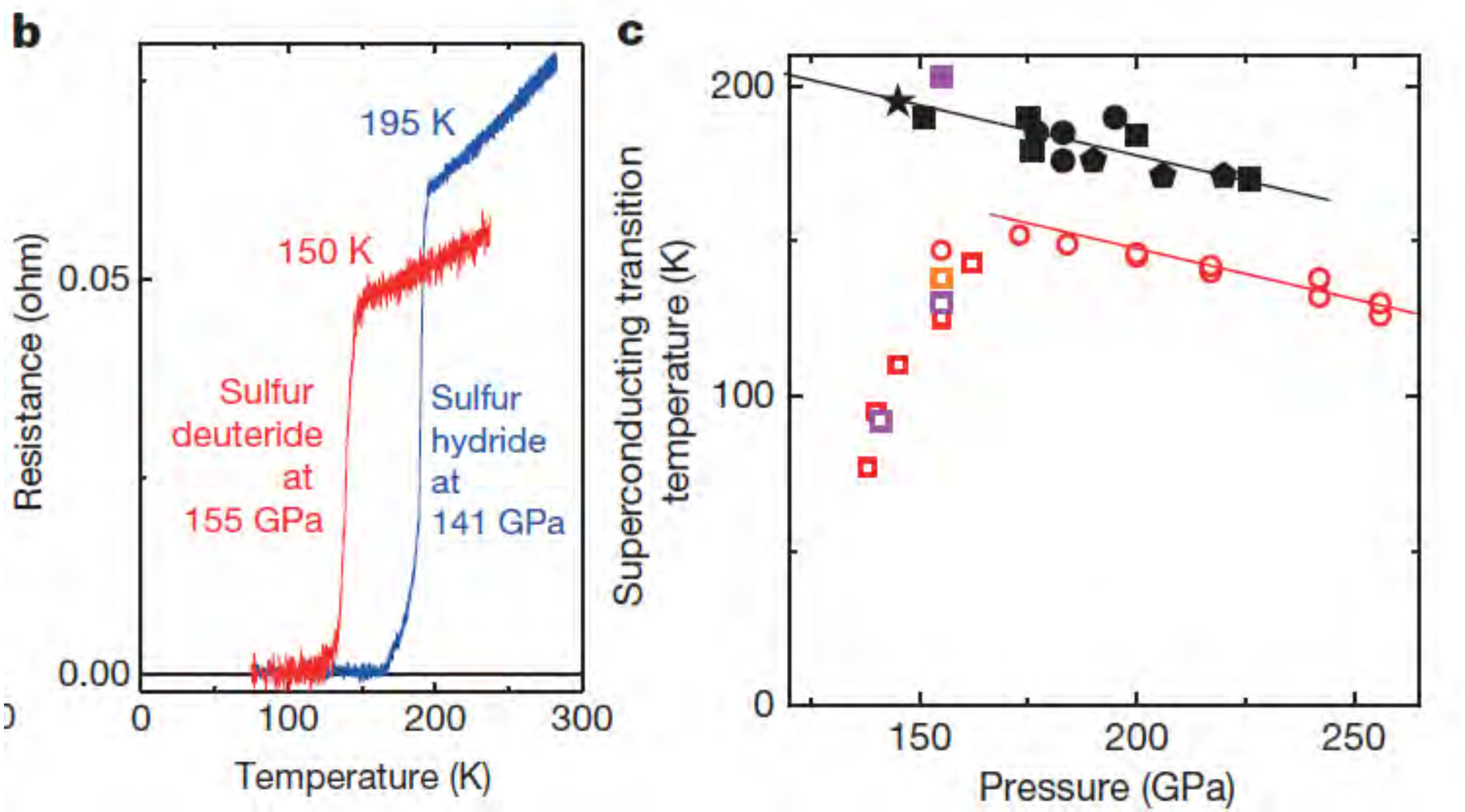
Ren-Shu Wang[1,2], Yun Gao[2], Zhong-Bing Huang[3] & Xiao-Jia Chen[1]



NOT Reproduced; but a SC-like gap is seen in ARPES (arXiv: 1704.04230)

H_3S conventional electron-phonon superconductivity

Drozdov et al., Nature 2015

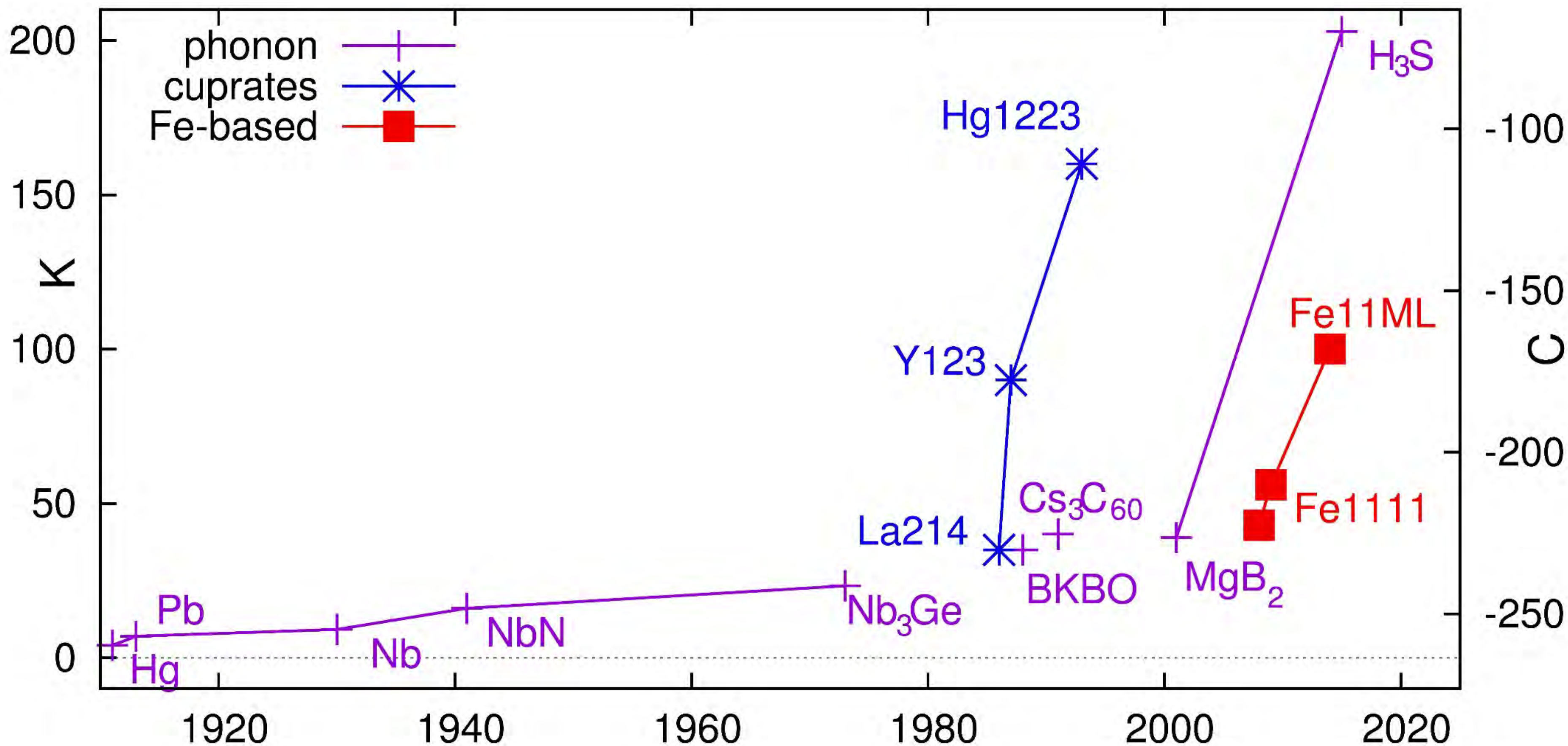


This result has been reproduced and Meissner effect observed!!

Theoretical prediction of Ashcroft is basically correct!!

Superconductivity Tc dramatically enhanced in 1987

Mueller-Bednorz discovery of cuprate SC materials—Nobel Prize 1988



Many Improved (and New) Experimental Techniques (and Better Materials) since 1987

ARPES
SI-STM (QPI)
RIXS
Quantum Design MPMS and PPMS
Higher Magnetic Fields

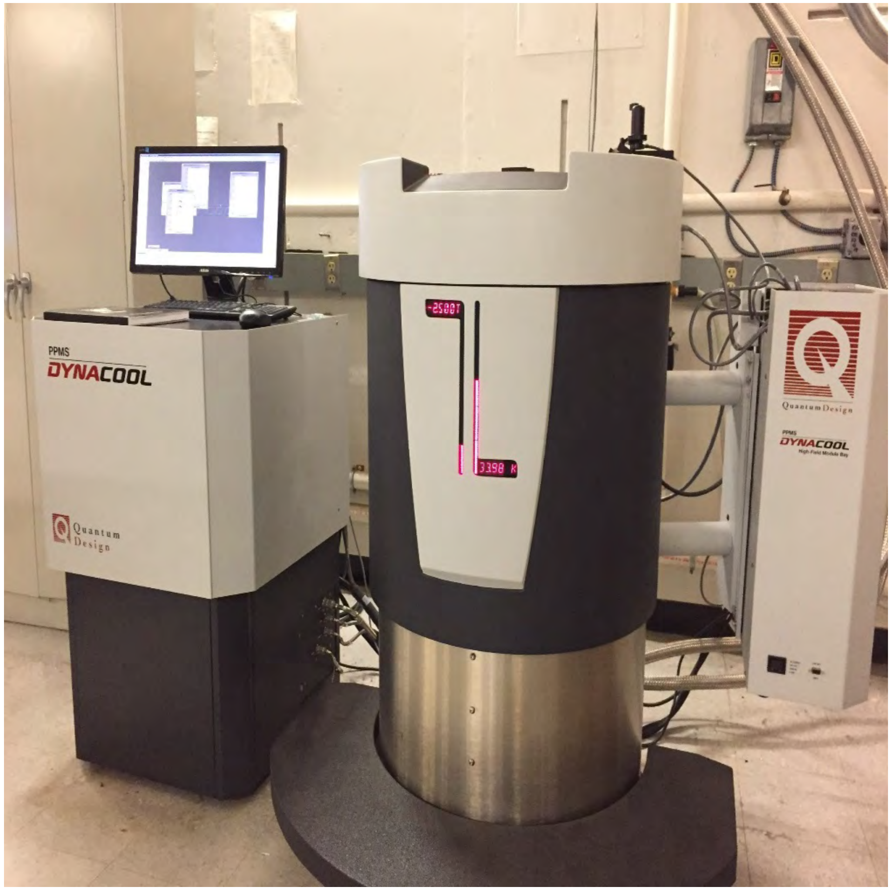
Improved YBCO crystals---UBC group
PLD and MBE cuprate films---many groups

ALSO: Improved Numerical methods for accurate computation of large (or at low temperature) correlated electron systems, e.g., for 2D Hubbard model

A transport measurements example

1911 Leiden (K. Onnes)

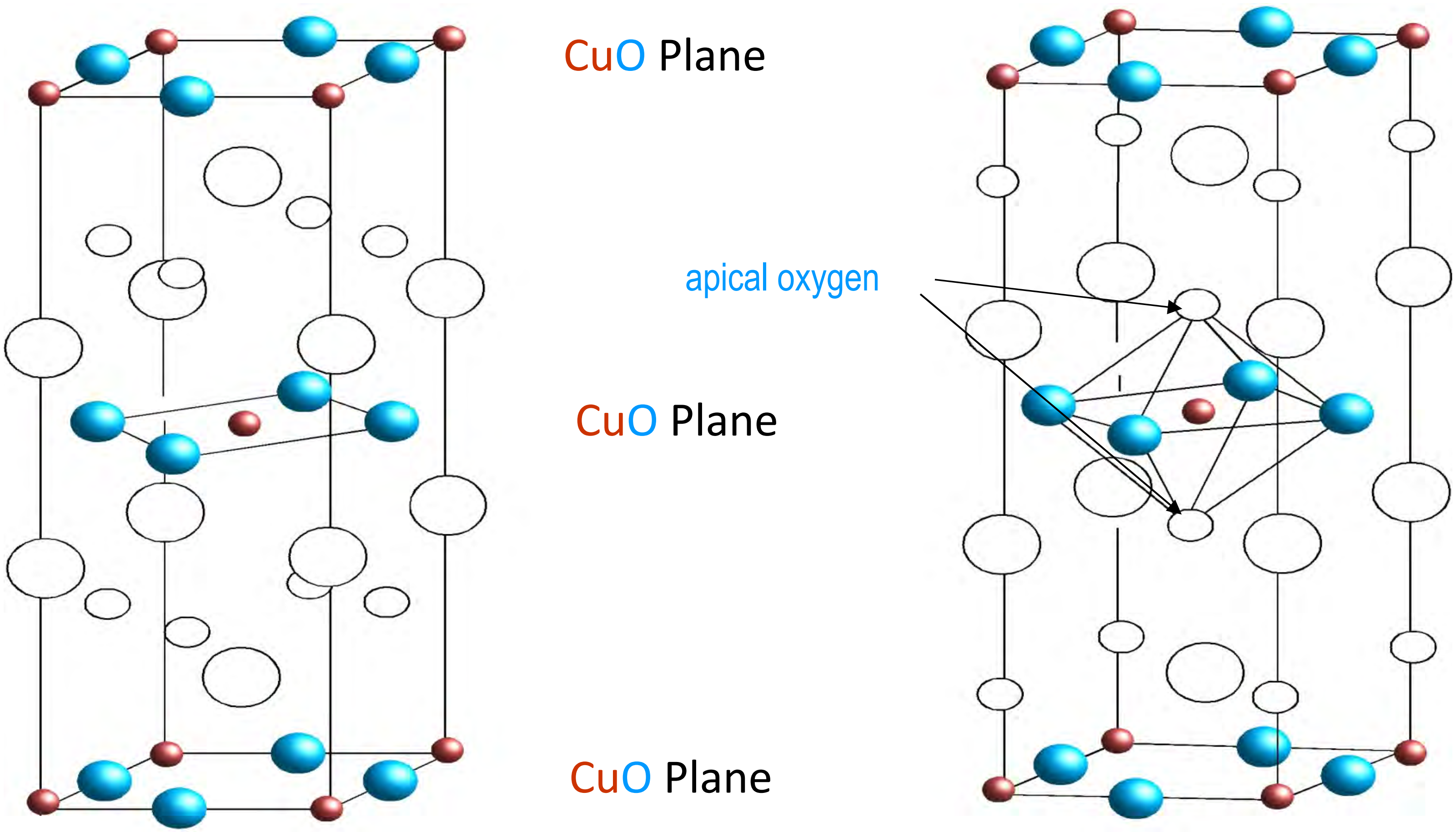
2016 Maryland and elsewhere



An extreme example, but the Leiden apparatus was not that different than what I used as a graduate student at Stanford in the late 1960s

