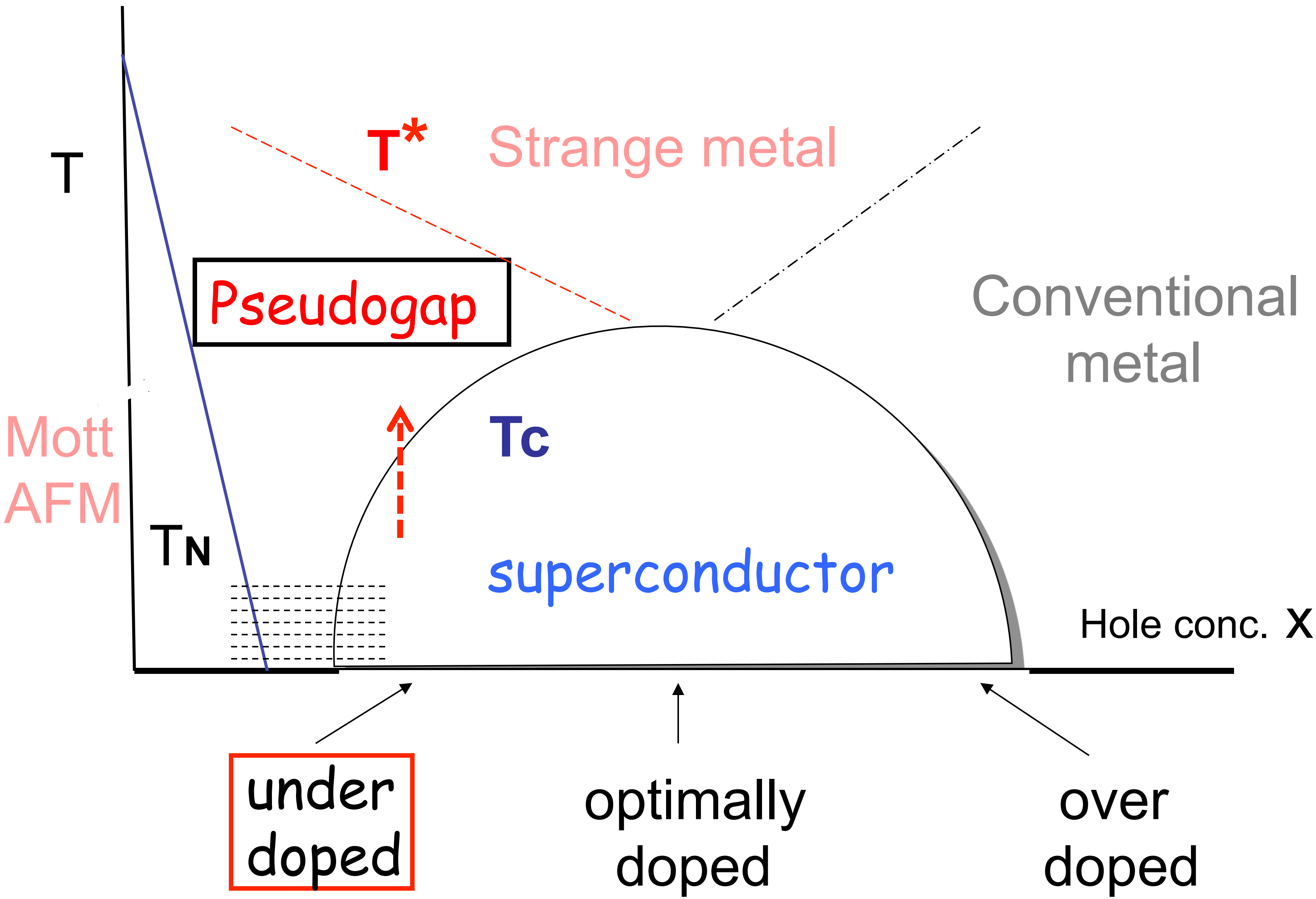
Lecture # 2

Phenomenology of High Tc Cuprates II

Pseudogap in Underdoped Cuprates

Mohit Randeria
Ohio State University

2014 Boulder School on
"Modern aspects of
Superconductivity"


T
T*
Strange metal
Pseudogap
Conventional metal
Mott AFM
Tc
TN
superconductor
Hole conc. X
under doped
optimally doped
over doped

Pseudogap in Underdoped Cuprates

- Underdoped SC state: gap anisotropy
- What determines Tc? Gap or superfluid density?

- Pseudogap above Tc
    -- specific heat, NMR, optics, STM
- ARPES & Fermi arcs

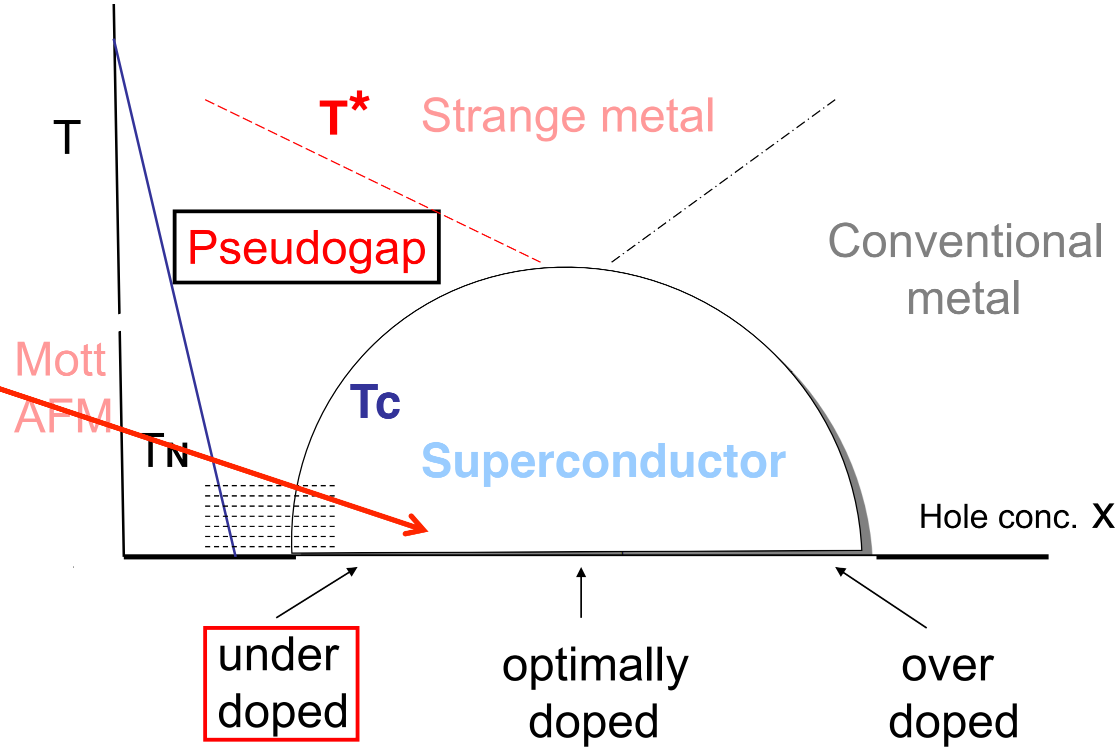
- SC fluctuations above Tc

- Quantum Oscillations

- Competing orders

(Borrowed from P. A. Lee)

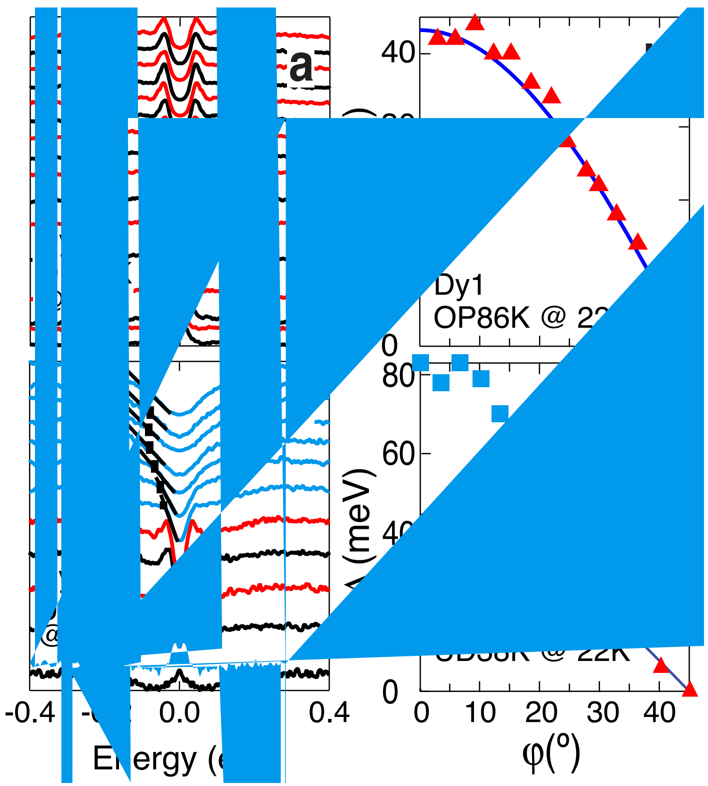
Start with
SC state as a function of underdoping
$T < T_c$
$x <$ optimal



* ARPES gap $\Delta(\mathbf{k})$ → antinodal gap $\Delta_{\max}$
  gap slope at node v_Δ

* Transport vs. ARPES $v_F, \; v_\Delta$

* Superfluid density $n_s/m^{\sqcup}$

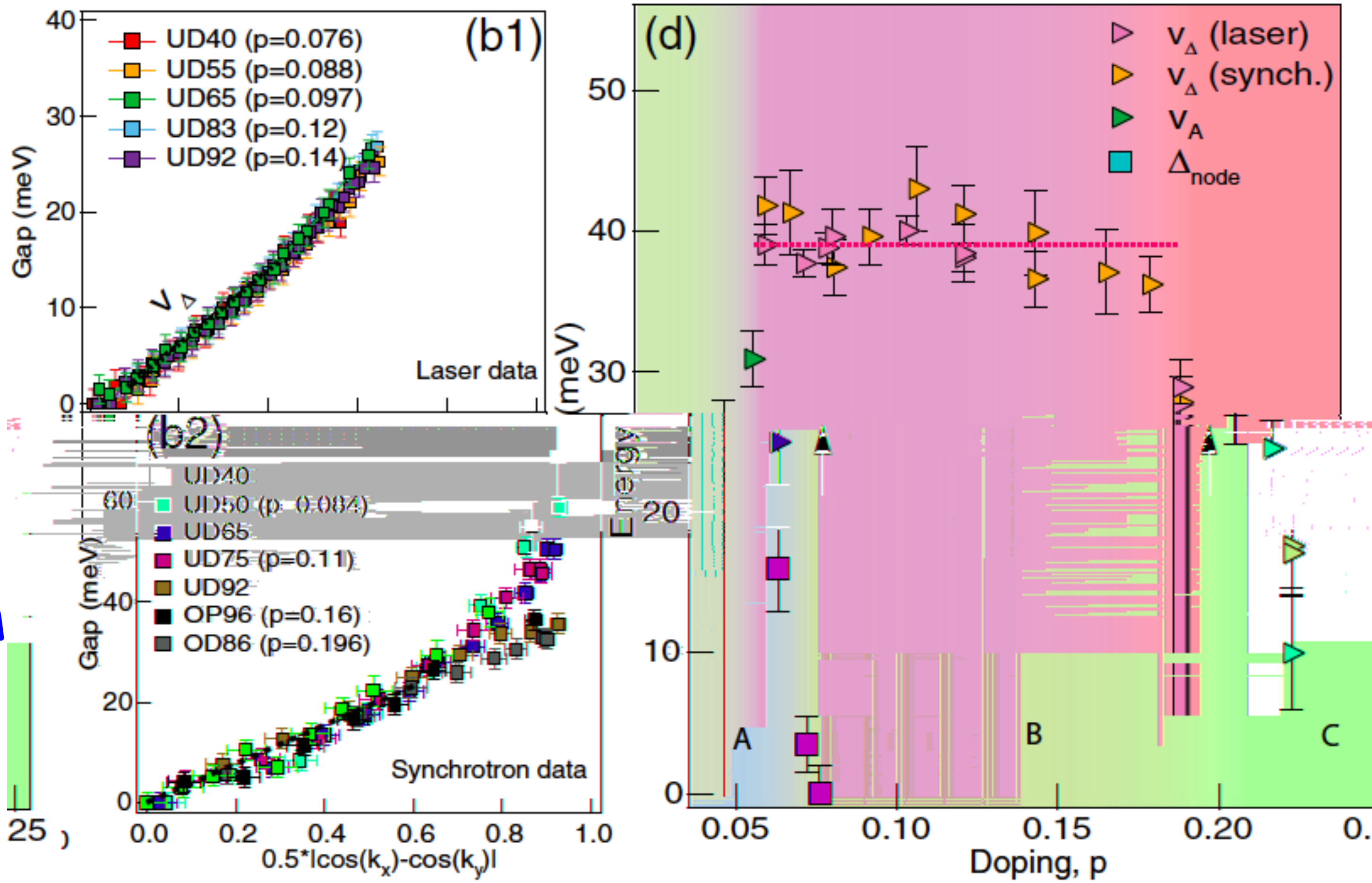


a
Dy1
OP86K @ 22
UD38K @ 22K
(meV)
-0.4
0.0
0.4
Energy (e
0
40
0
20
40
60
80
0
10
20
30
40
φ(°)