High-temperature Cuprate Superconductors

Layered structure: quasi-2 dimensional



$Pr_{2-x}Ce_xCuO_4$

N-doped

$La_{2-x}Sr_xCuO_4$

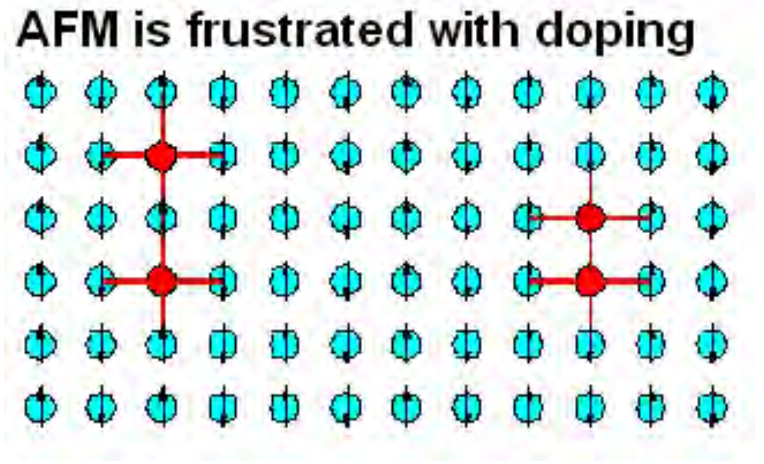
P-doped

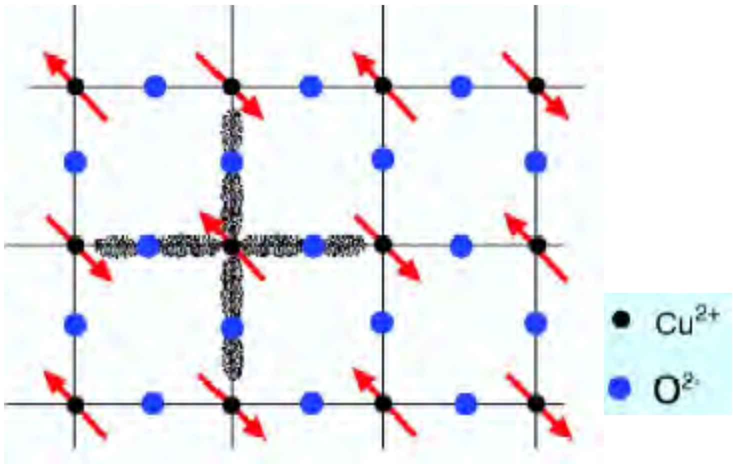
La_2CuO_4

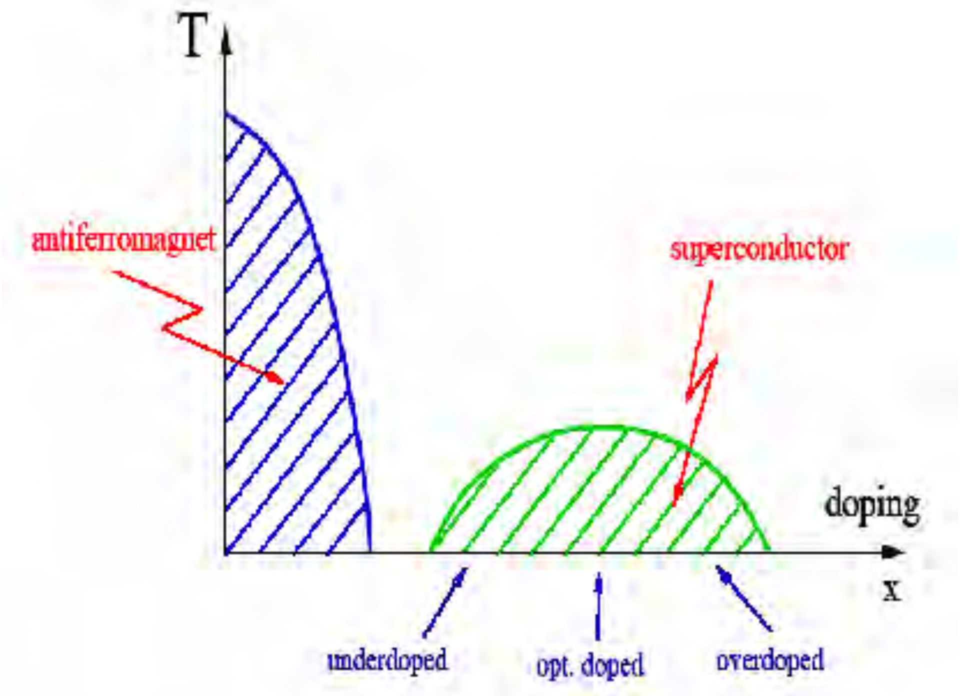
La:[Xe]$5d^1 6s^2$ ⇒ La^{3+} filled
O:[He]$2s^2 2p^4$ ⇒ O^{2-} filled

Cu:[Ar]$3d^{10} 4s^1$ ⇒ Cu^{2+}:$3d^9$
unfilled orbital ⇒ should be a metal

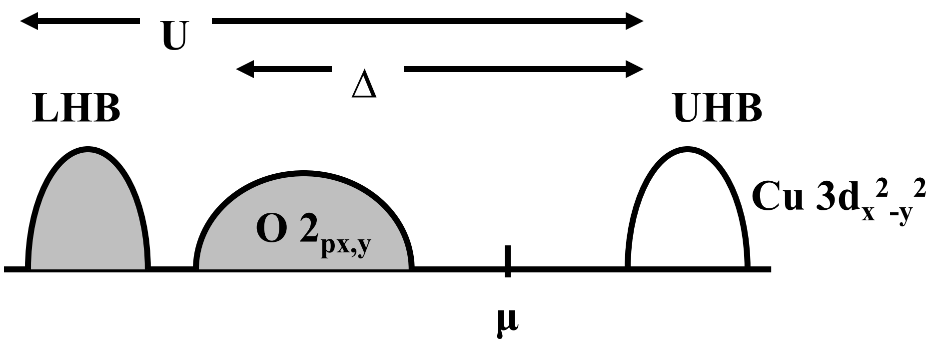
Coulomb interactions ⇒Mott insulator







High-T_c Cuprates are doped charge-transfer insulators

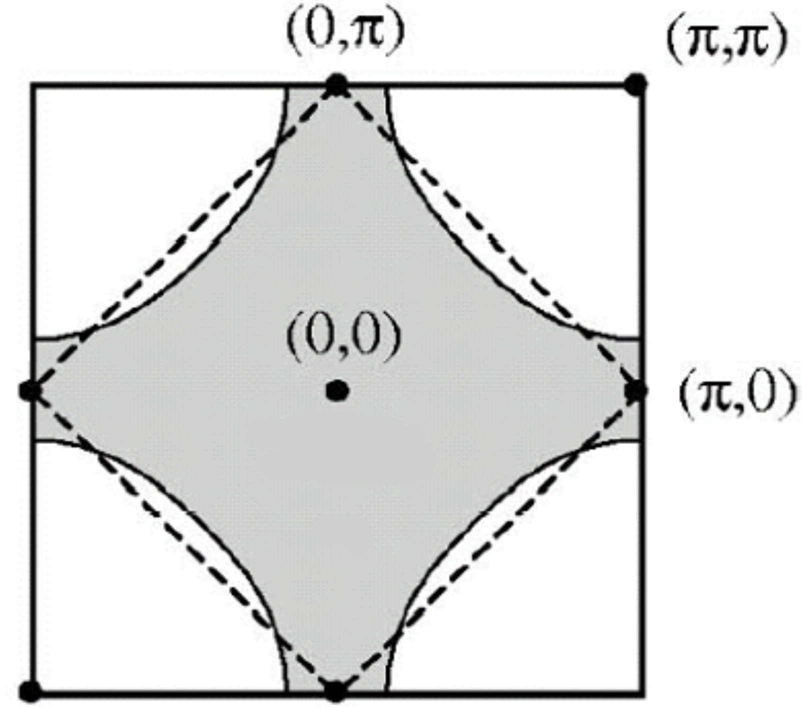


Hybridization → hole-doped Zhang-Rice singlet → t-J model

$La_{2-x}Sr_x^{2+}CuO_4$ → Holes

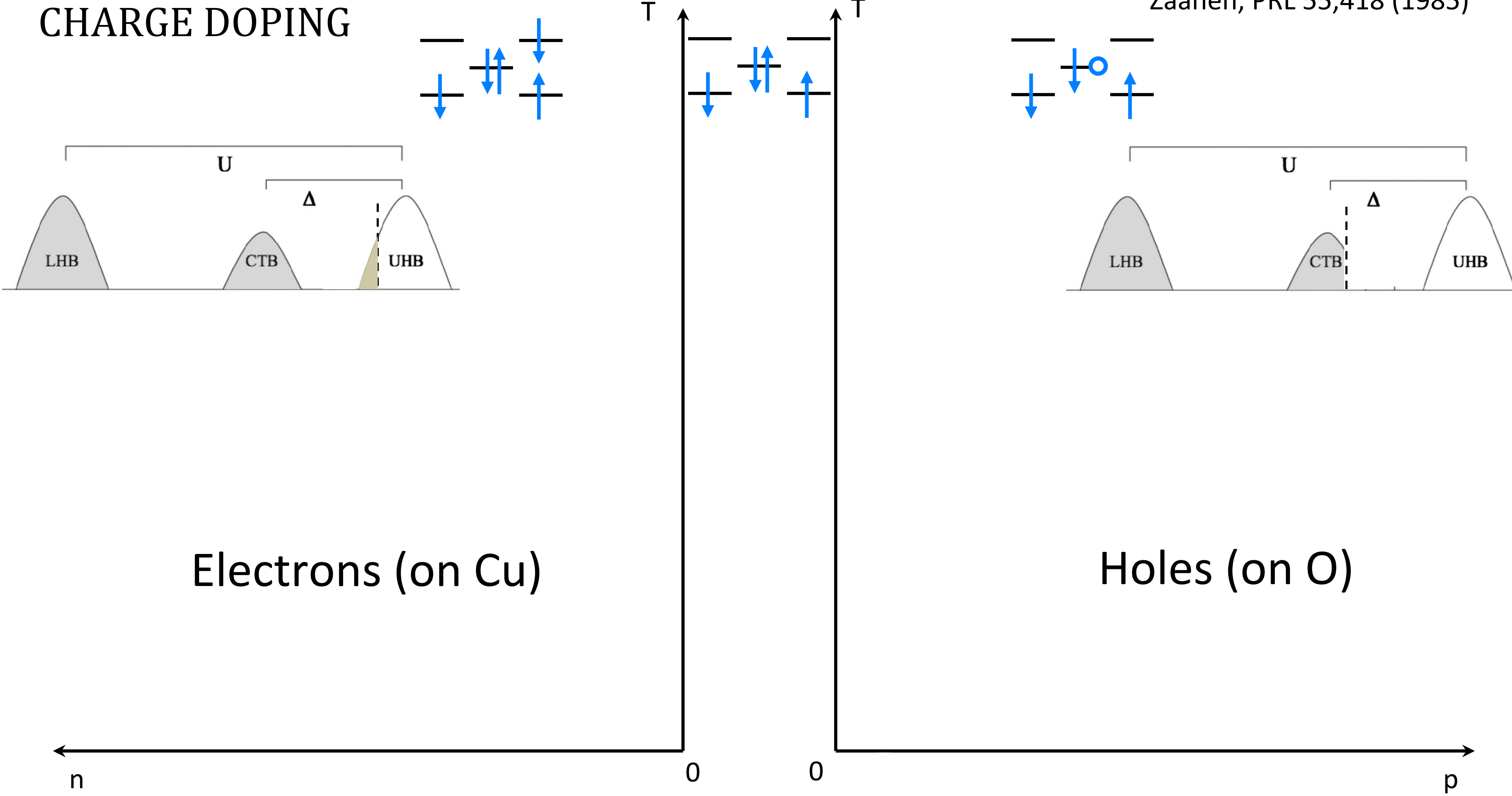
$Nd_{2-x}Ce_x^{4+}CuO_4$ → Electrons

2D Fermi Surface (AN and N points)

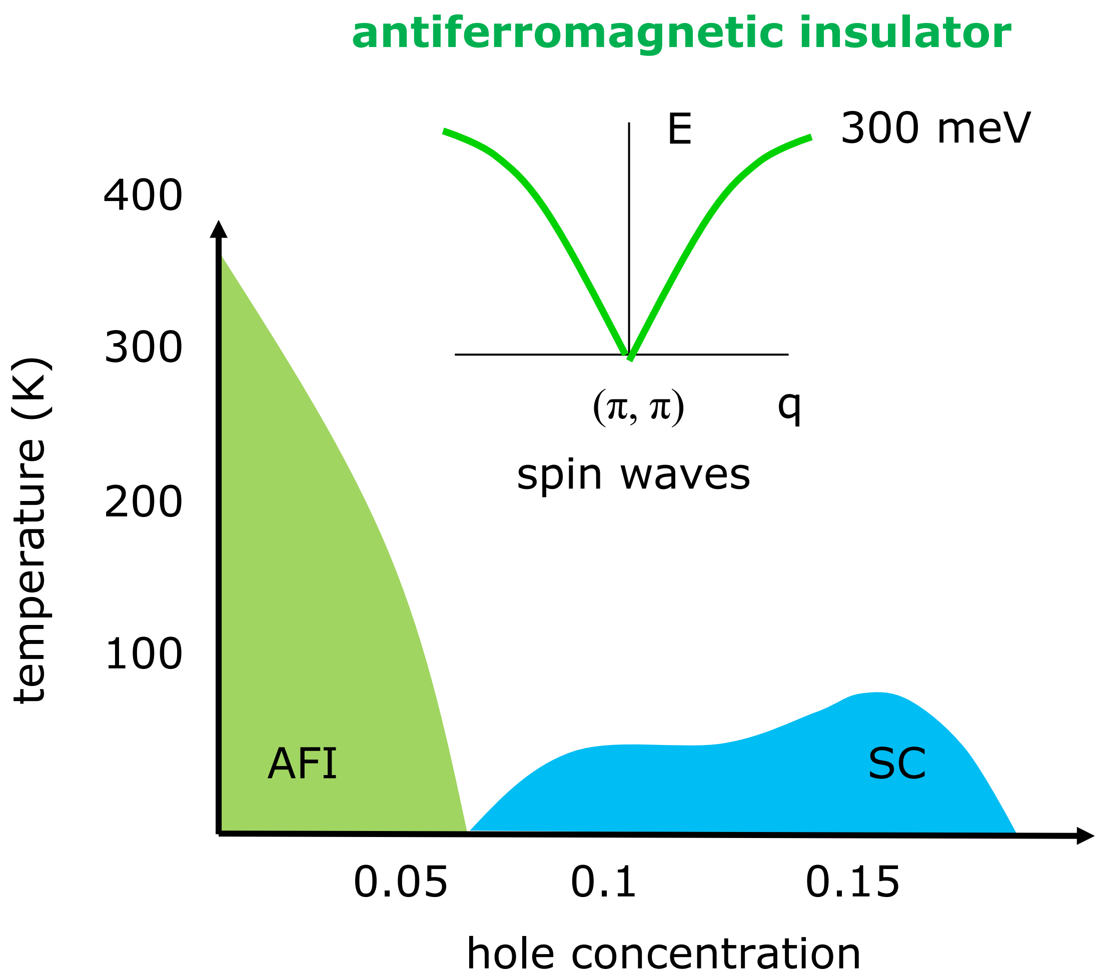


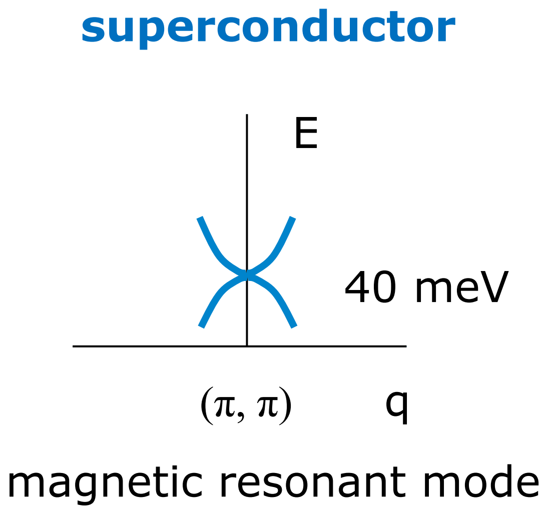
CHARGE DOPING

Zaanen, PRL 55,418 (1985)