Gap anisotropy & gap-slope v_Δ with underdoping

constant gap-slope at node over broad underdoping range

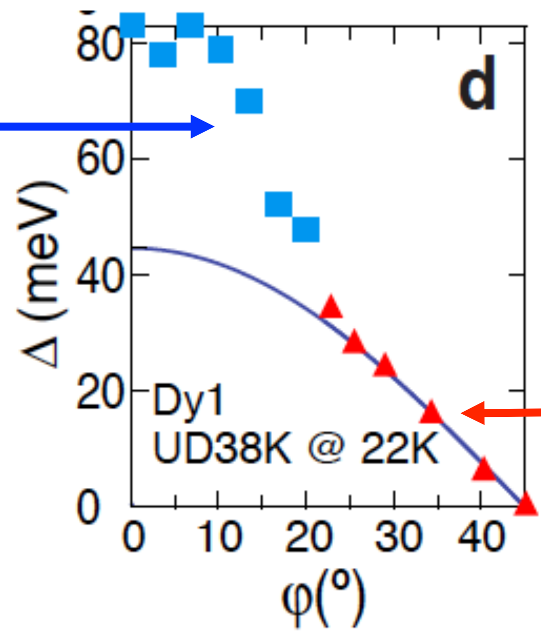
Systematic deviation from simple d-wave $\Delta(k)$ with underdoping



I. Vishik et al, PNAS 109, 18332 (2012)

Terminology commonly used in the literature to describe the energy gap for T << Tc (which may be potentially confusing)

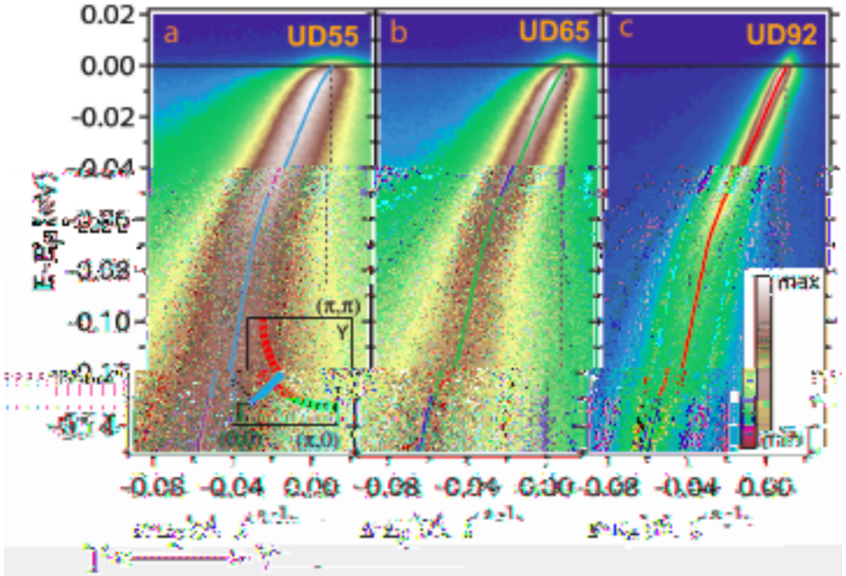
Antinodal gap is called the "Pseudogap" (because it persists above Tc in the Pseudogap Regime)

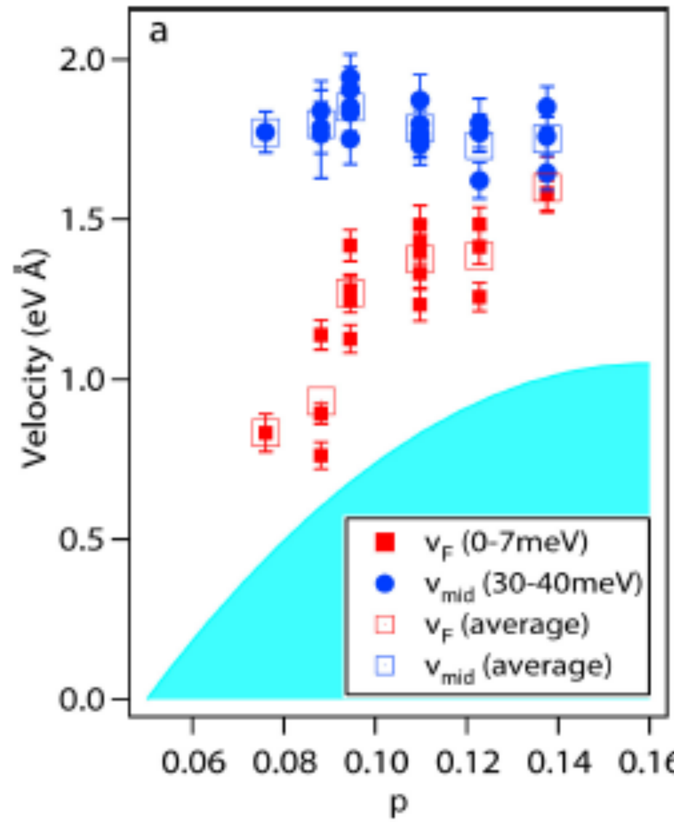


Near-nodal gap is called the "Superconducting Gap"

Is antinodal gap caused by some other Order parameter?

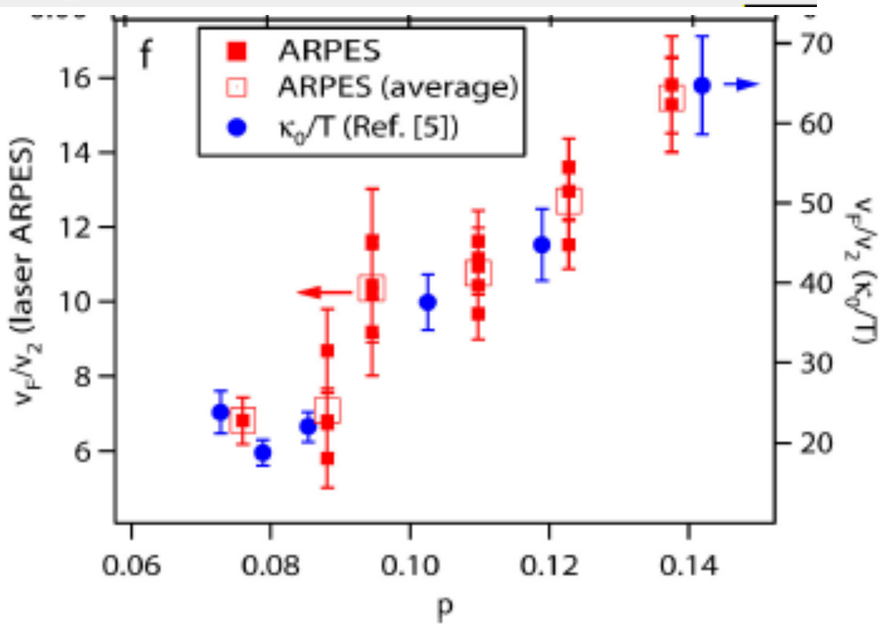
$v_F, \ v_\Delta$ from ARPES & thermal transport





"old"

"new"
laser
ARPES



Qualitative
agreement between
ARPES & transport

Vishik et al, PRL 104 207002 (2010)

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* Antinodal gap $\Delta_{\max}$ increases
* gap slope at node v_Δ constant
* Tc decreases with underdoping

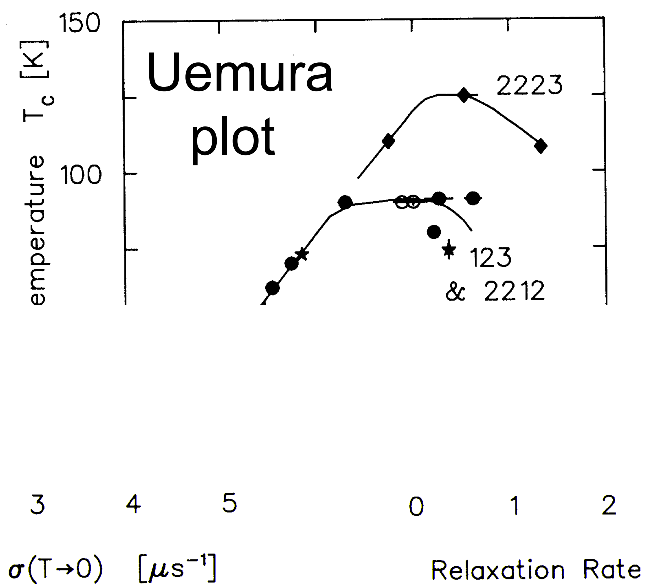
No part of the Energy gap correlates with doping dependent Tc

cf. BCS 2Δ/Tc

If not the gap, then what determines T_c?

Phase fluctuations destroy superconductivity

Emery & Kivelson, Nature (1995)

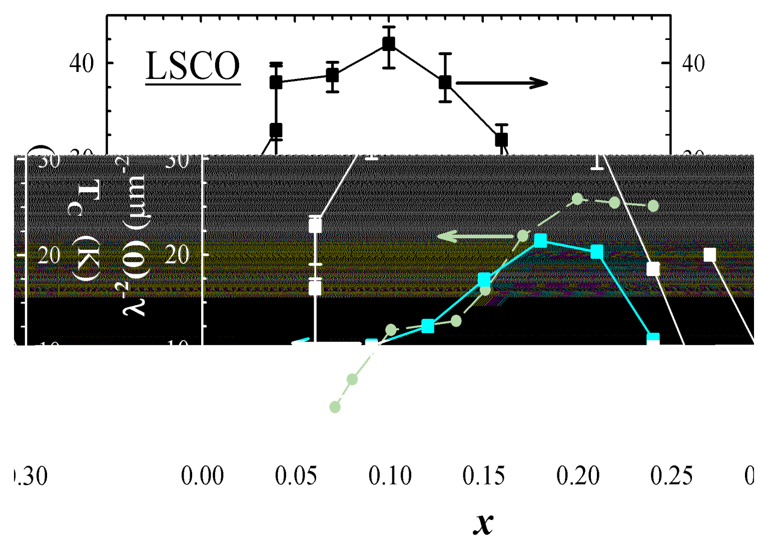


Uemura et al, PRL (1989)

Superfluid stiffness ρ_s

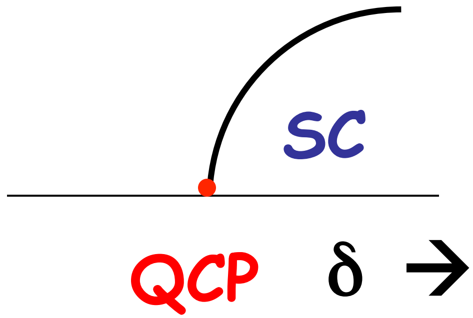
$$T_c \sim \rho_s$$

$$\rho_s = \frac{n_s}{m^*}$$



Lemberger et al, PRB (2010)

Scaling of Tc and Superfluid Density near a QCP



$$T_c \propto \delta^{z\nu}$$

$$\rho_s \propto \delta^{(z+d-2)\nu}$$

$$T_c \sim \rho_s^{z/(z+d-2)}$$

d = spatial dim.