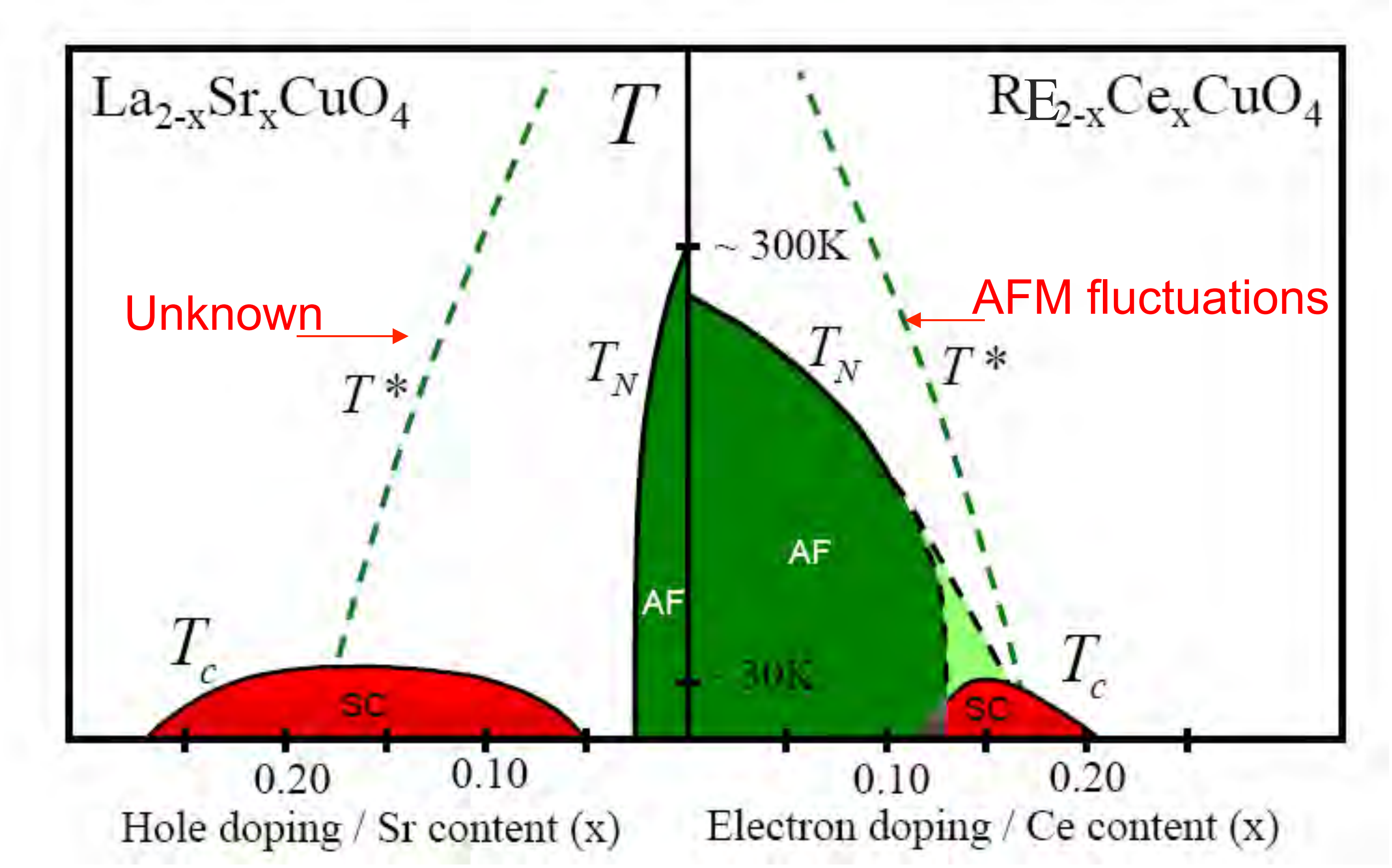


Spin dynamics in cuprate superconductors





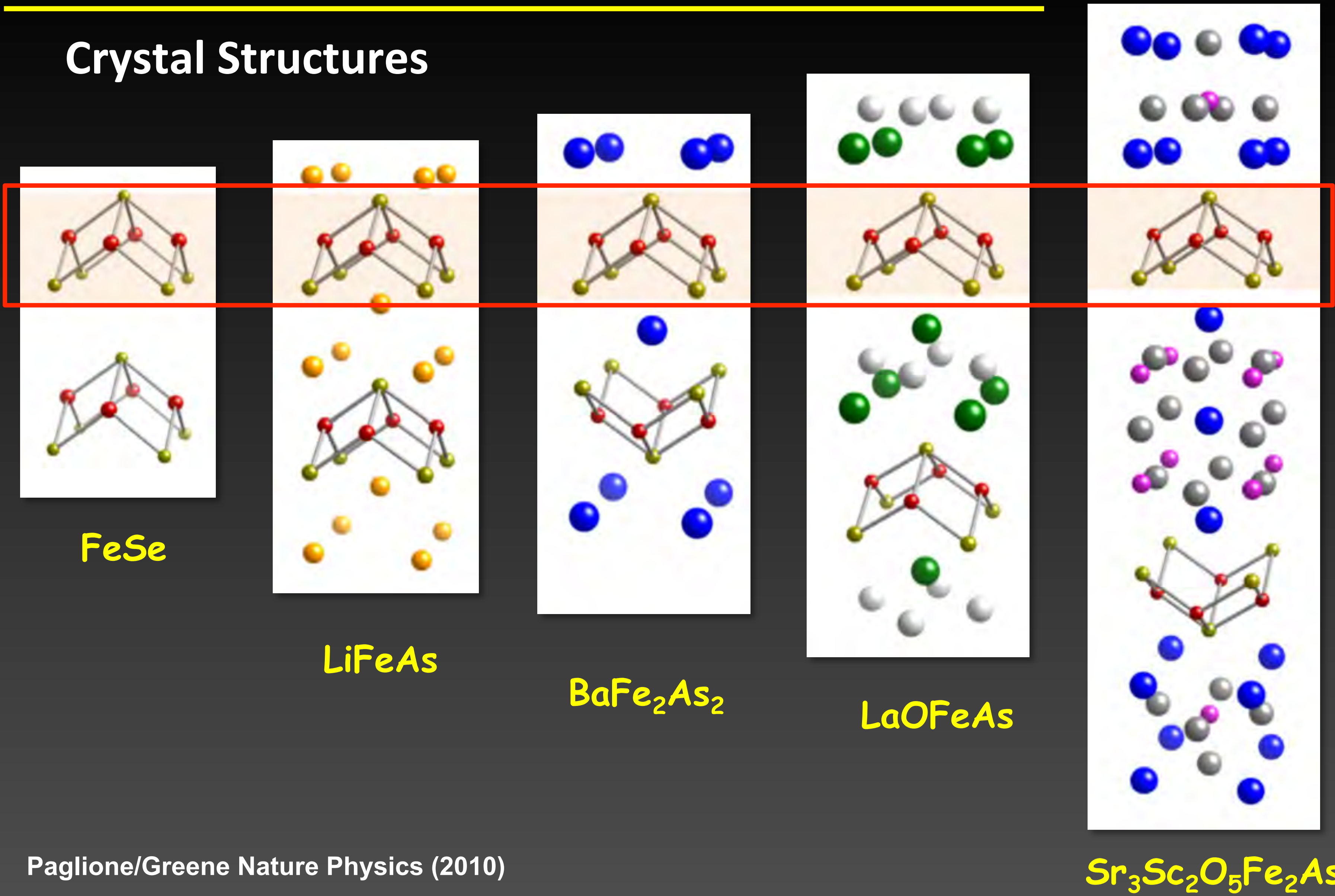
Phase diagram of the cuprates



N.P. Armitage, P. Fournier and R.L. Greene, *Rev. Mod. Phys.* ***82****, 2421(2010)*

Iron-Based Superconductors

Crystal Structures



Paglione/Greene Nature Physics (2010)

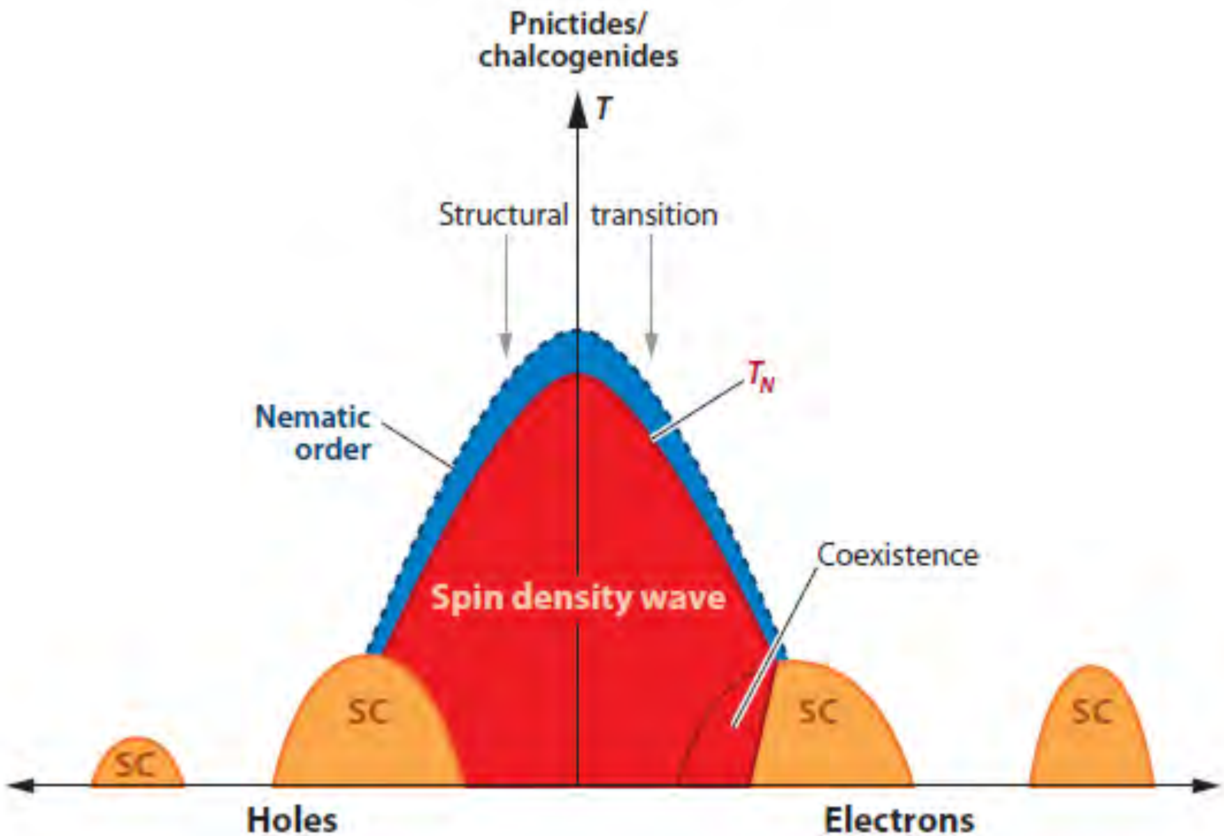
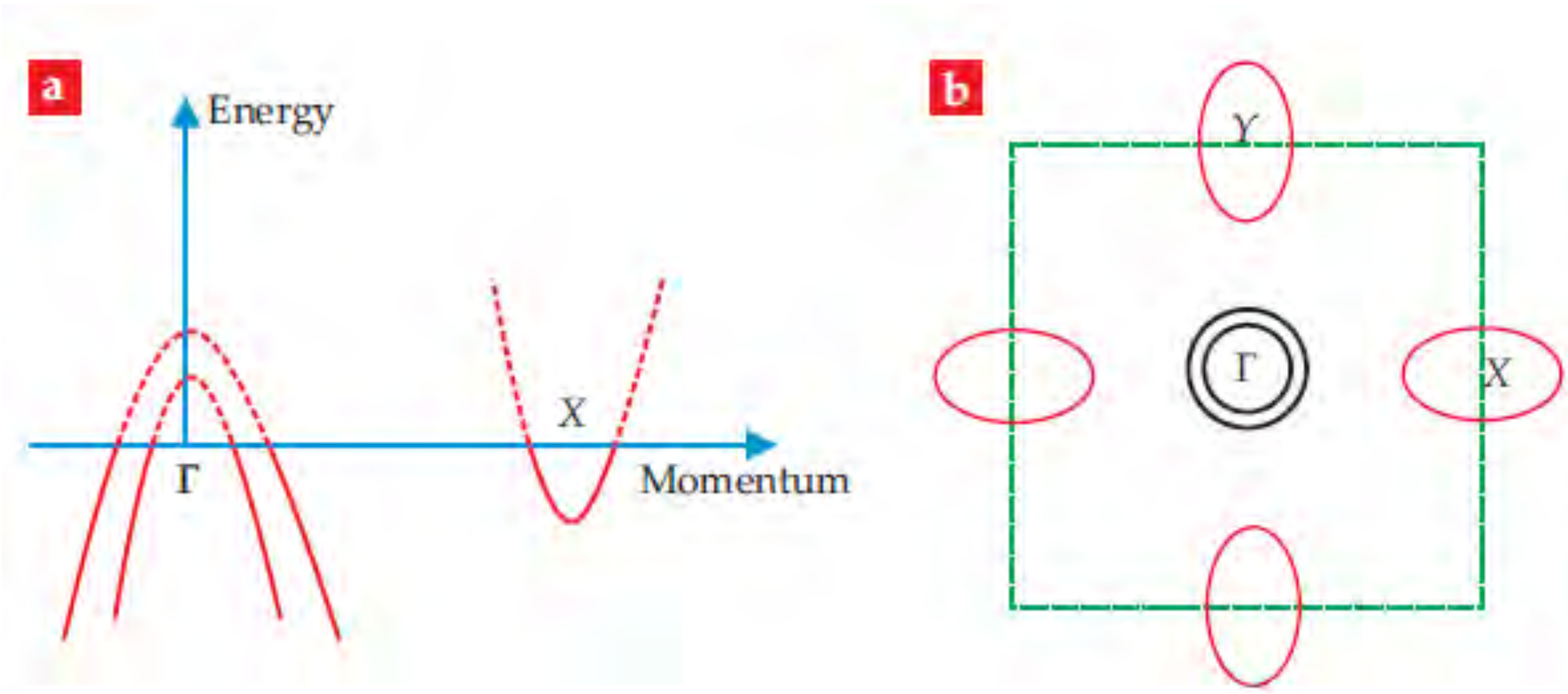


Figure 1

Schematic phase diagram of Fe-based pnictides upon hole or electron doping. In the shaded region, superconductivity (SC) and antiferromagnetism coexist. Not all details/phases are shown. Superconductivity can be initiated not only by doping but also by pressure and/or isovalent replacement of one pnictide element by another (8). The nematic phase at $T > T_N$ is the subject of debate. Superconductors at large doping are KFe_2As_2 for hole doping (42, 43) and $A_xFe_{2-y}Se_2$ (A = K, Rb, Cs) for electron doping (11, 12). Whether superconductivity in pnictides exists at all intermediate dopings is not clear yet. Taken from Reference 24.