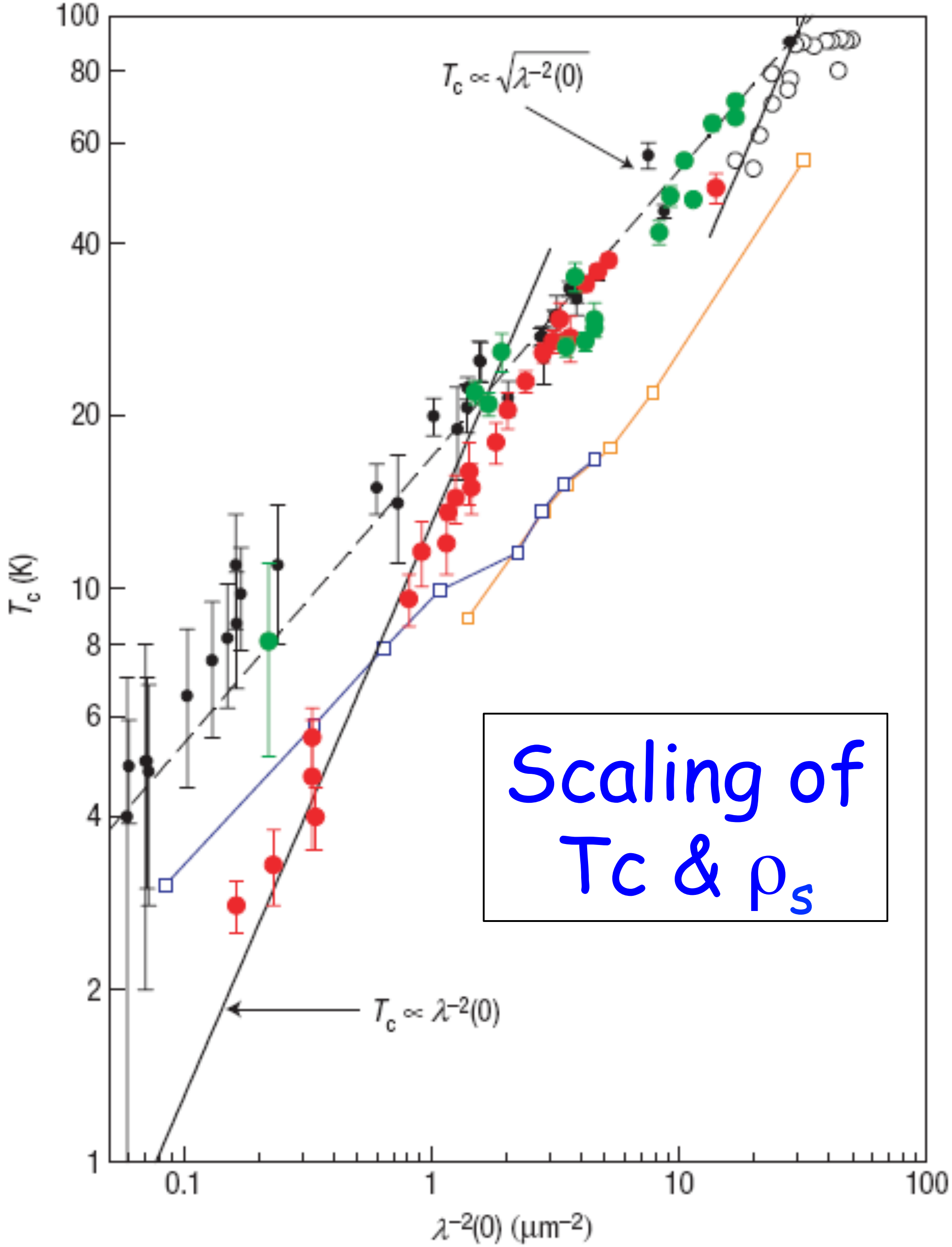
$$d = 3$$

$$T_c \sim \rho_s^{z/(z+1)}$$

$$z \geq 1$$

$$d = 2$$

$$T_c \sim \rho_s$$



○ Uemura

□ Bonn & Hardy single x'tals

$$T_c \sim \sqrt{\rho_s}$$

● Lemberger 40 u.c. films

● Lemberger 2 u.c. films

$$T_c \sim \rho_s$$

Hetel, Lemberger & Randeria, Nature Phys. **3**, 700 (2007)
Broun et al., PRL (2007)

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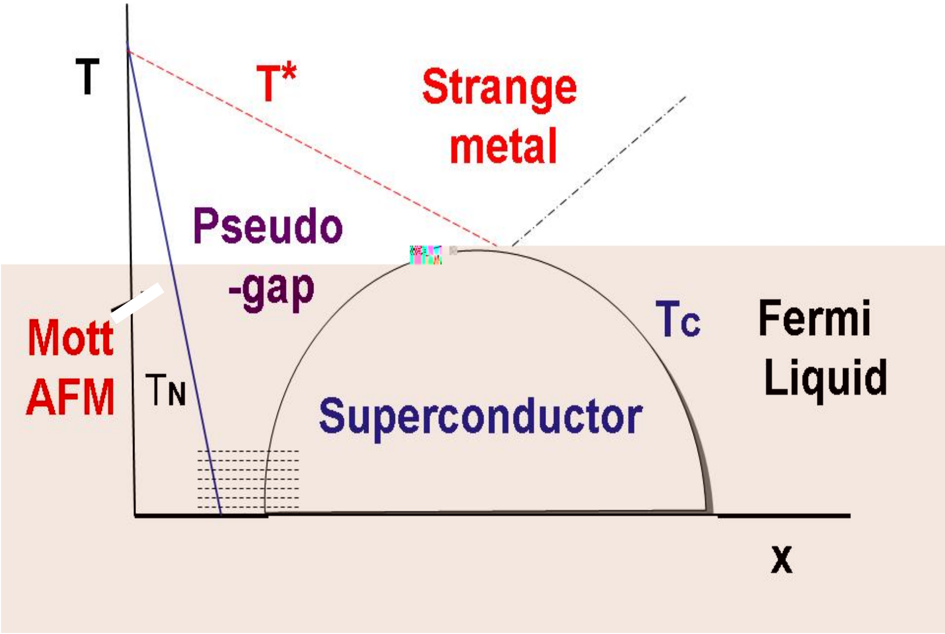
What happens above Tc?

The pseudogap for underdoped cuprates

↓

Loss of low-energy spectral weight } Highly anisotropic Gap persists up to T*, well above Tc

* Spin
* Charge
* Entropy
* Single-particle spectral function

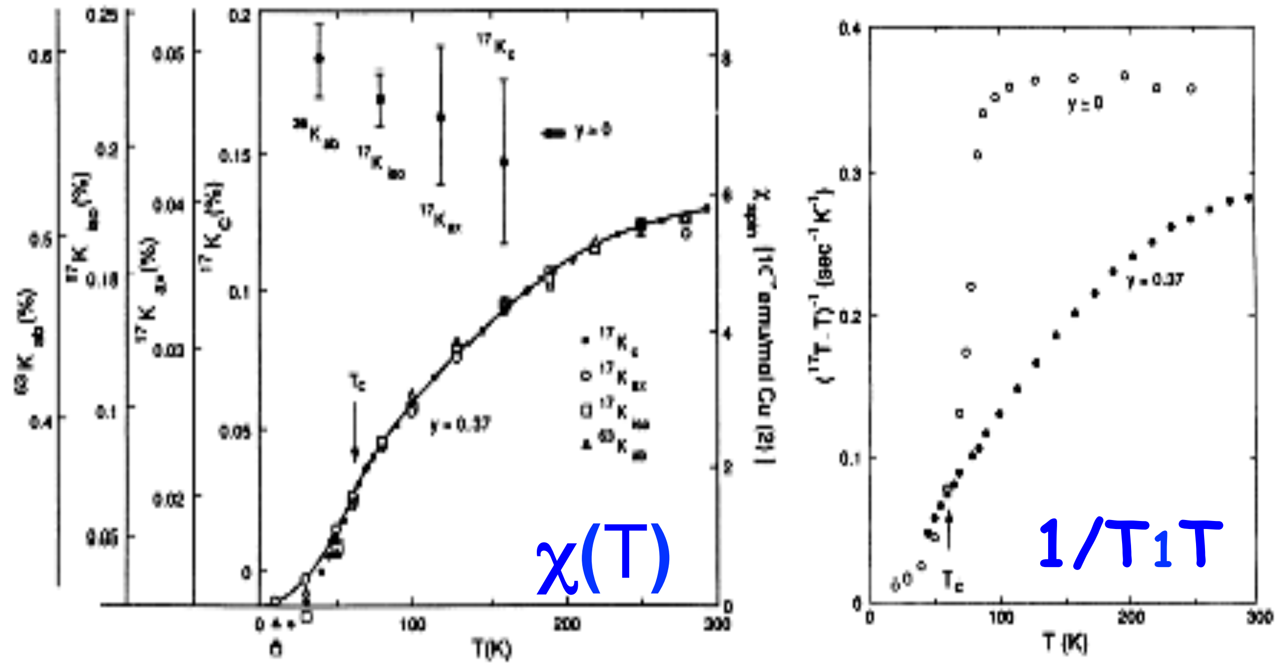


PHYSICAL REVIEW B VOLUME 43, NUMBER 1 1 JANUARY 1991

Cu and O NMR studies of the magnetic properties of $YBa_2Cu_3O_{6.63}$ ($T_c = 62$ K)

M. Takigawa,* A. P. Reyes,† P. C. Hammel, J. D. Thompson, R. H. Heffner, Z. Fisk, and K. C. Ott

Pseudogap:
Loss of Spectral Weight For low energy Spin excitations Above Tc



$$1/T_1T = \lim_{\omega \to 0} \sum_{q} F(q) \chi''(q,\omega)/\omega$$

$$1/T_1T \sim \chi(T)$$

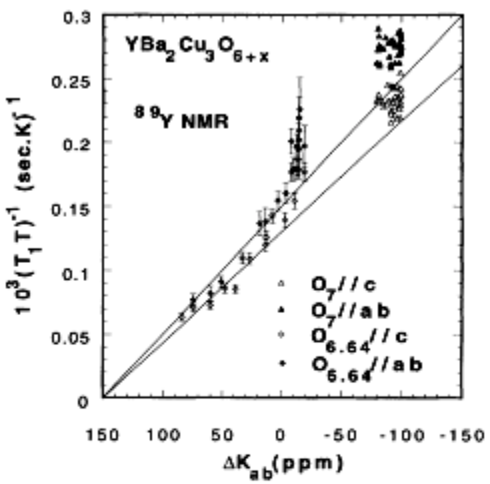


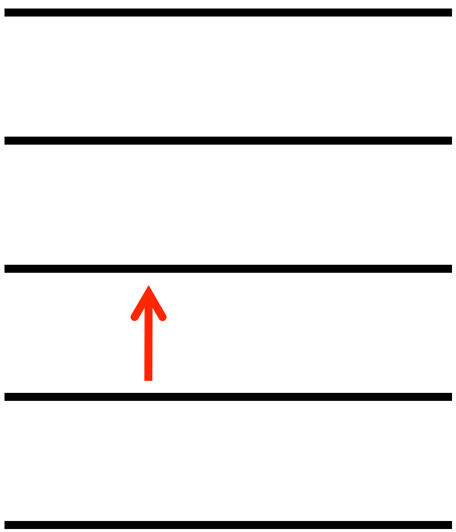
FIG. 4. The data for $(T_1T)^{-1}$ vs ΔK_{ab} for the two samples. Linear relations hold for the data for $T < 300$ K for the $x = 0.64$ sample and extend nearly through the results for $x = 1$. Those plotted here have been forced to extrapolate to zero for $K_{ab} = \delta_{ab} = 150$ ppm.

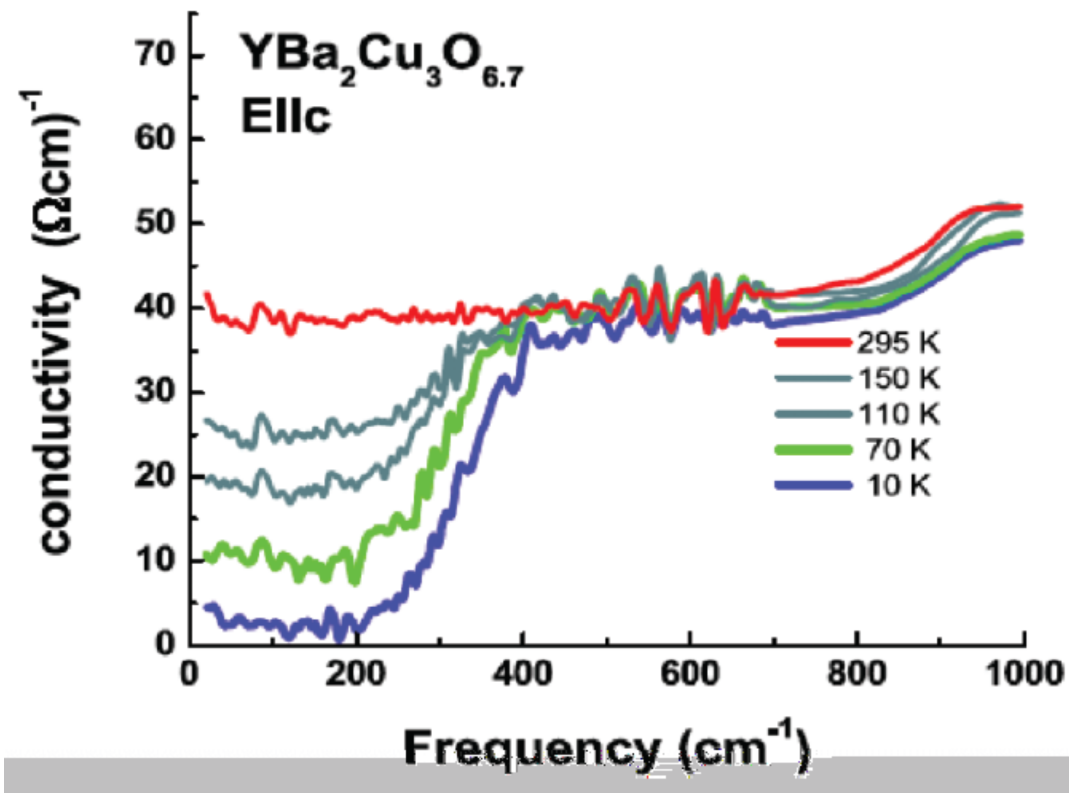
LUME 70, NUMBER 8 PHYSICAL REVIEW LETTERS 22 FEBRUARY 1993

^{89}Y NMR Study of the Anisotropy of the Static and Dynamic Susceptibilities in $YBa_2Cu_3O_{6+x}$

H. Alloul, A. Mahajan, H. Casalta, and O. Klein[a]

Pseudogap in Transport: c-axis optical conductivity





Homes et al, PRL (1993)

c-axis transport dominated by tunneling near the antinode

$$t_\perp(\mathbf{k}) \sim (\cos k_x - \cos k_y)^2$$

* Much more subtle changes in ab-plane optical conductivity see Basov-Timusk RMP (2005)

Pseudogap → Loss of entropy <u>above</u> Tc in Underdoped cuprates

VOLUME 71, NUMBER 11 PHYSICAL REVIEW LETTERS 13 SEPTEMBER 1993

Electronic Specific Heat of $YBa_2Cu_3O_{6+x}$ from 1.8 to 300 K

J. W. Loram, K. A. Mirza, J. R. Cooper, and W. Y. Liang

Specific heat → Entropy

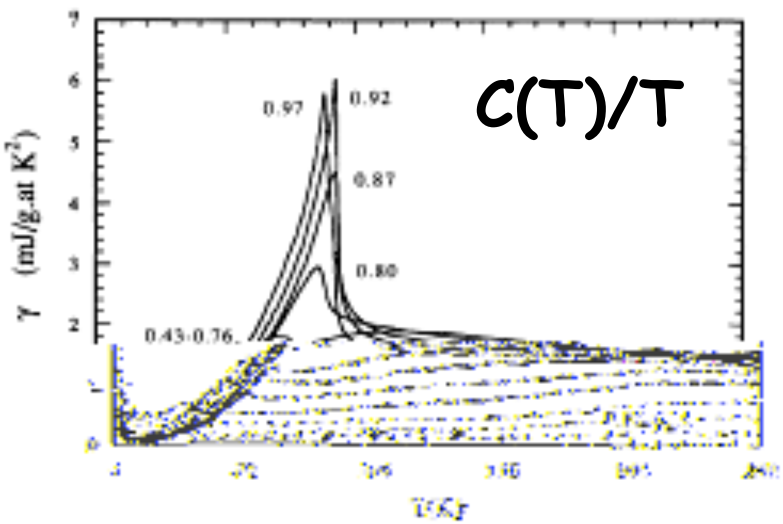


FIG. 4. Electronic specific heat coefficient γ(x,T) vs T for $YBa_2Cu_3O_{6+x}$ relative to $YBa_2Cu_3O_6$. Values of x are 0.16, 0.29, 0.38, 0.43, 0.48, 0.57, 0.63, 0.76, 0.80, 0.87, 0.92, and 0.97.

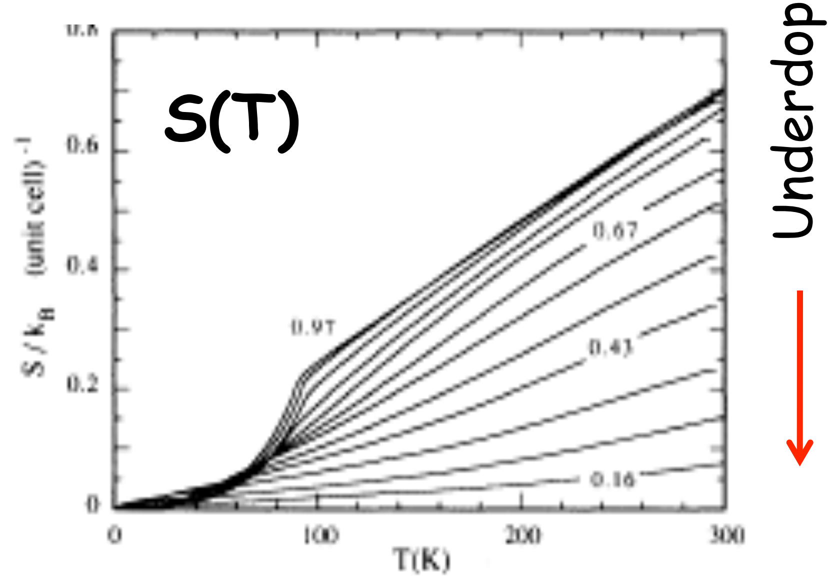


FIG. 5. Electronic entropy $S(x,T)$ for $YBa_2Cu_3O_{6+x}$. Values of x as in Fig. 4.

Pseudogap in Tunneling (STM):

Energy gap above Tc

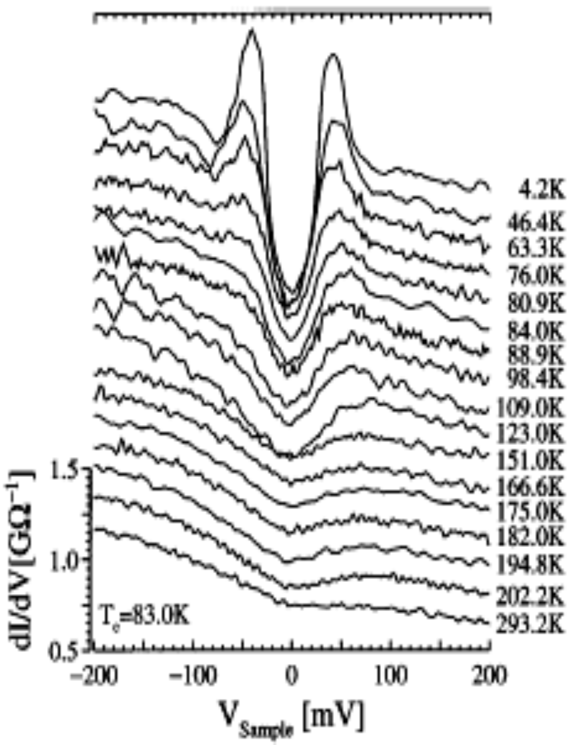
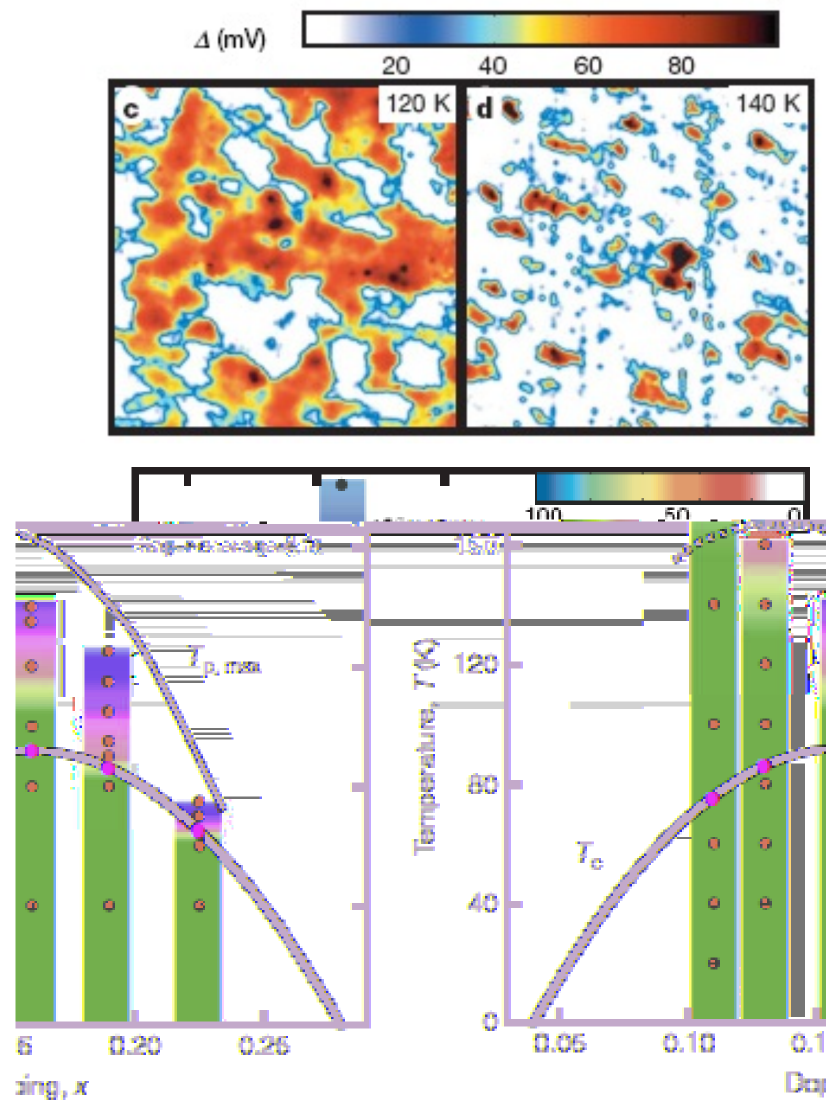


FIG. 2. Tunneling spectra measured as a function of temperature on underdoped Bi2212. The conductance scale corresponds to the 293 K spectrum, the other spectra are offset vertically for clarity.

Ch. Renner et al, PRL (1998)



K. Gomes et al, Nature (2007)

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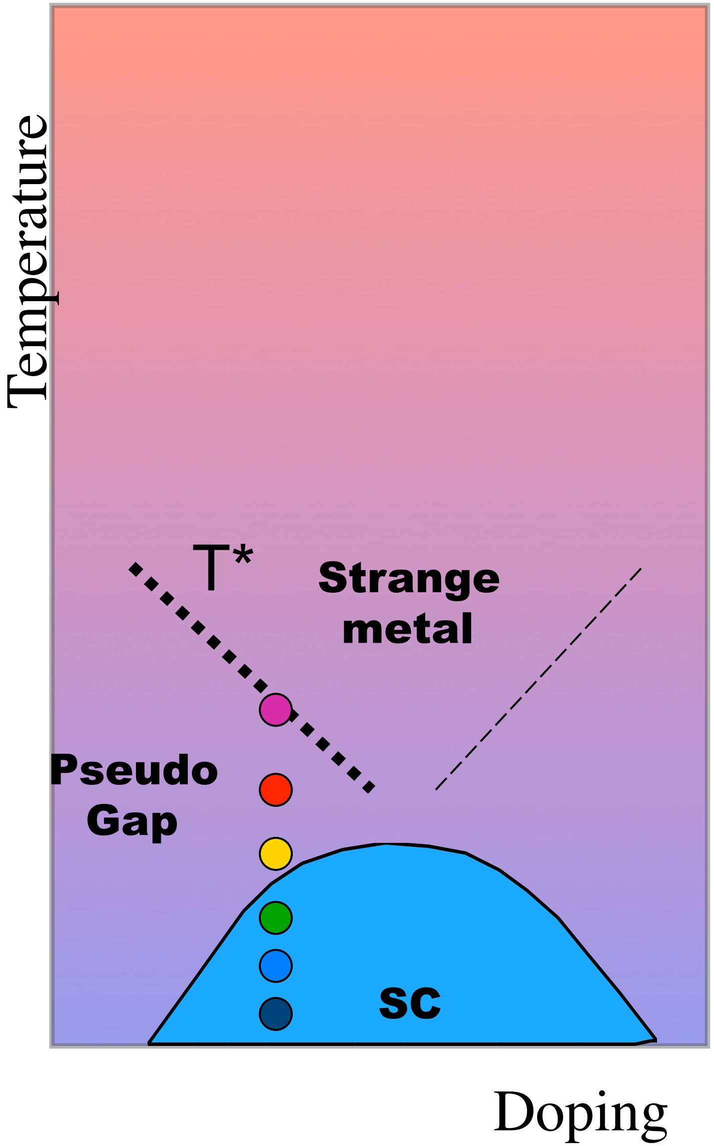
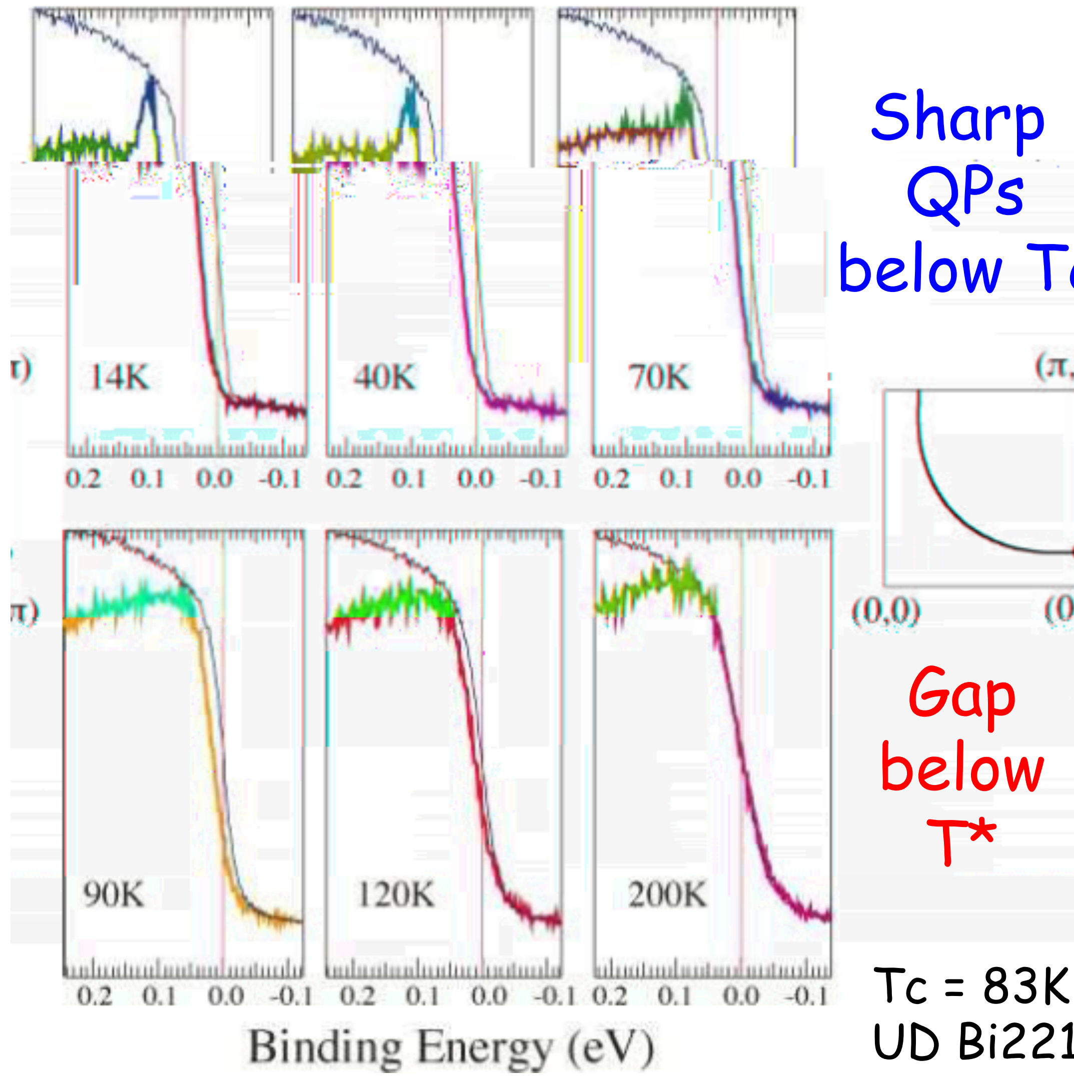
ARPES Pseudogap in UD Cuprates: Tc < T < T*