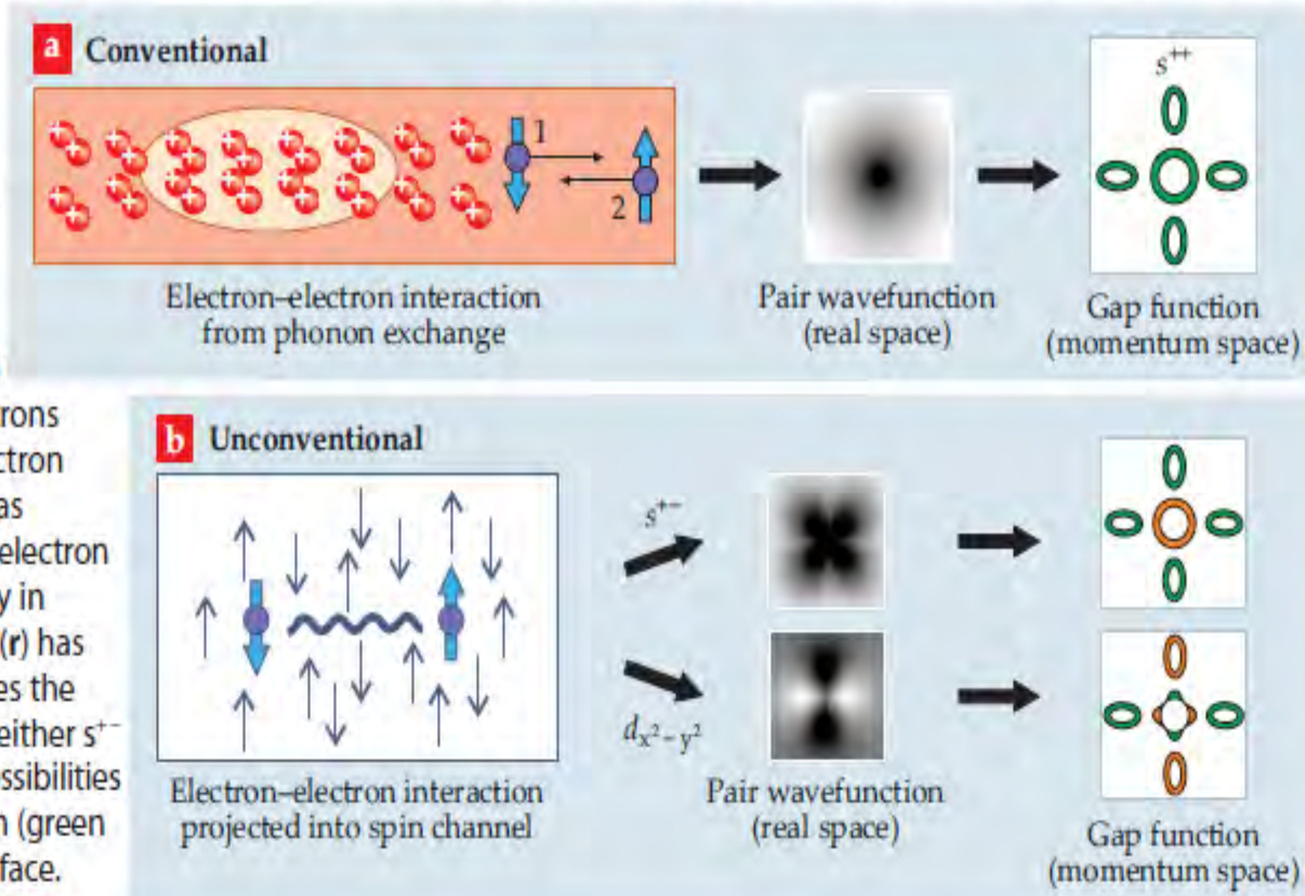
2D Fermi surface of iron-based SCs



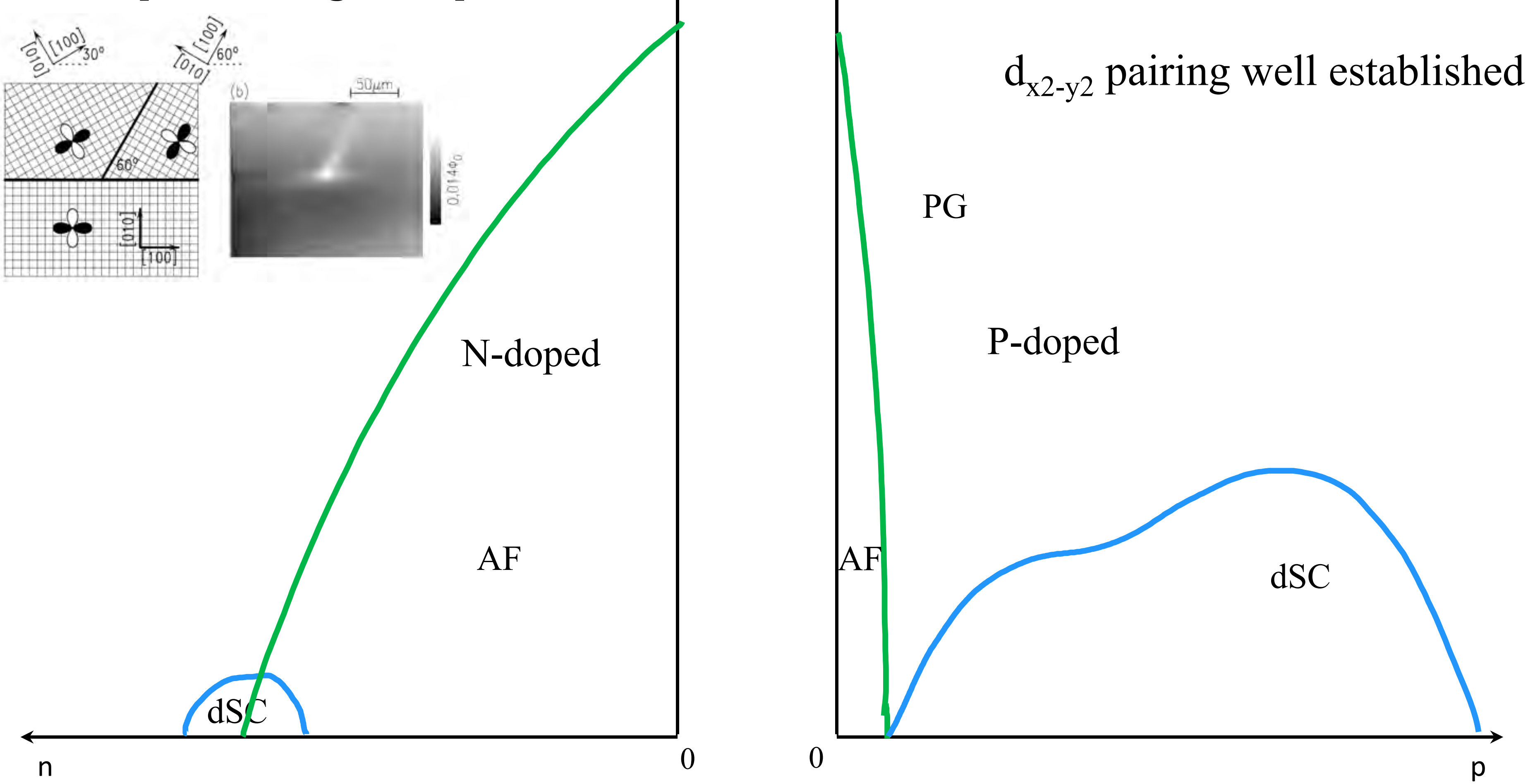
In contrast to cuprates these materials are metals without doping

Superconductivity: Cooper Pair Symmetry

Figure 5. Two routes to superconductivity. (**a**) Two electrons attract each other when the first polarizes a local region (yellow) of the lattice and the second is attracted to that region. The pair wavefunction Ψ(**r**), where **r** is the relative electronic coordinate, has the full symmetry of the crystal and gives rise to a gap function Δ(**k**), where **k** is the momentum, with the same sign throughout the Fermi surface. (**b**) Electrons interact with each other via the Coulomb interaction. In this example, the dominant interaction is the magnetic exchange (blue wavy line) arising between opposite-spin electrons due to Coulomb forces. The first electron polarizes the conduction electron gas antiferromagnetically, and a second electron of opposite spin can lower its energy in that locally polarized region. Here Ψ(**r**) has a node at the origin, which minimizes the Coulomb interaction, and can have either s^{+-} or $d_{x^2-y^2}$ form, as shown. The two possibilities lead to gap functions of varying sign (green for +, orange for −) on the Fermi surface.



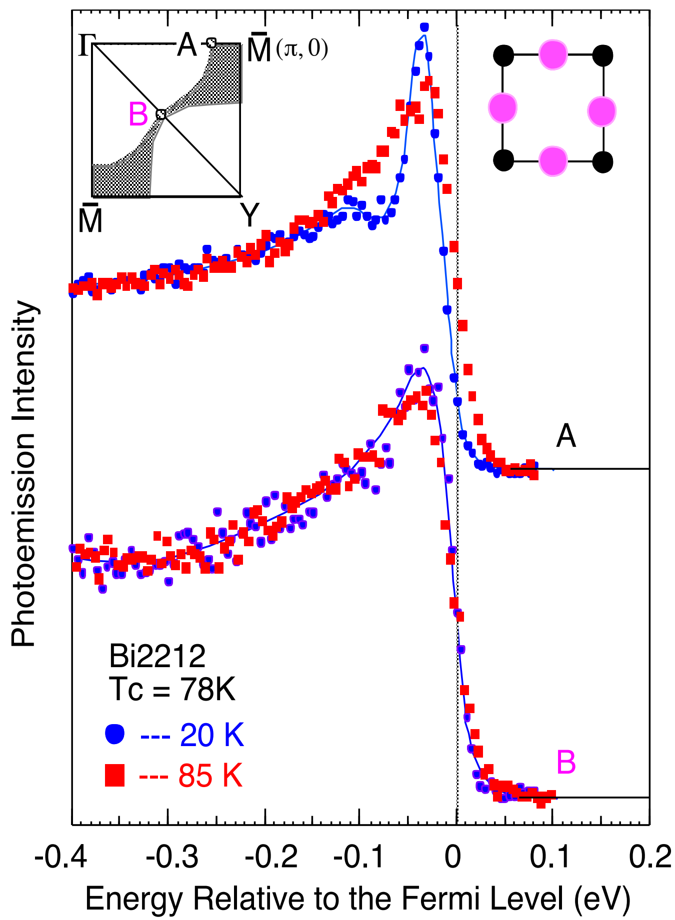
Cooper Pairing in Cuprates

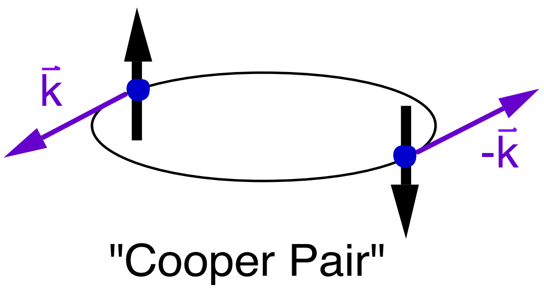


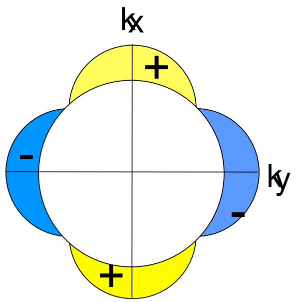
-T-linear penetration depth
-ARPES zone diagonal node
-Phase sensitive Josephson
-Phase sensitive tri-crystal

W. Hardy et al (UBC), PRL 70, 3999 (1993)
Z. X. Shen et al., PRL 70, 1553 (1993)
D. J. van Harlingen et al., 71, 2134 (1993);
C. Tsuei , J. Kirtley et al., PRL 73, 593 (1994)

ARPES---anisotropic d-wave gap structure

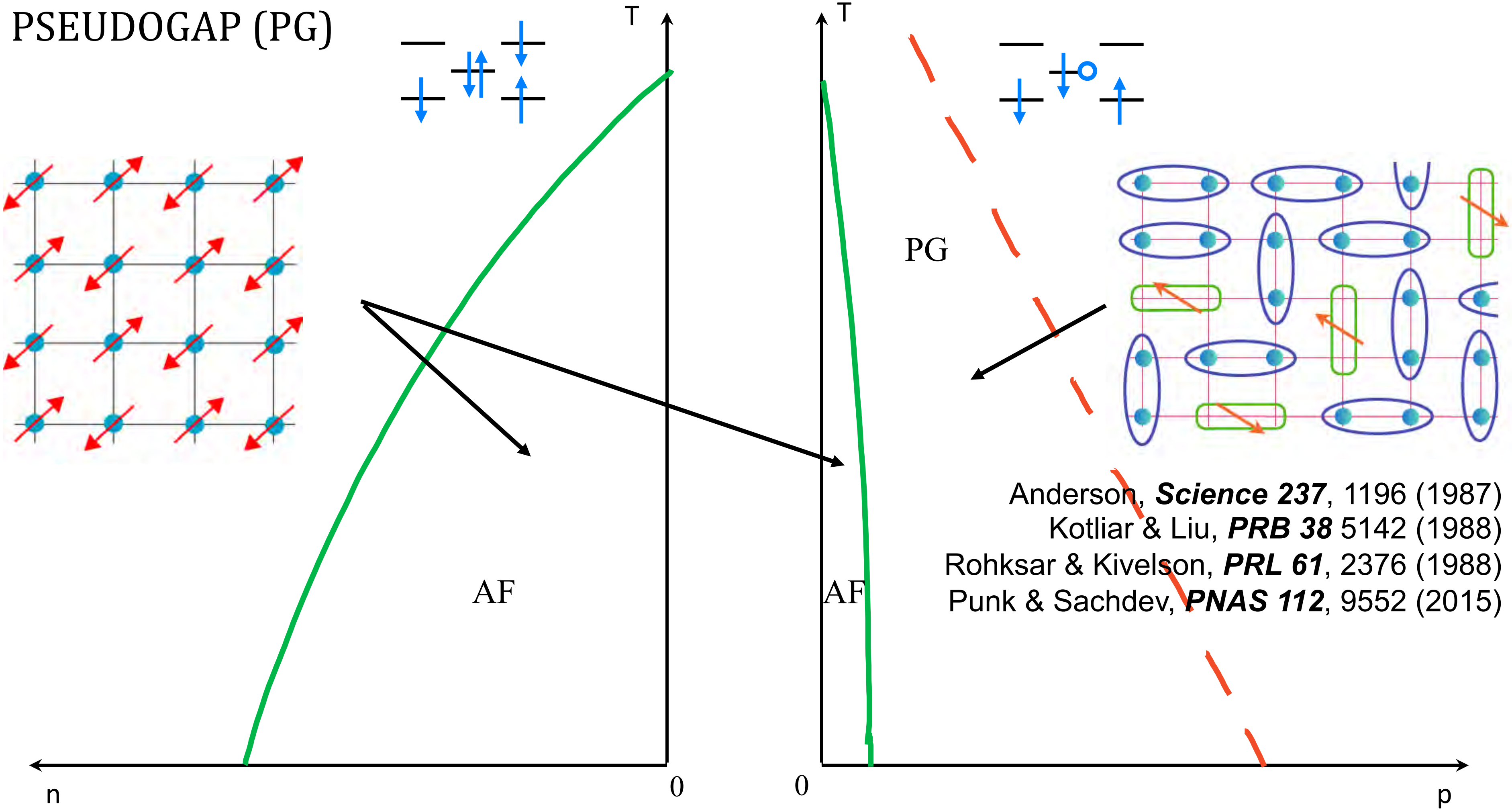






Anomalously Large Gap Anisotropy in the a-b plane of Bi2212, Z.-X. Shen et al., Phys. Rev. Lett. 70, 1553 (1993)

PSEUDOGAP (PG)

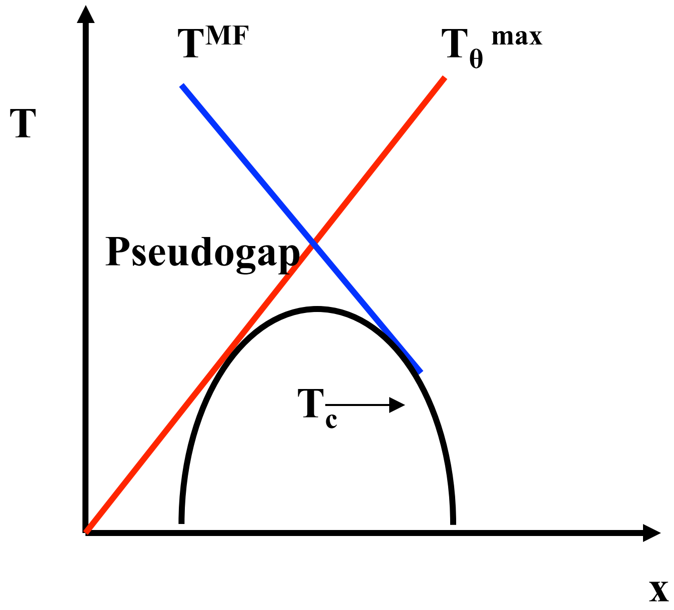


Anderson, ***Science 237***, 1196 (1987)
Kotliar & Liu, ***PRB 38*** 5142 (1988)
Rohksar & Kivelson, ***PRL 61***, 2376 (1988)
Punk & Sachdev, ***PNAS 112***, 9552 (2015)

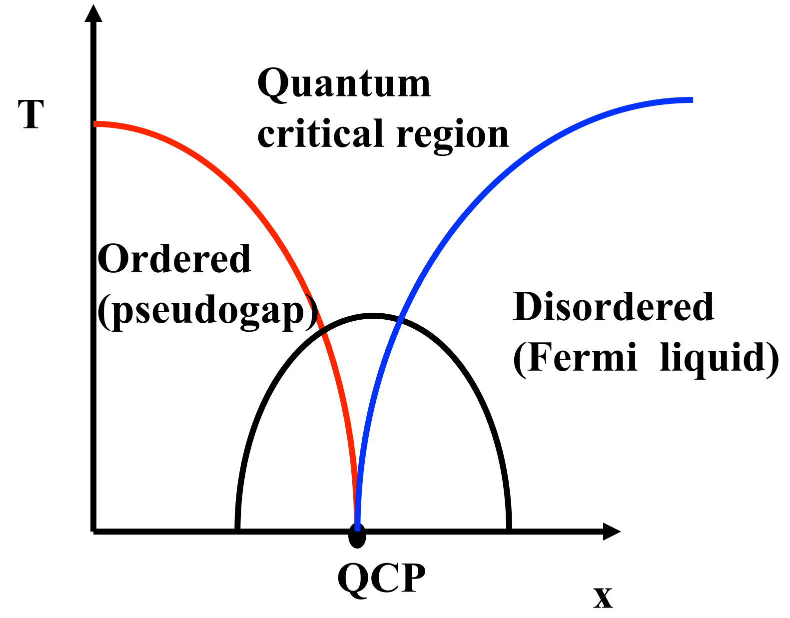
Electronic Dark Matter

Theoretical Phase Diagrams

Phase Ordering

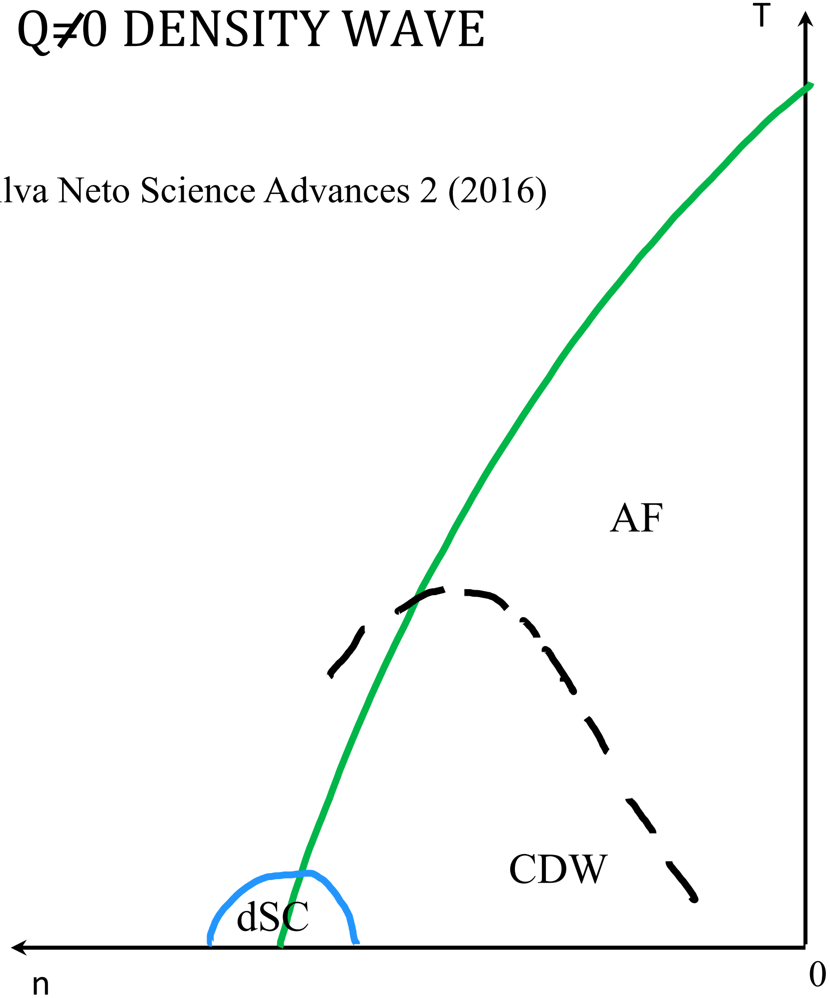


Quantum Critical

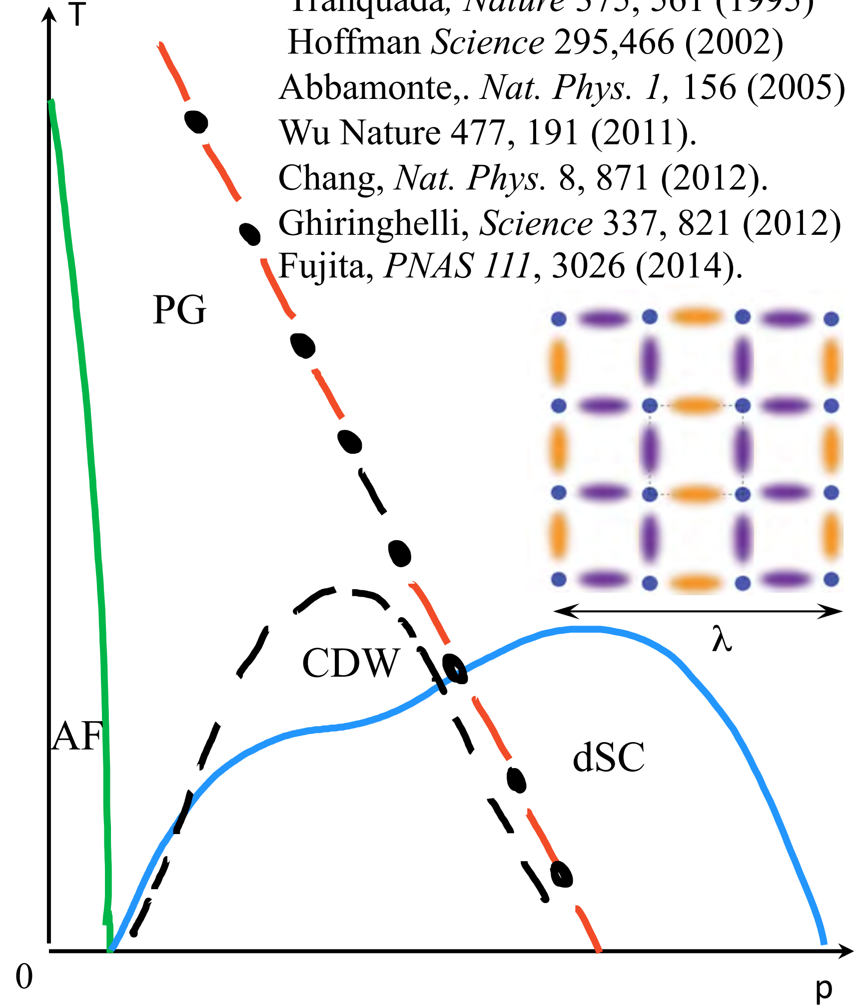


Q≠0 DENSITY WAVE

Silva Neto Science Advances 2 (2016)



Tranquada, *Nature* 375, 561 (1995)
Hoffman *Science* 295,466 (2002)
Abbamonte,. *Nat. Phys. 1,* 156 (2005)
Wu Nature 477, 191 (2011).
Chang, *Nat. Phys.* 8, 871 (2012).
Ghiringhelli, *Science* 337, 821 (2012)
Fujita, *PNAS 111*, 3026 (2014).

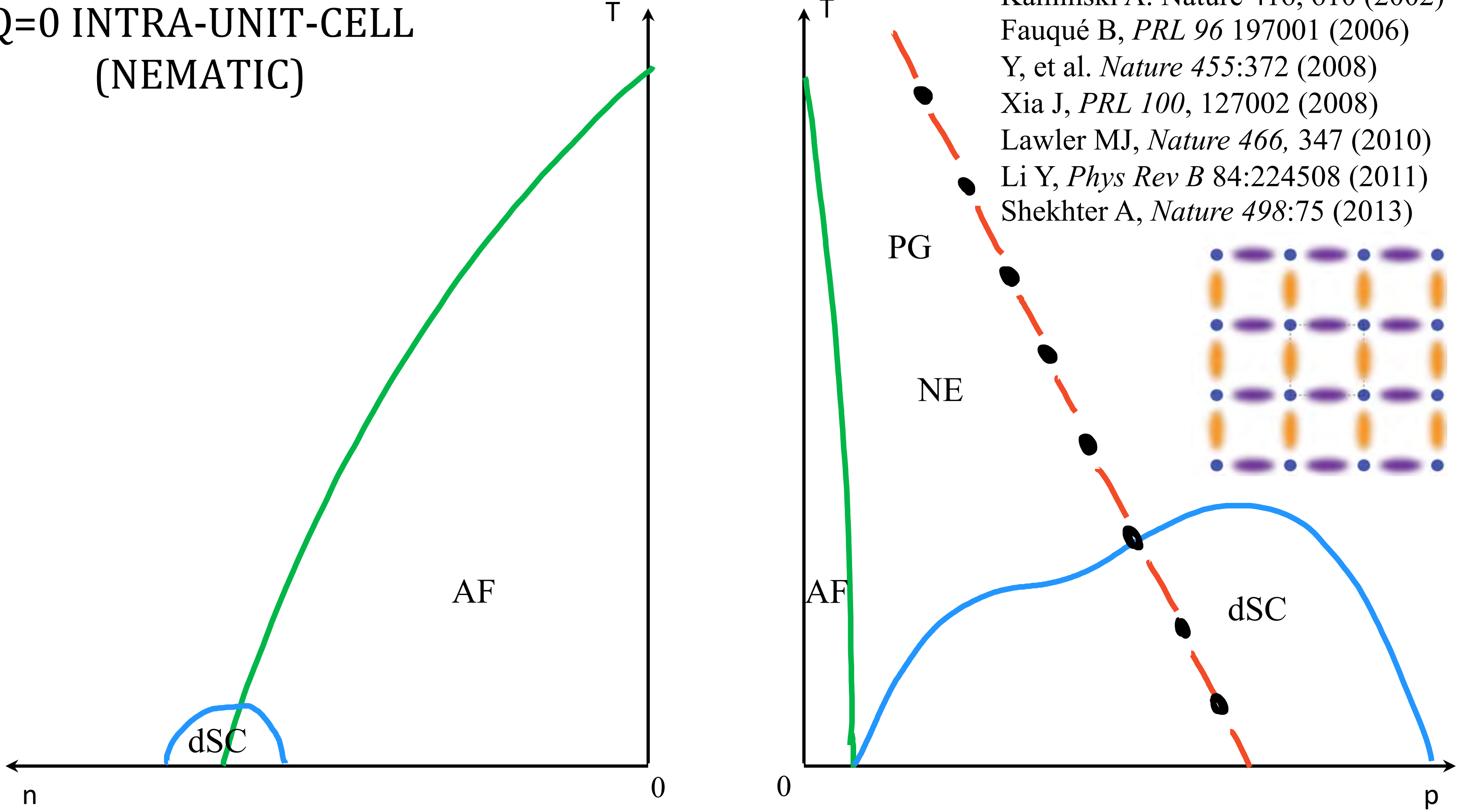


always short range CO;
unaffected by SC

long range CO in a field;
competes with SC

Q=0 INTRA-UNIT-CELL (NEMATIC)