Sharp QPs below Tc

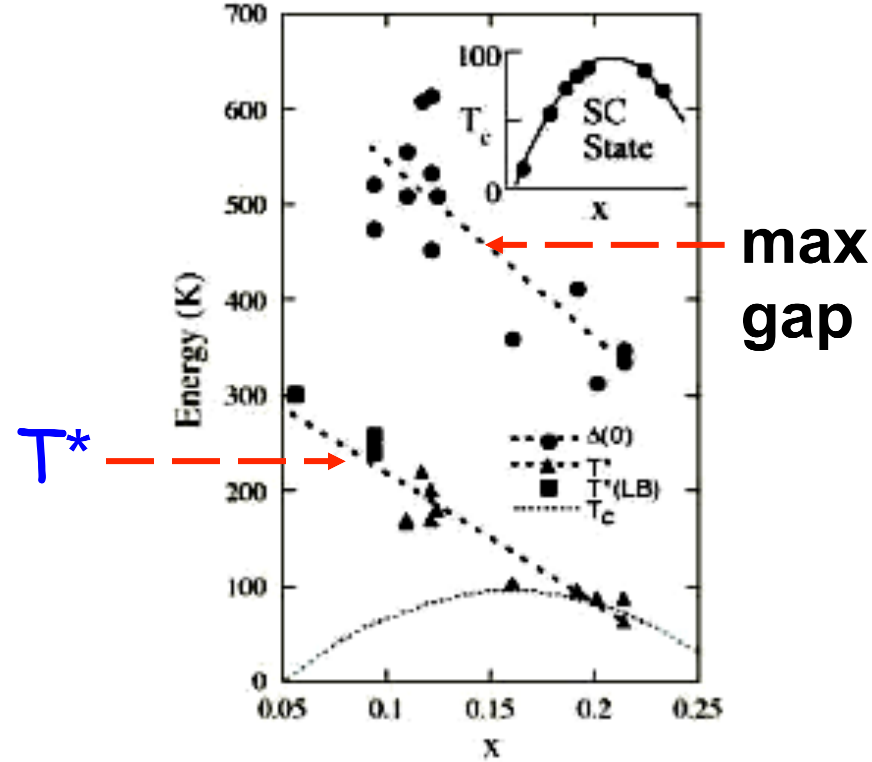
Gap below T*

Tc = 83K
UD Bi2212

Ding et al, Nature **382**, 51 (1996)
See also: Loesser et al, Science (1996)

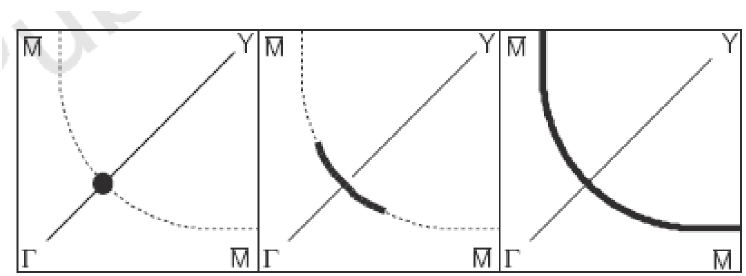
Pseudogap:
Suppression of low-energy spectral weight above Tc

- PG near antinode ~T-indep.
- PG appears below a temp. T* which scales with gap
- PG is strongly anisotropic. Anisotropy is T-dependent → "Fermi arcs"



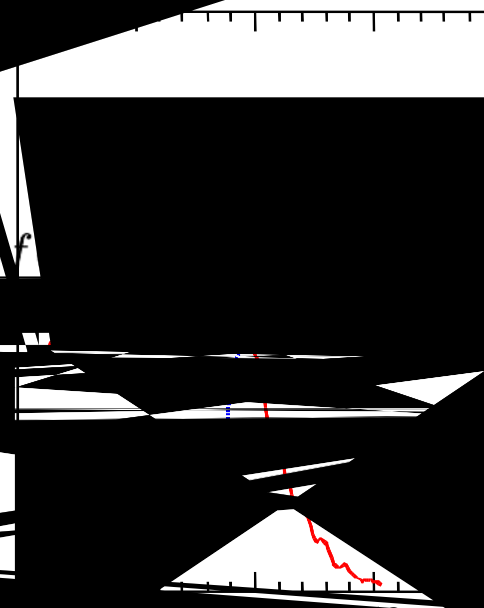
Campuzano et al, PRL 83, 3709 (1999)

Norman et al, Nature 392, 157 (1998)



$T \ll T_c$ $T_c < T < T^*$ $T > T^*$

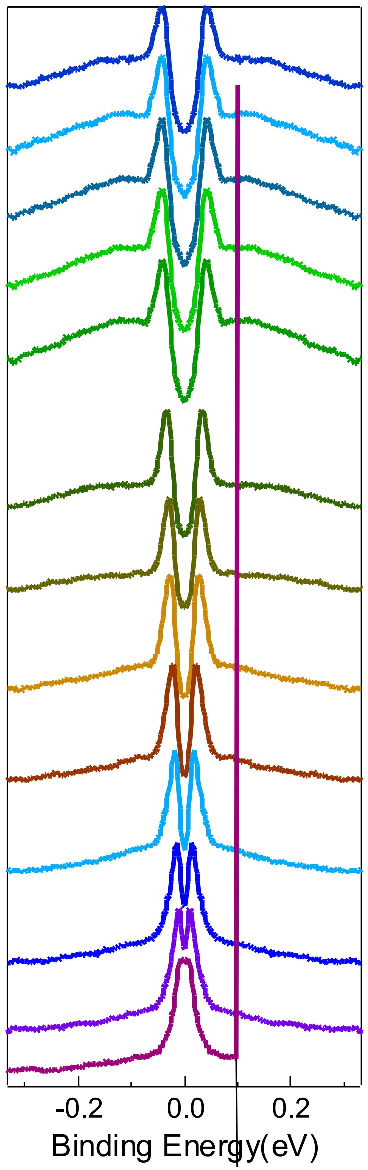
$I(\omega) = A(\mathbf{k},\omega) f$ … $\omega) = A(\mathbf{k},-\omega) f(-\omega)$



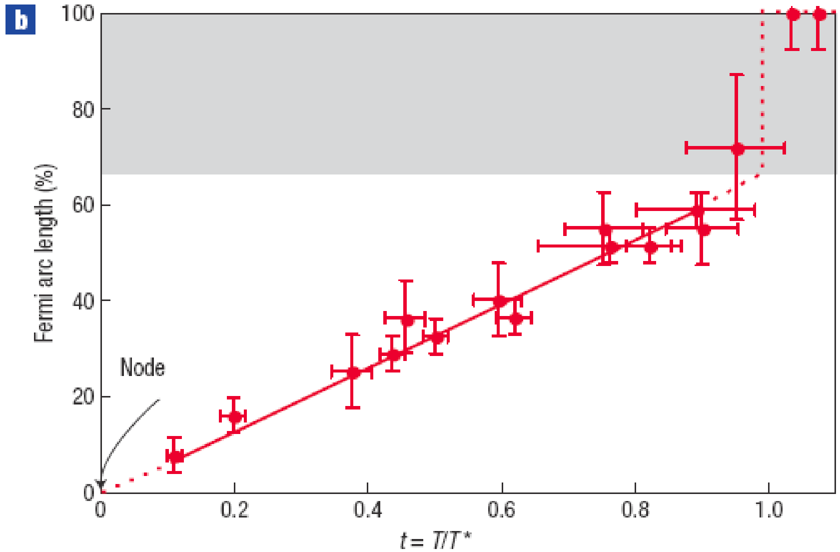
… $f(-\omega)$ … $[1 - f(\omega)]$

Binding energy (meV)

Momentum dependence of the gap

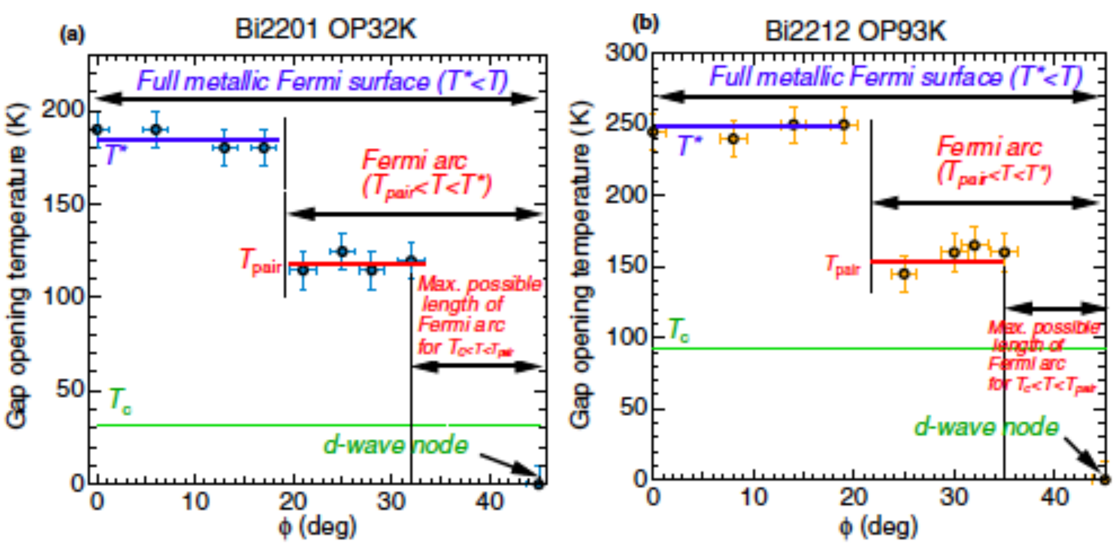


T-dependence of the "Fermi arcs"



Scaling with $t = T/T^*(\phi)$

Kanigel *et al*,
Nature Phys. (2006)

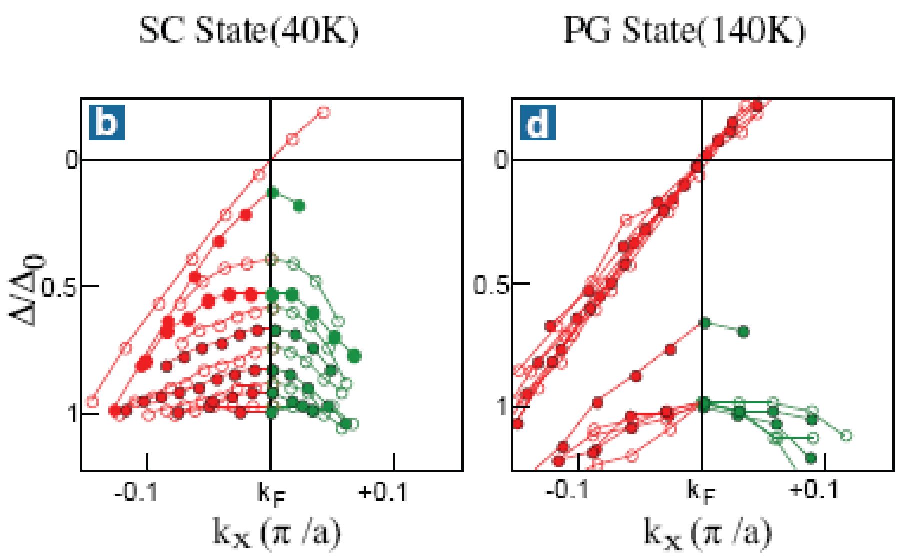


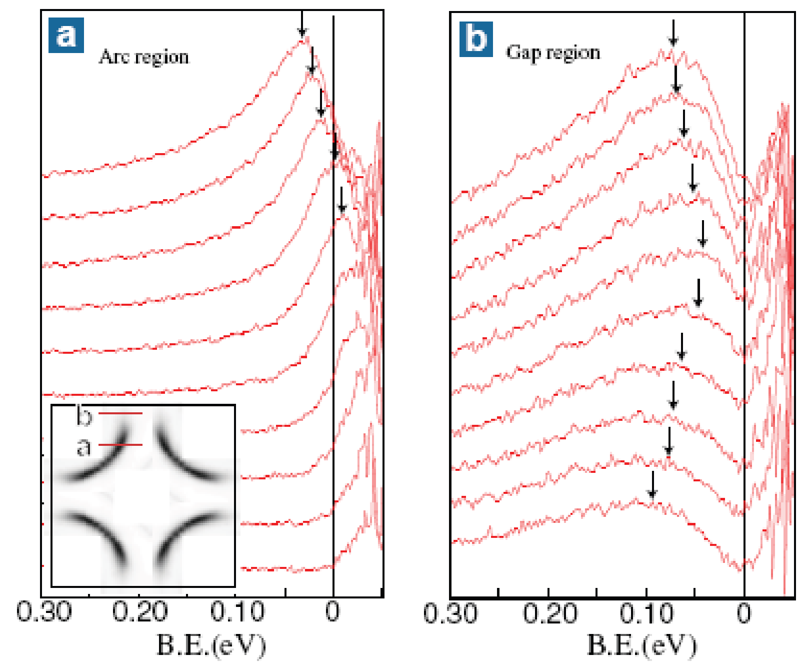
Different conclusions
From a different way
of analyzing the data

Kondo et al, PRL 111, 157003 (2013)

Bogoliubov-like dispersion in Pseudogap

Kanigel, et al, PRL (2008)

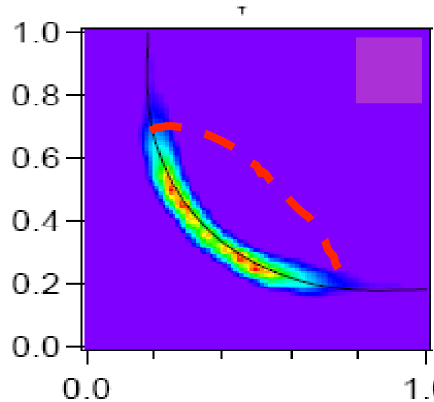




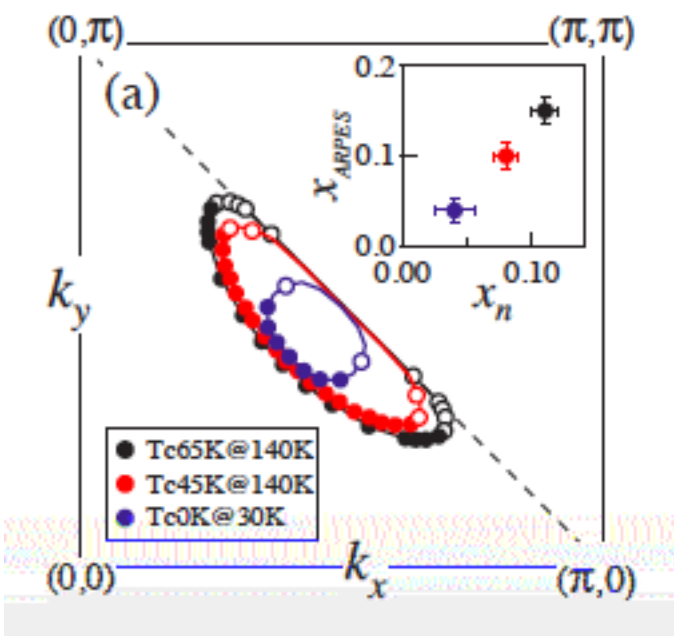
Dispersion through Ef on the arc

Bogoliubov-like bending back near AN

Fermi Arcs or hole pockets?



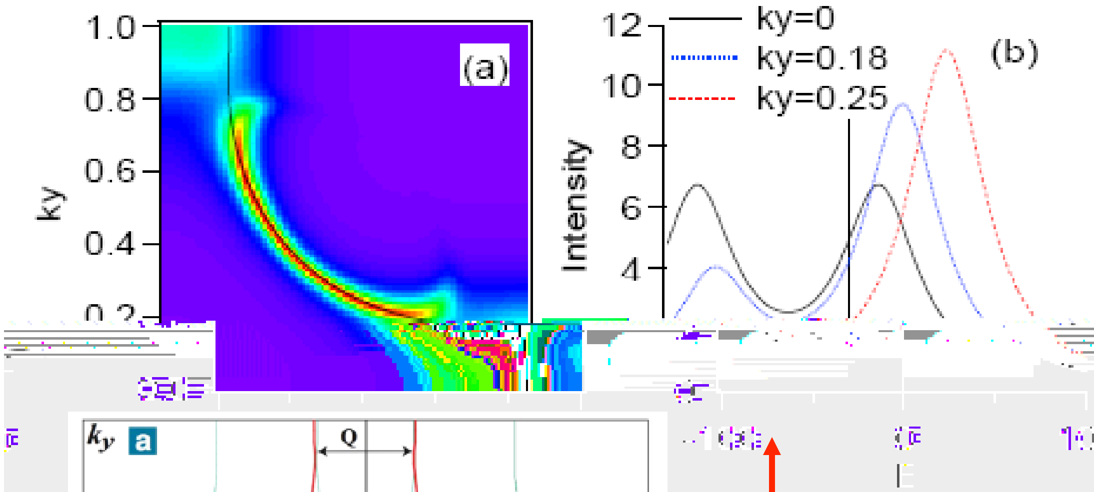
No evidence for Pockets or umklapp bands associated with a finite Q Order parameter

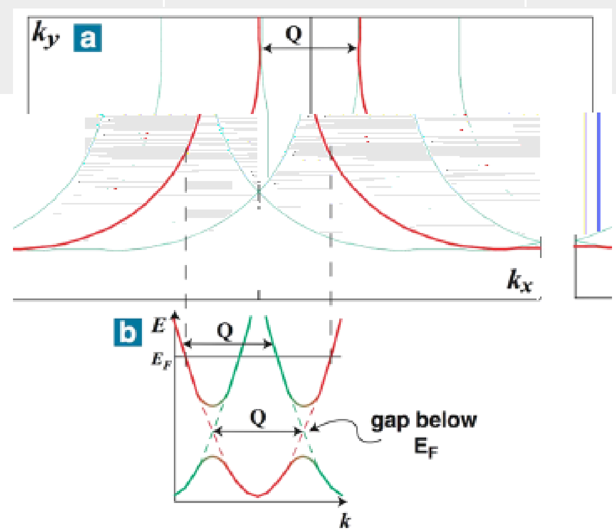


BNL group: H-B Yang et al, Nature (2008) & PRL (2011)

Non-zero q model

kx=1





Norman, Kanigel, MR, Chatterjee & Campuzano Phys Rev B 76, 174501 (2007)

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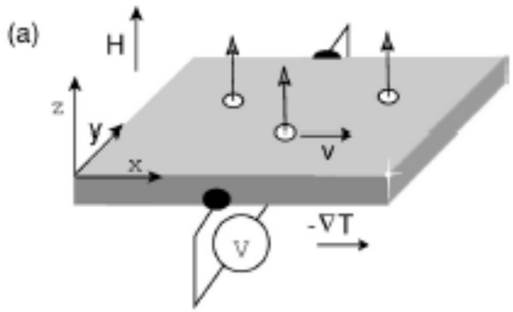
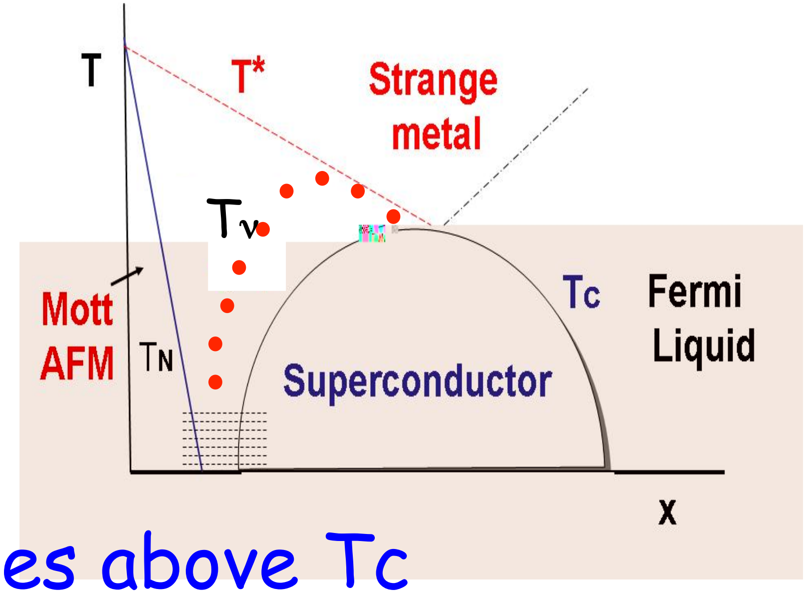
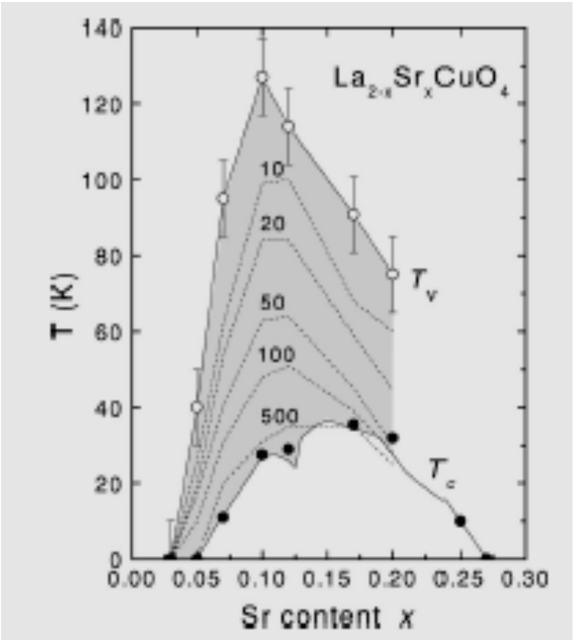
Nernst effect above Tc



$$\nu_N = \frac{E_y}{|\partial_x T| B}$$





N. P. Ong's group
(2000 – 04)

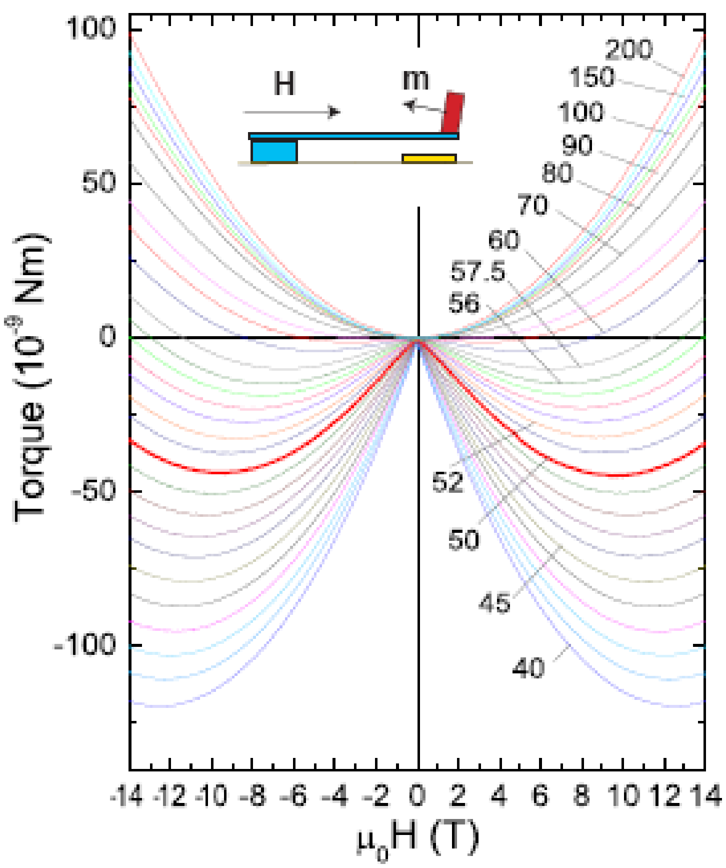
Vortices above Tc

SC short range order

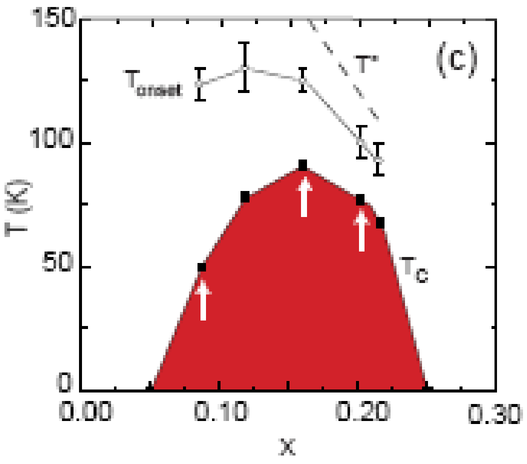
Temperature gradient → Vortices motion
Phase slip → Josephson voltage (transverse)