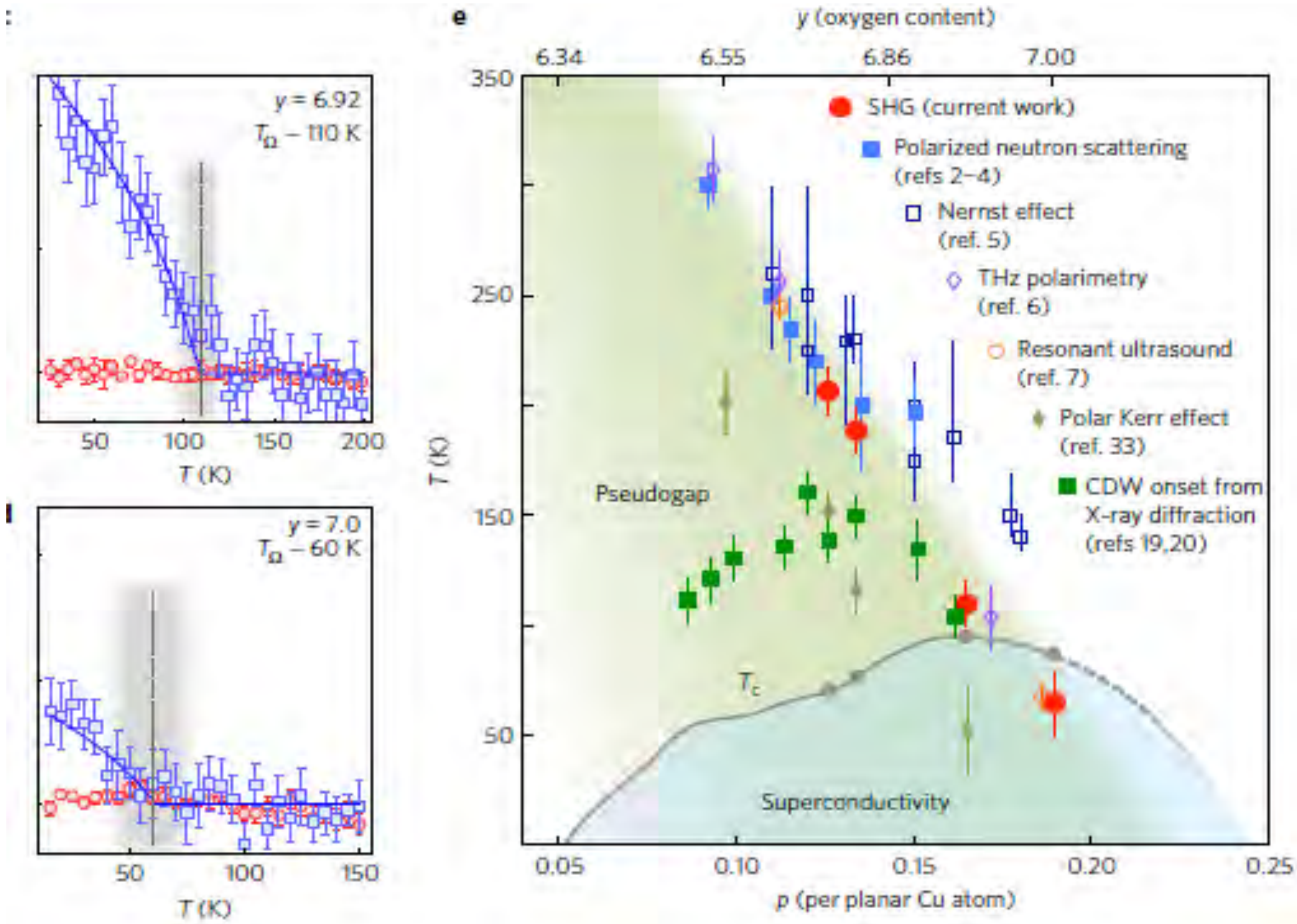
Kaminski A. Nature 416, 610 (2002)
Fauqué B, *PRL 96* 197001 (2006)
Y, et al. *Nature 455*:372 (2008)
Xia J, *PRL 100*, 127002 (2008)
Lawler MJ, *Nature 466,* 347 (2010)
Li Y, *Phys Rev B* 84:224508 (2011)
Shekhter A, *Nature 498*:75 (2013)



A global inversion-symmetry-broken phase inside the pseudogap region of $YBa_2Cu_3O_y$

L. Zhao[1,2], C. A. Belvin[3], R. Liang[4,5], D. A. Bonn[4,5], W. N. Hardy[4,5], N. P. Armitage[6] and D. Hsieh[1,2]*

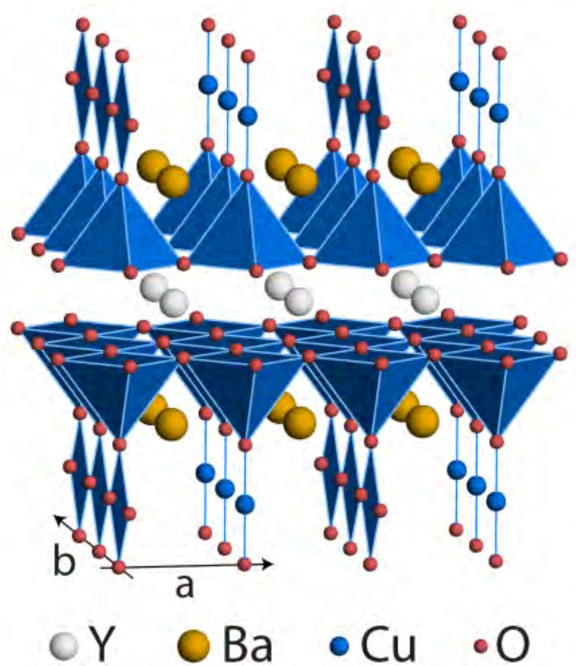
Nat. Phys. 2016

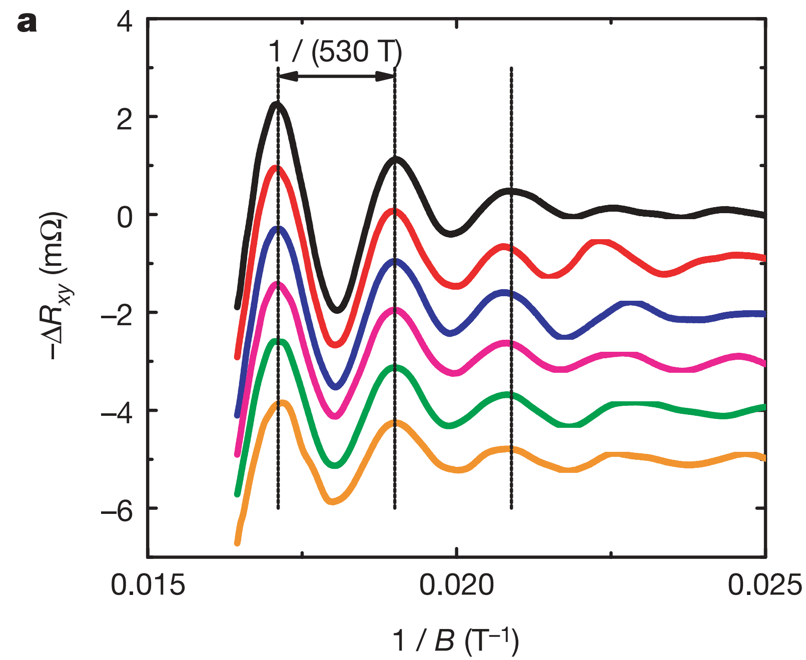


Cleaner crystals (UBC group) lead to a big surprise: Quantum Oscillations in the PG region

ortho-II structure of $YBa_2Cu_3O_{6+x}$

a clean underdoped high-temperature superconductor





Doiron-Leyraud *et al*., Nature **447**, 565 (2007)

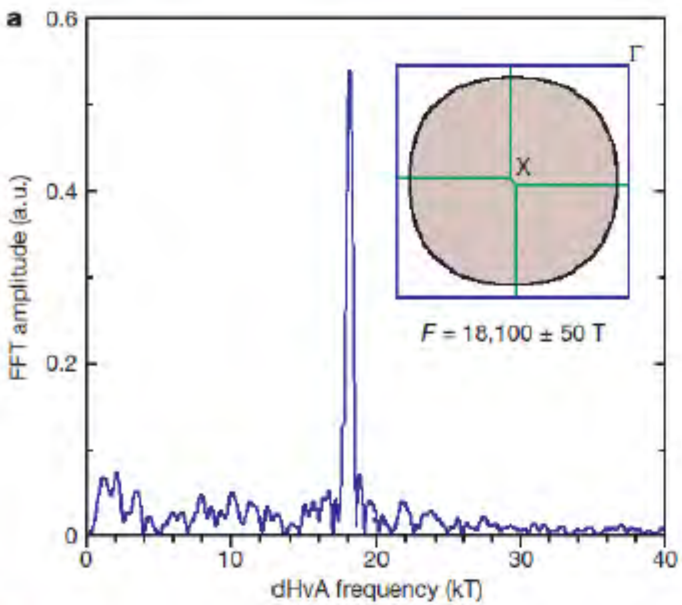
dopant atoms arranged in chains with correlation length > 100 Å

→ minimal disorder

First observation of quantum oscillations in a cuprate!

Quantum oscillations in cuprates

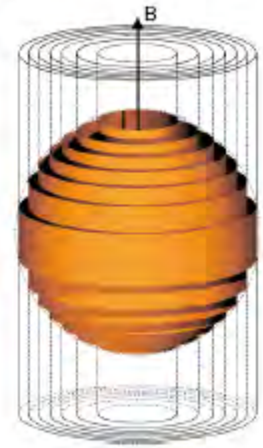
B. Vignolle et al., 2008



Landau quantization

$$\frac{\Delta R}{R} \propto R_T R_D \cos\left[2\pi\left(\frac{F}{B} - \gamma \frac{1}{j}\right)\right]$$