Note: Nernst region
(1) does not go up to T*
(2) onset has x-dep. similar to Tc

Fluctuation Diamagnetism above Tc

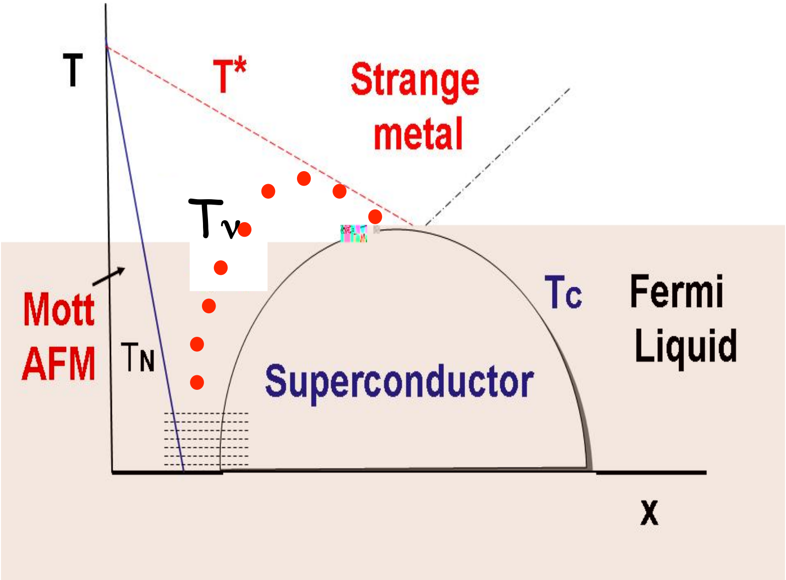


L. Li & N. P. Ong (2006)



Pseudogap summary
(thus far)

* Anisotropic gap above Tc
* Pseudogap temp. scale T*
* T-dep Fermi arcs
* No sharp QP's
* Spin pairing up to T*
* SC fluctuations
  (but not all the way to T*)



Next:
* Quantum oscillations
* Competing order parameters
  & their relation to pseudogap

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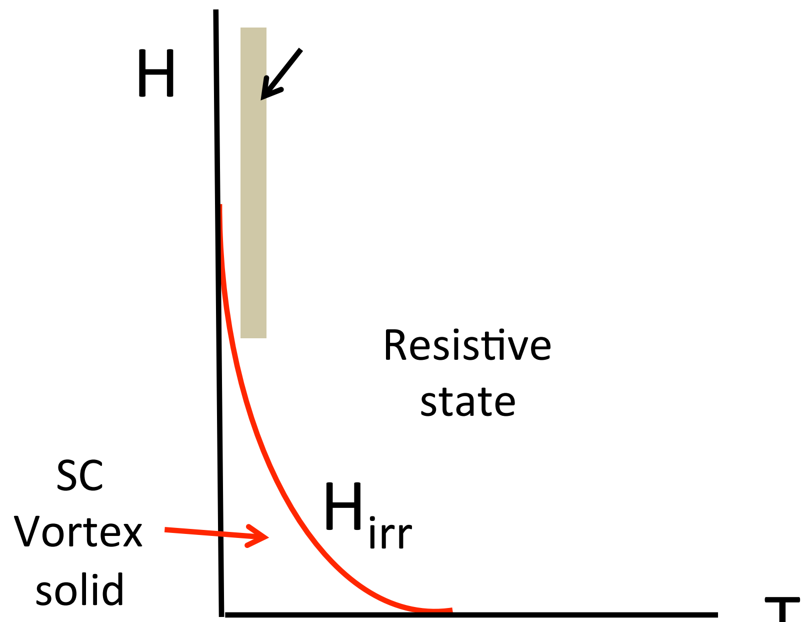
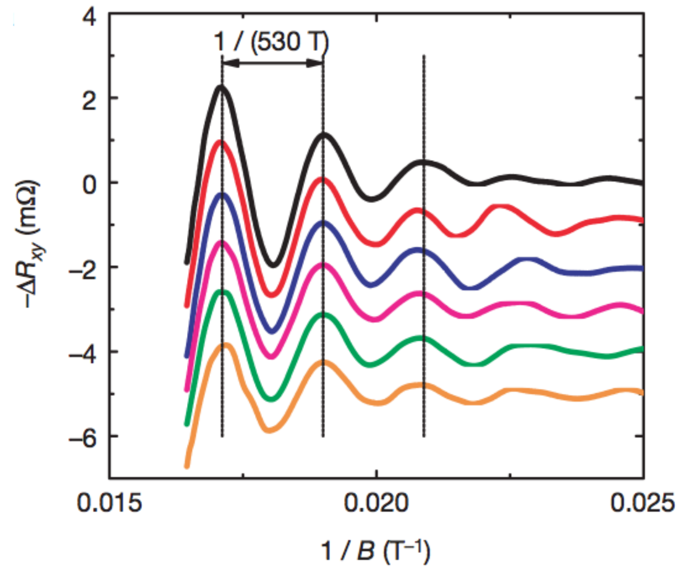
Destroy SC with temp vs. Destroy SC with B field

Quantum Oscillations in UD cuprates:



Field-induced low temperature resistive state

Quantum oscillations
Periodic in 1/H

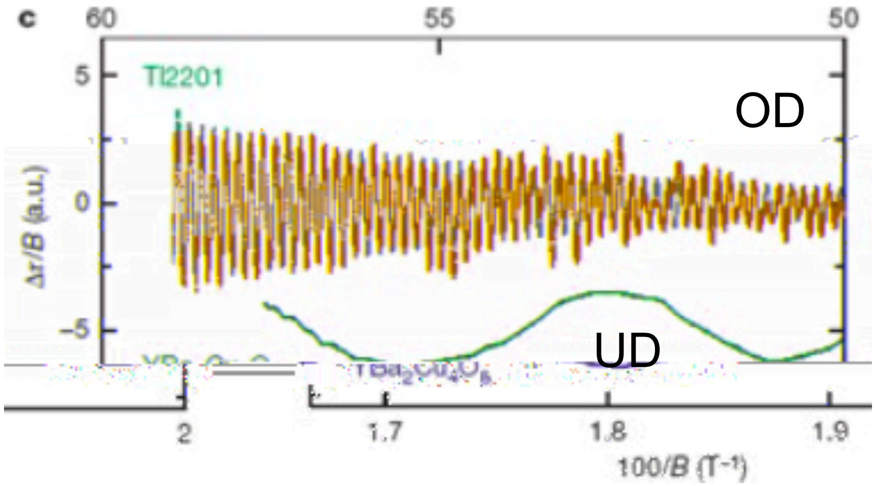


Tc = 57.5 K UD YBCO (p=0.10)

N. Doiron-Leyraud …Taillefer. Nature **447** 565 (2007)

S. Sebastian *et al.* Nature **454** 200 (2008)
New measurements up to 100 Tesla!

OD vs. UD Cuprates: FS reconstruction



Vignolle,…, Hussey, Nature (2008)

OD Tl2201

F = 18100 Tesla ~ 63% of BZ

Luttinger count (1+x) holes

UD YBCO

* F = 530 Tesla ~ 3% of BZ
* Electron pocket (sign of Hall & Seebeck)

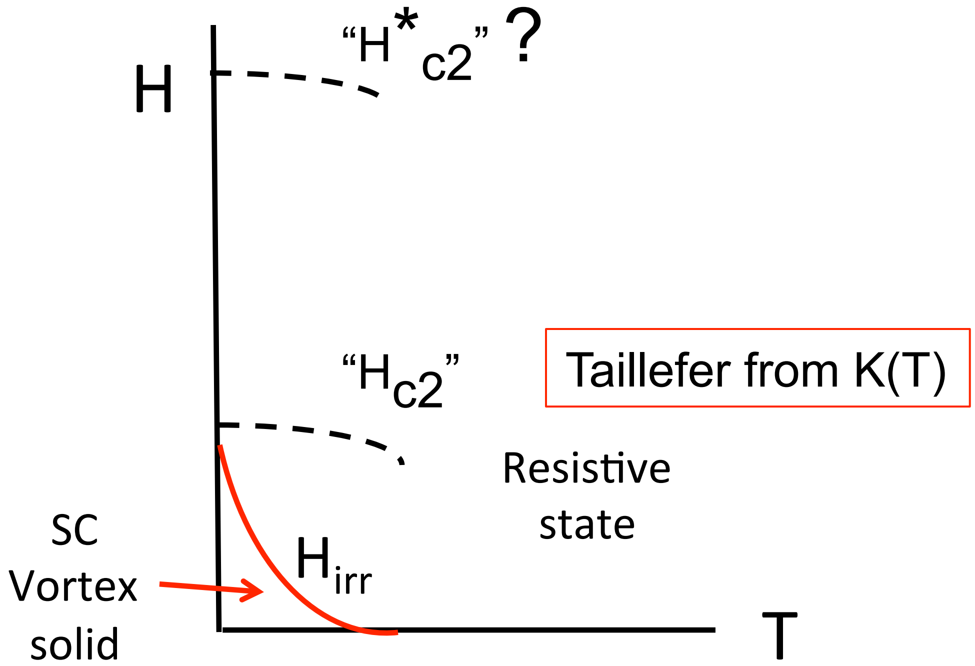
small electron pockets with area inconsistent with Luttinger count (in original Brillouin zone)

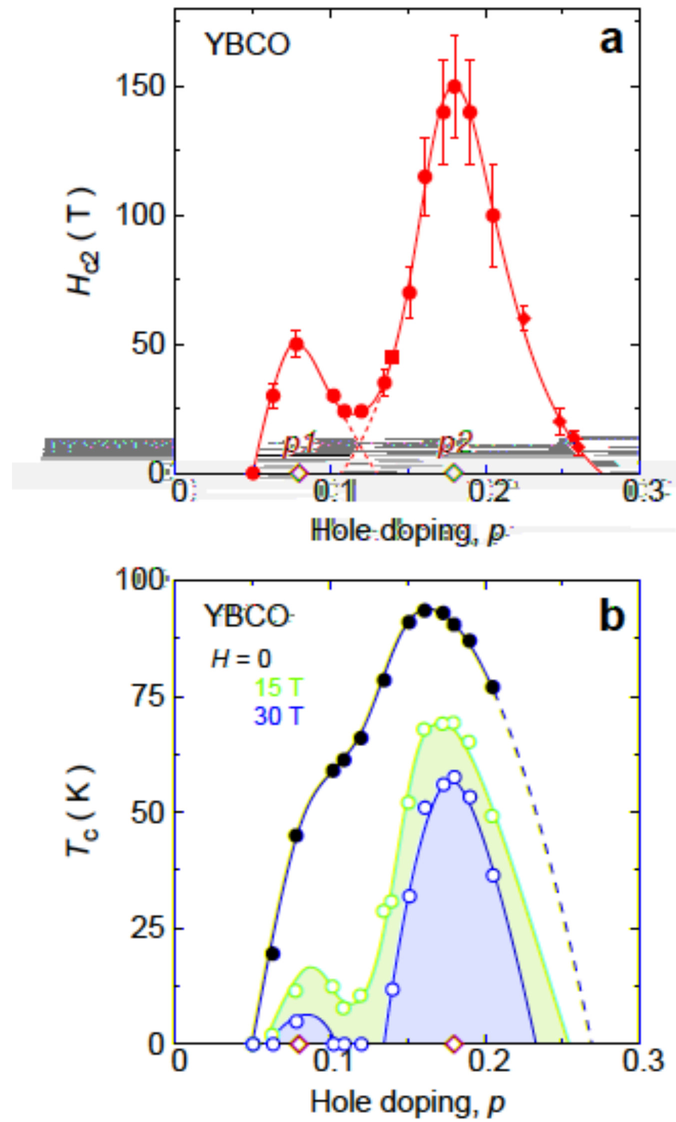
→ Translational symmetry breaking leads to Fermi surface reconstruction