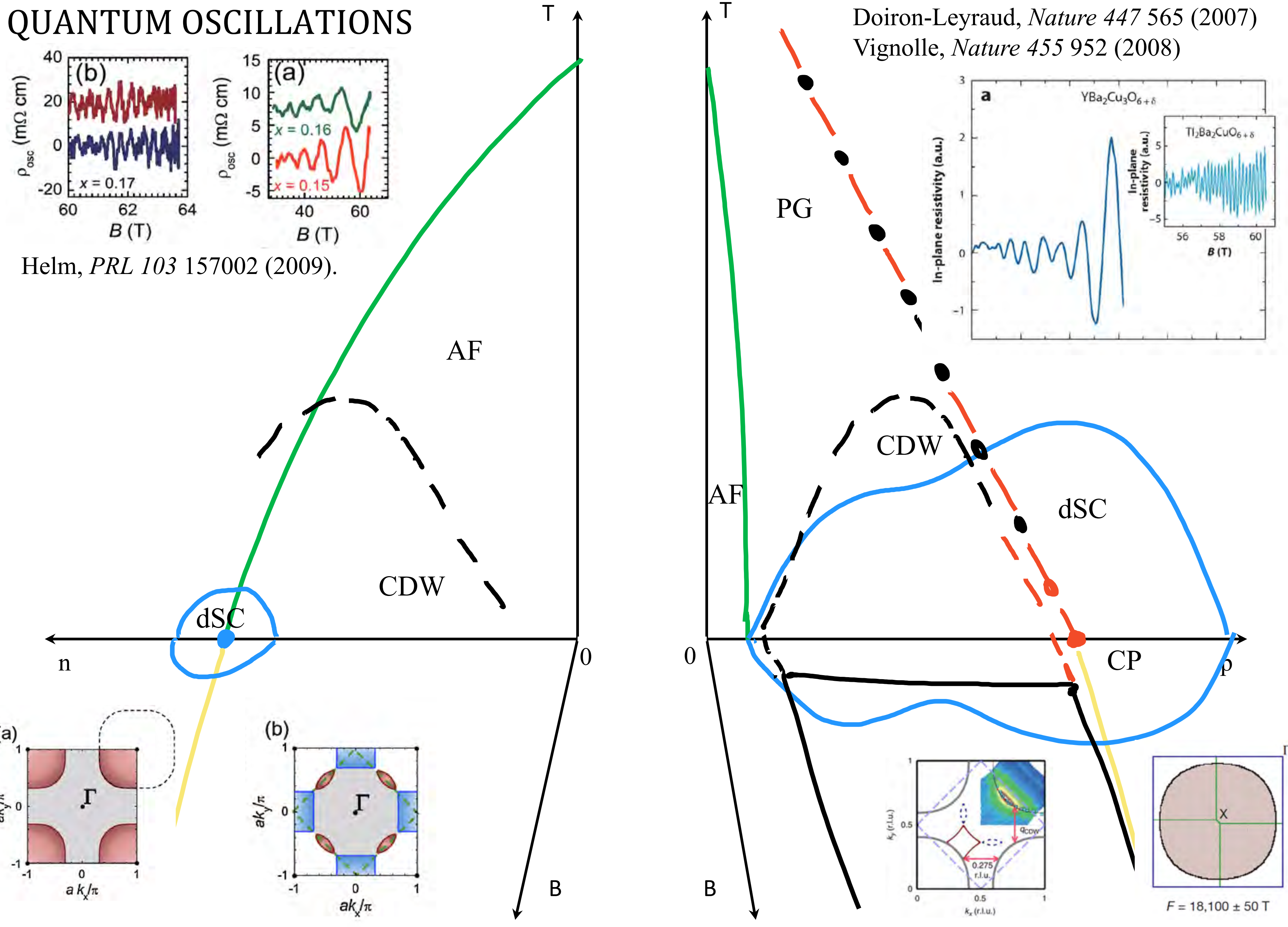
$$F = \frac{\Phi_0}{2\pi^2} A_k$$



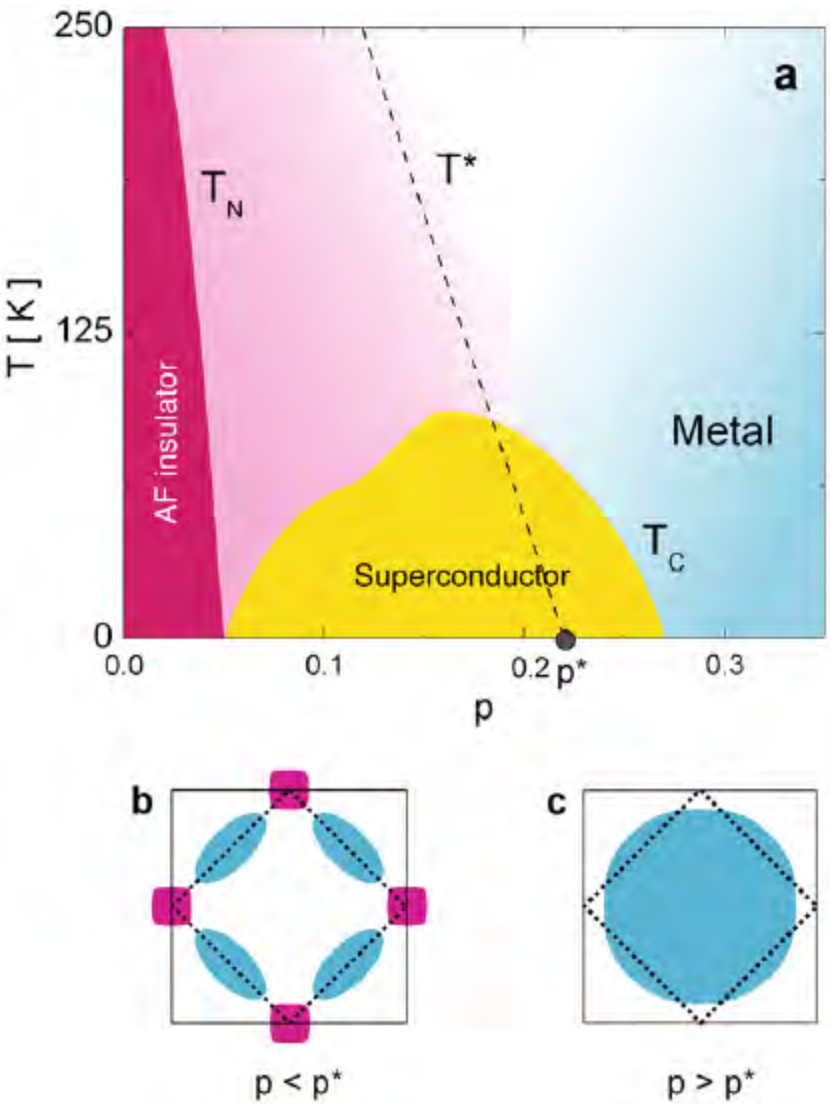
Overdoped Tl-2201 ***p*** **= 0.3**

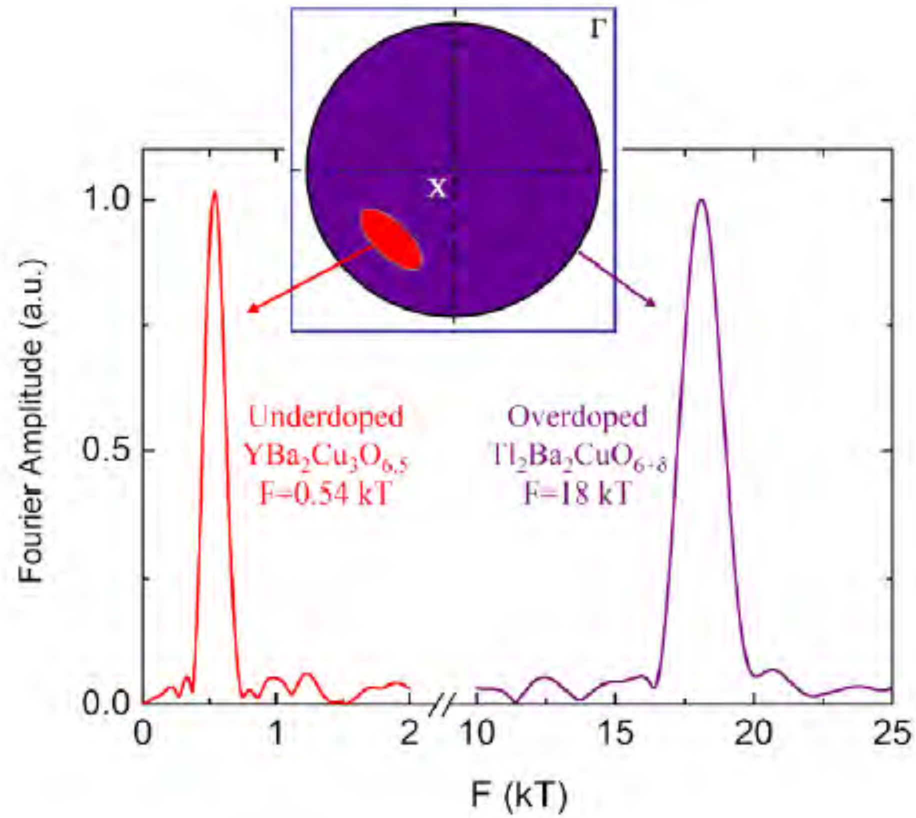
QUANTUM OSCILLATIONS

Doiron-Leyraud, *Nature 447* 565 (2007)
Vignolle, *Nature 455* 952 (2008)



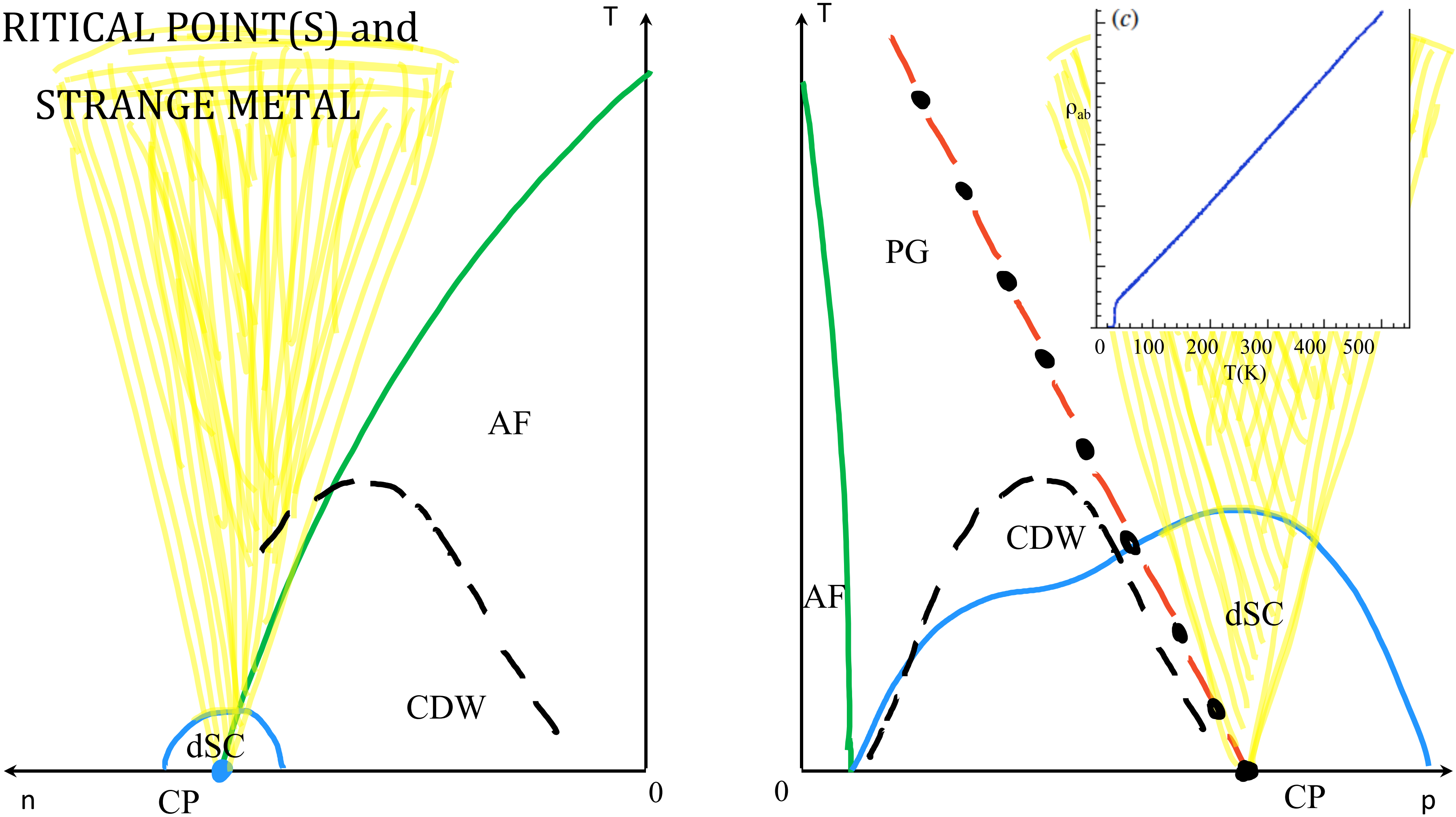
Fermi surface reconstruction from QO experiments in hole-doped cuprates





Figures from L. Taillefer, J. Phys. Cond. Matter 21, 164212 (2009)

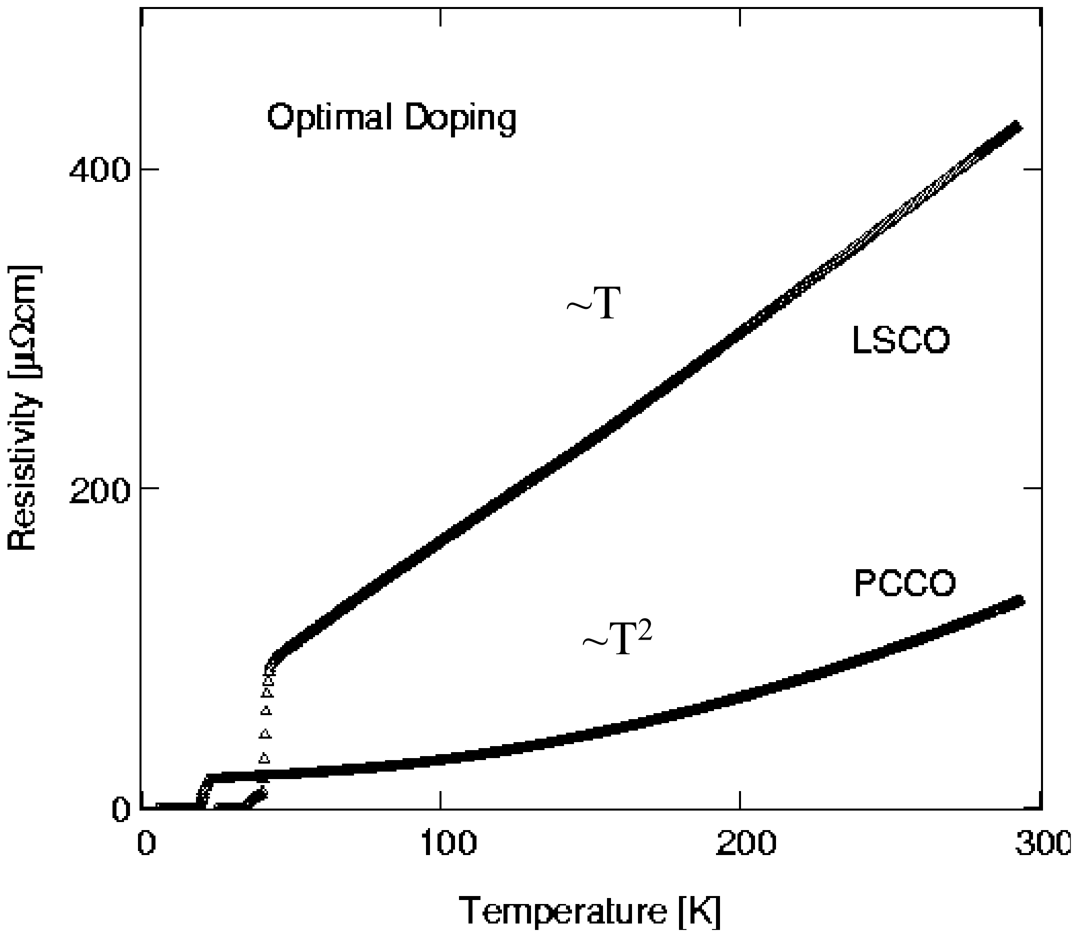
CRITICAL POINT(S) and STRANGE METAL



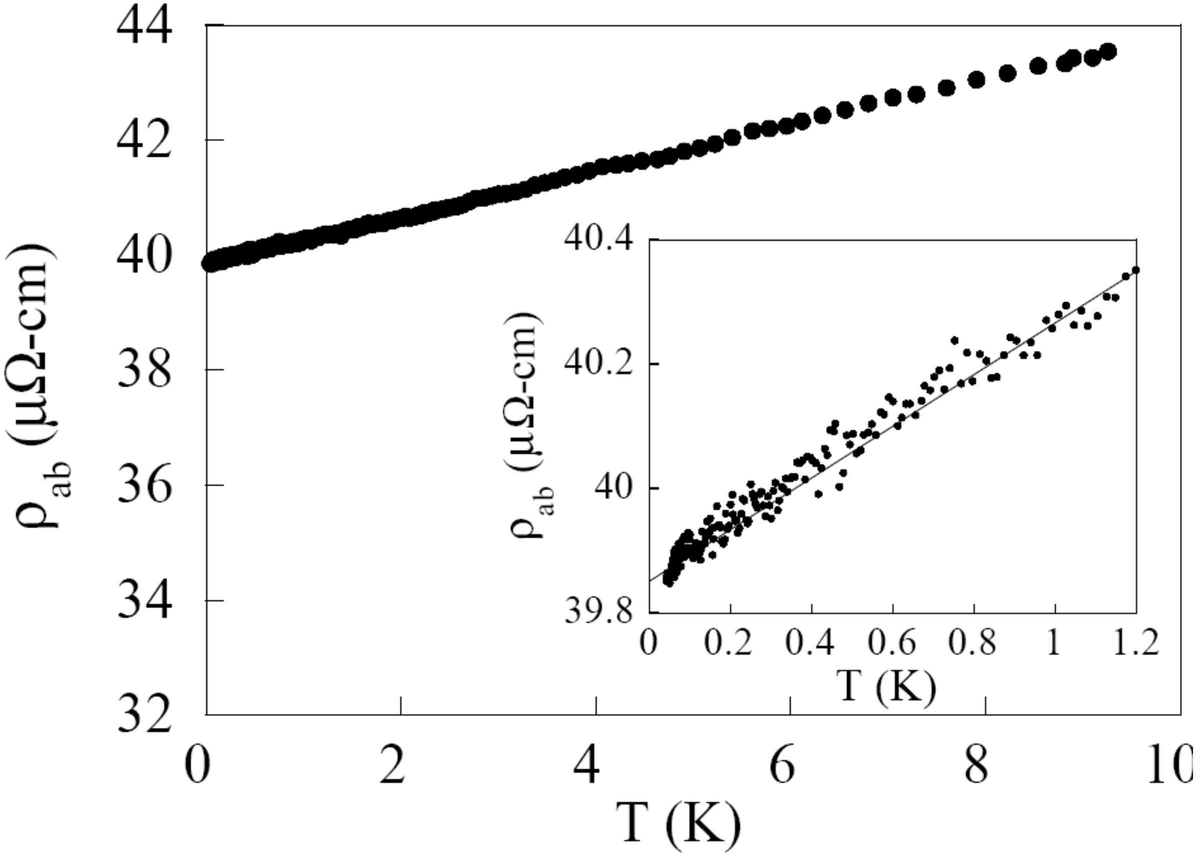
Bad Metal----resistivity exceeds the MIR limit

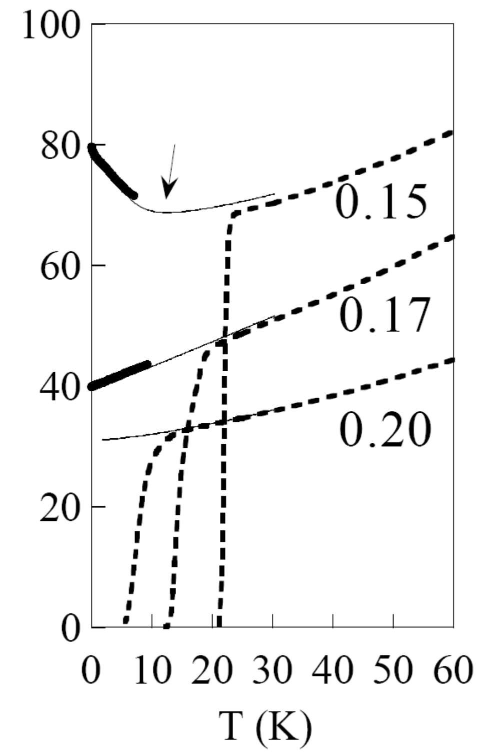
Anomalous Transport in Cuprates

Resistivity vs Temperature



Resistivity linear in T from 35mK to 10K in PCCO for Ce=0.17 at H=10T > Hc2

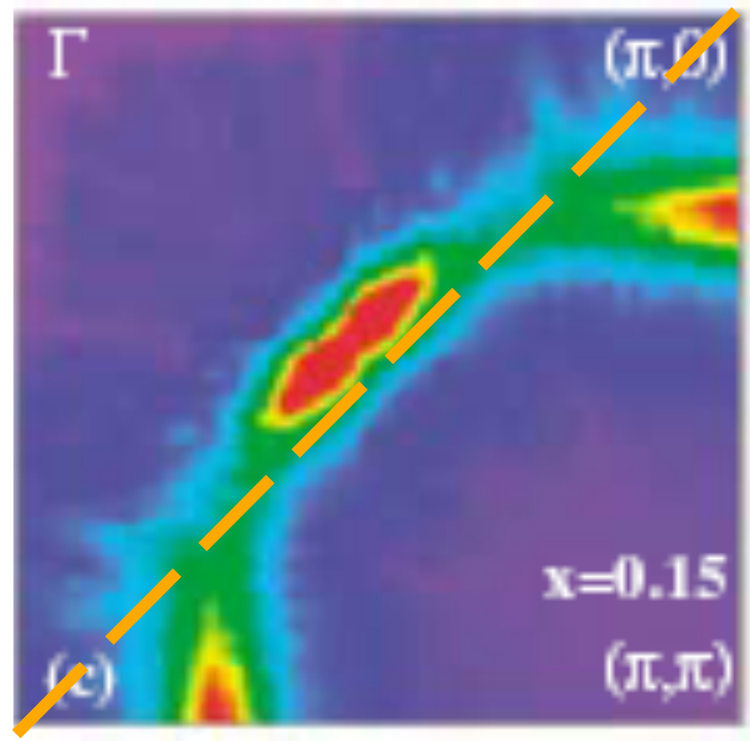




P. Fournier *et al.*, Phys. Rev. Lett. **81**, 4720 (1998).

What's the origin of the T-linear resistivity?

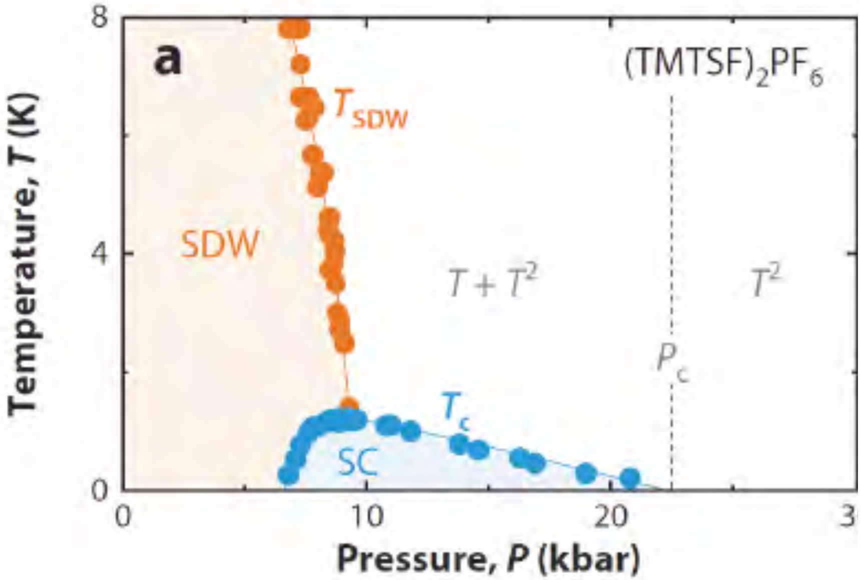
Scattering from (π , π) commensurate SDW fluctuations?

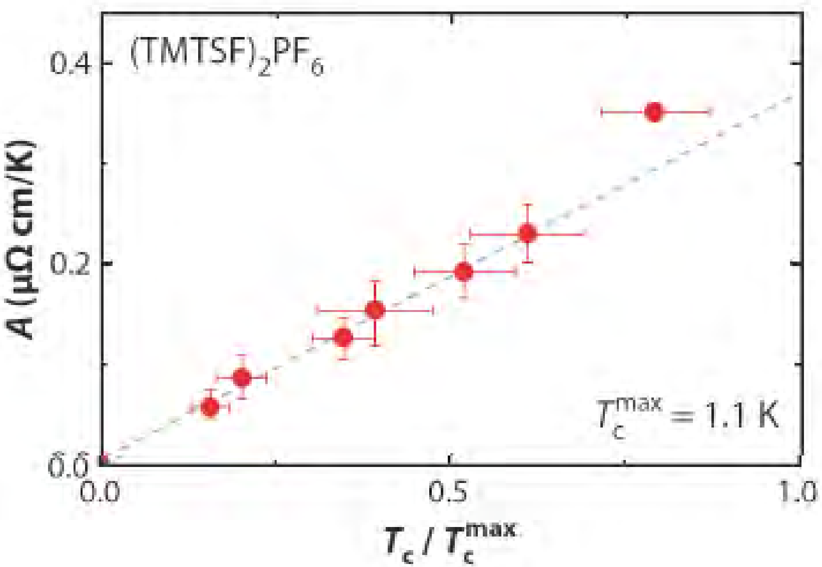


T. Moriya and K. Ueda *Adv. Phys.* **49**, 555 (2000).
N. P. Armitage *et.al. Phys. Rev. Lett.* **88**, 257001 (2002).
B. Kyung, *et.al. Phys. Rev. Lett.* **93**, 147004 (2004).
N.P. Armitage, P.Fournier and R.L. Greene, RMP 82, 2421 (2010)
C. Bourbonnais and A. Sedeki, *et.al. Phys. Rev. B* **80**, 085105 (2009).

Organics: Correlation between linear resistivity and Tc

Doiron-Leyraud et al., PRB **80**, 214531 (2009)

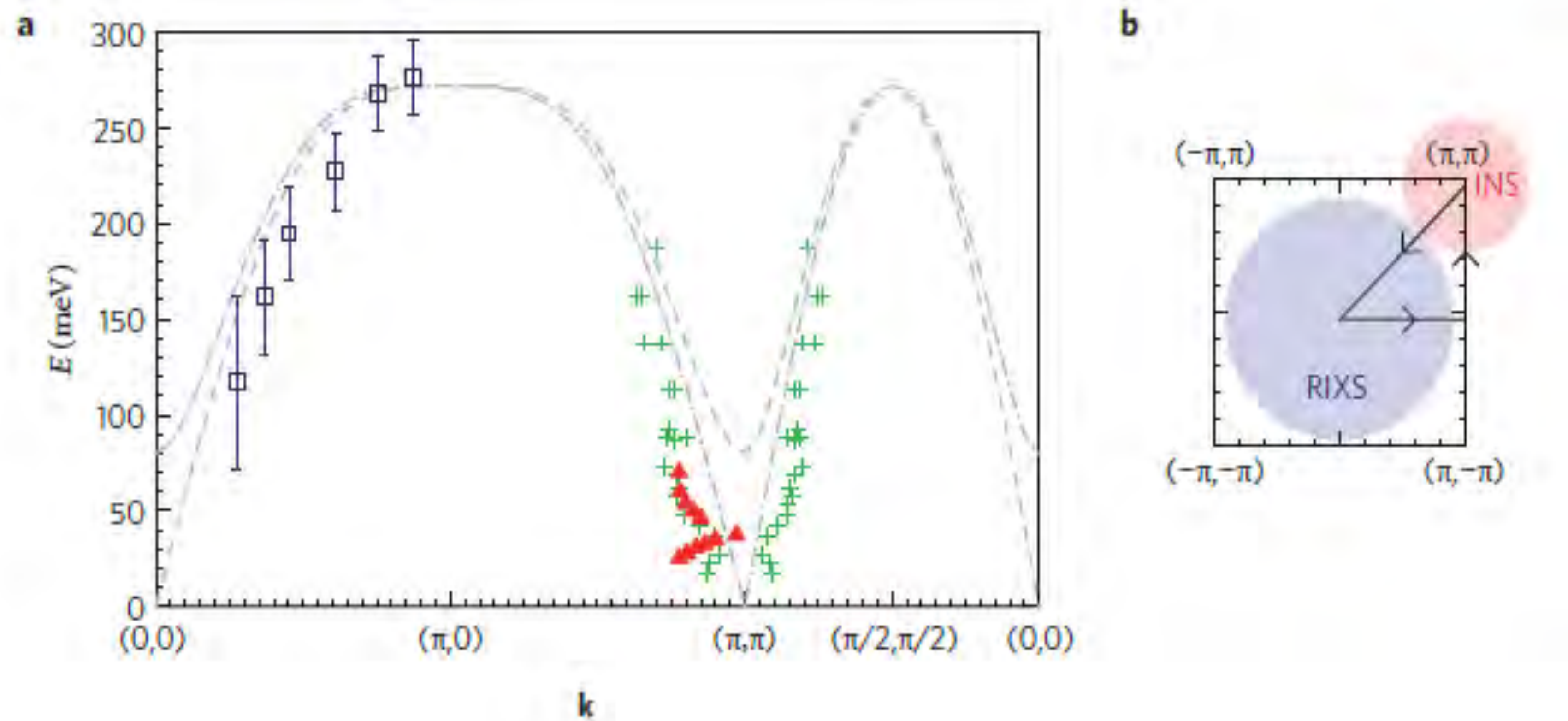




<u>Since only spin excitations dominate low temperature in n-type cuprates and organics, this suggests that T-linear resistivity is from their electron scattering and the superconductivity is also caused by magnetic interactions.</u>

RIXS and INS measured magnetic excitations in YBCO

Figure from: M. Vojta, Nature Physics 7, 674(2011)
RIXS data from: M. Le Tacon et al., Nature Physics 7, 725 (2011)



Spin excitations (paramagnons) are seen at all dopings in YBCO, LSCO, and n-doped PLCCO

My Opinion: In all cuprates the pairing is driven by AFM fluctuations!

Support for this comes from the RIXS study: M. Le Tacon et al., Nature Physics 7, 725 (2011)

Intense paramagnon excitations in a large family of high-temperature superconductors

low-energy excitations in a small range of momentum space. Here we use resonant inelastic X-ray scattering to show that a large family of superconductors, encompassing underdoped $YBa_2Cu_4O_8$ and overdoped $YBa_2Cu_3O_7$, exhibits damped spin excitations (paramagnons) with dispersions and spectral weights closely similar to those of magnons in undoped cuprates. The comprehensive experimental description of this surprisingly simple spectrum enables quantitative tests of magnetic Cooper pairing models. A numerical solution of the Eliashberg equations for the magnetic spectrum of $YBa_2Cu_3O_7$ reproduces its superconducting transition temperature within a factor of two, a level of agreement comparable to that of Eliashberg theories of conventional superconductors.

Other evidence: SC tunneling experiments show coupling to AFM excitations in both n-doped(Niestemski et al. Nature Physics 7, 719 (2011) and p-doped cuprates(Zasadzinski et al., PRL 2010).

Role of Phonons and Nematicity?

Oxygen isotope effect	Khasanov et al., PRL 92, 057602 (2004)
ARPES: Dispersion kink and oxygen isotope effect	Lanzara et al., Nature 412, 510 (01); 430, 187 (04)
ARPES: Anisotropic e-p interaction	Cuk et al., PRL 93, 117003 (2004); Devereaux et al., PRL 93, 117004 (2004)
Nematicity and intertwined orders	Fradkin, Kivelson, Tranquada, RMP 87, 457 (2015)
Nematic Tc boost	Lederer et al., PRL 114, 097001 (2015)

The e-p interaction can product HTSC, e.g., H_3S!!!

BIG questions remain

--What causes the Cooper pairing in HTSC?

What is the Electronic Dark Matter?

--How to explain the strange and bad-metal normal state?

--What causes the PG (T* crossover) and does it matter for the Cooper pairing?

Many ideas

Jahn-Teller polarons
Interlayer tunneling
Resonating valence bonds
Spin fluctuations
Stripes
Nematic fluctuations
Intertwined orders
Loop currents
Amperion currents

YES---I predict there will be a room temperature SC found within the next 30 years

.

The End

Thanks for your attention and patience