[Millis & Norman. PRB (2007); Chakravarty & Kee PANS (2008); Yao, Lee & Kivelson. PRB (2011); Harrison &Sebastian. PRL (2012)]

Field scales:

"upper critical field H_{c2}"





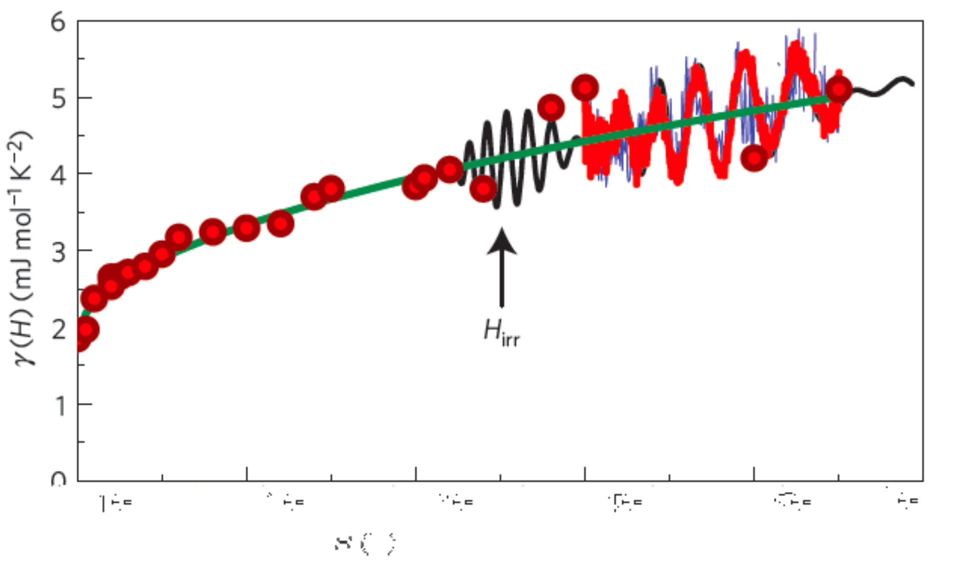
Grissonnanche … Taillefer, Nature Comm. 5, 3280 (2014)

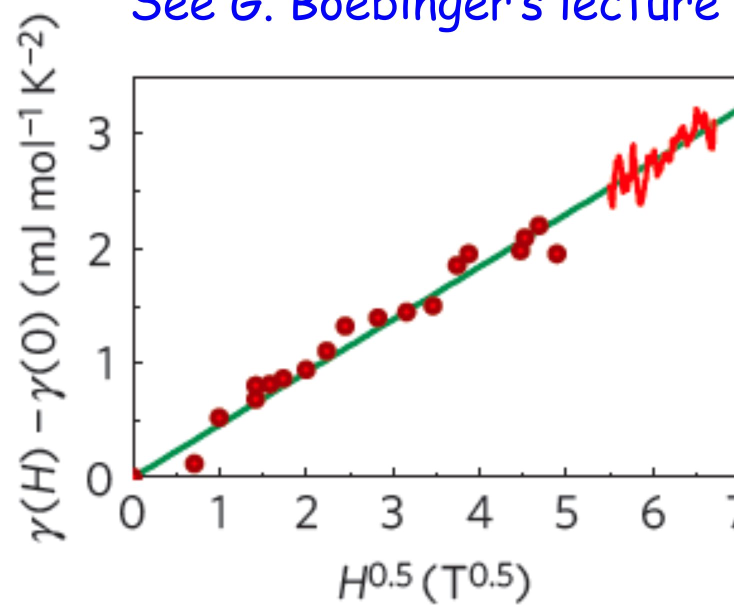
Note:

- "1/8 anomaly" (see below) Competing charge order
- Two QCPs

Heat Capacity in a Field

S. Riggs *et al.* Nature Phys. **7** 332 (2011)
See G. Boebinger's lecture





* Quantum oscillations with a (constant + $H^{1/2}$) background

$\gamma \sim H^{1/2}$ Volovik effect → SC nodes in resistive state?

* Specific heat strongly suppressed relative to {high T, H=0} normal state → "normal state" degrees of freedom not recovered at 50 T

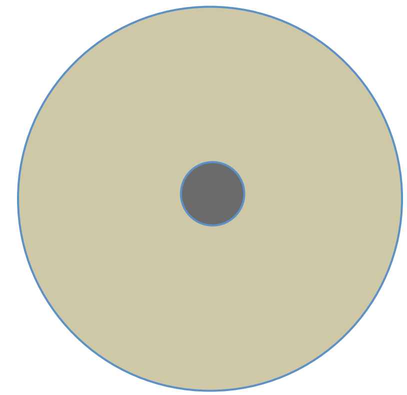
$\gamma << \gamma_0 \approx 18$ mJ/mol K^2 for T > Tc
J. Loram *et al.*, PRL **71** 1740 (1993)

Implications of Phase Fluctuations for Vortex State

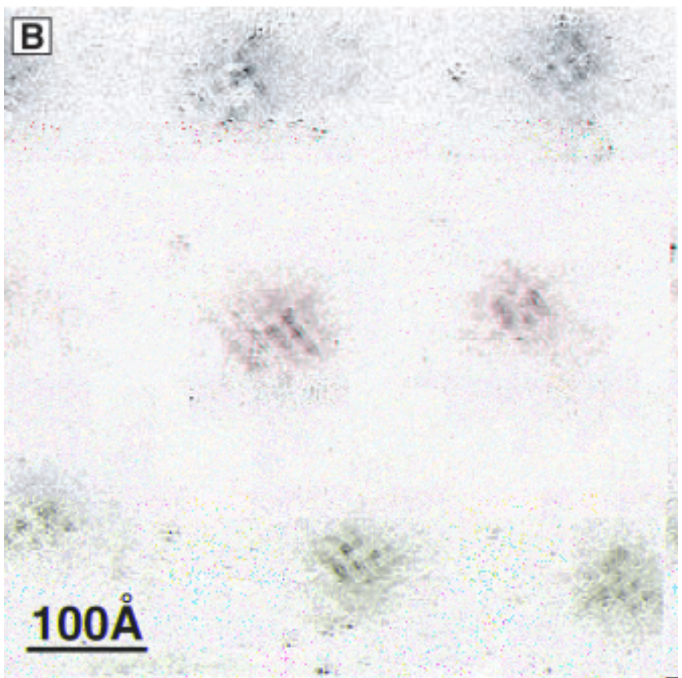
Two length scales:
core & halo

$$\xi_{\text{core}} = \frac{\hbar v_F}{\pi \Delta} \quad □ \quad \xi_{\text{halo}} = \frac{\hbar v_F}{\pi T_c} \quad \text{(Superflow)}$$

Lee & Wen, PRL (1997); Ioffe & Millis, PRB (2002)



Field scales: $H_{\text{irr}} \approx H_{c2}^{\text{halo}} \ll H_{c2}^{\text{core}}$



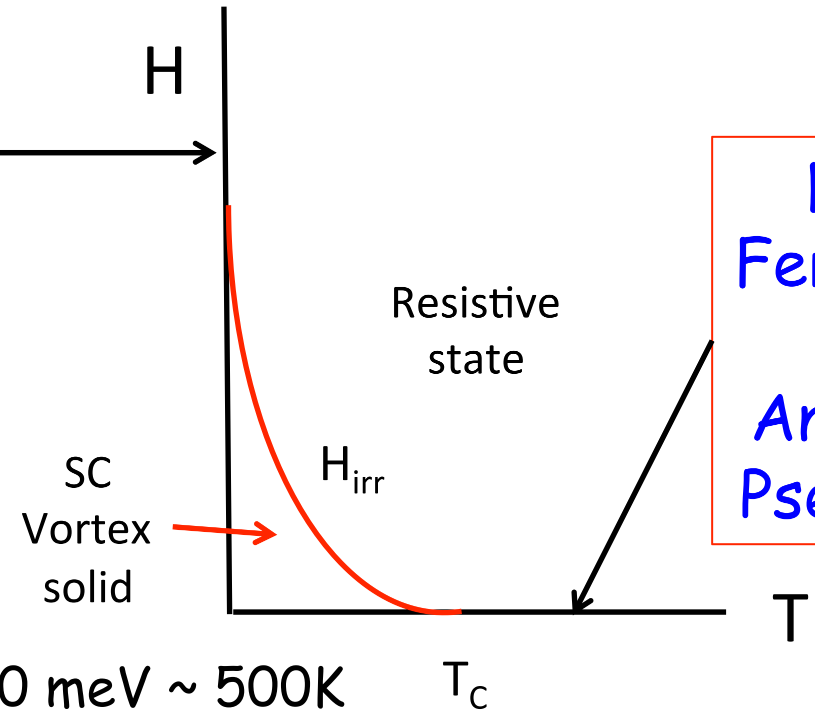
J.E. Hoffman et al, Science (2002)

Halo region:
-- suppressed superconductivity
-- enhanced competing order

Neutrons (LSCO): Lake et al, Science (2001)
STM (Bi2212): Hoffman et al, Science (2002)

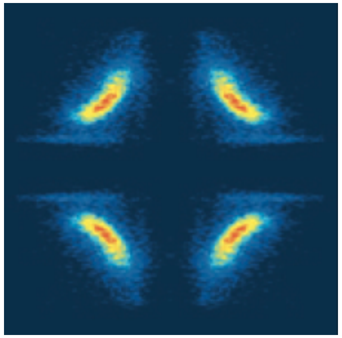
How to reconcile the electronic excitations seen by quantum oscillations and ARPES?

Small electron pockets



Nodal Fermi arcs + Antinodal Pseudogap

H=0; T >Tc



Pseudogap ~ 50 meV ~ 500K
Fields ~ 50 T ~ 50 K

Senthil and Lee PRB (2009)
Banerjee, Zhang & Randeria, Nature Comm. (2013)
Allais, Chowdhury, Sachdev, arXiv (2014)

Pseudogap in Underdoped Cuprates

- Underdoped SC state: gap anisotropy
- What determines Tc? Gap or superfluid density?

- Pseudogap above Tc
  -- specific heat, NMR, optics, STM
- ARPES & Fermi arcs

- SC fluctuations above Tc

- Quantum Oscillations

- Competing order parameters

Plethora of broken symmetries in pseudogap state

* Translational -- stripes, CDW

* Rotational -- nematicity

* Time-reversal -- will not discuss
  * neutrons (Bourges,Greven...) → Orbital Currents (Varma)
  * polar Kerr (Kapitulnik)

- Is T*(x) a Crossover or Phase Transition?

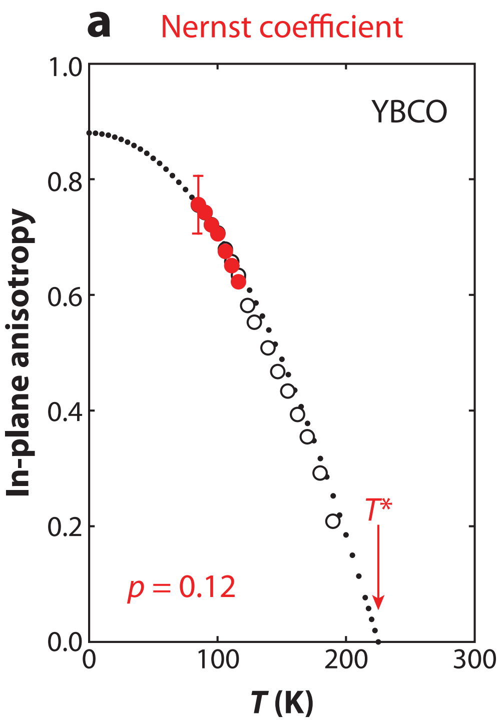
- Which of these broken symmetries – if any – are responsible for large antinodal "pseudogap" in H=0?

- Broken translational required for large H by quantum oscillation frequency

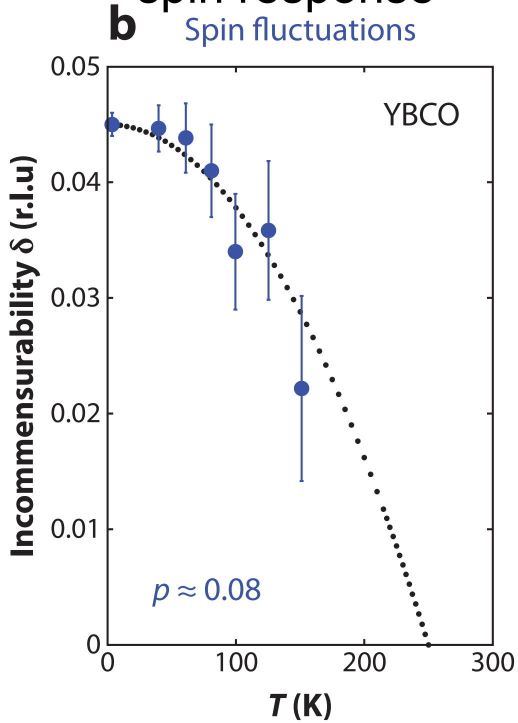
Broken Rotation Symmetry: Electronic Nematic Order

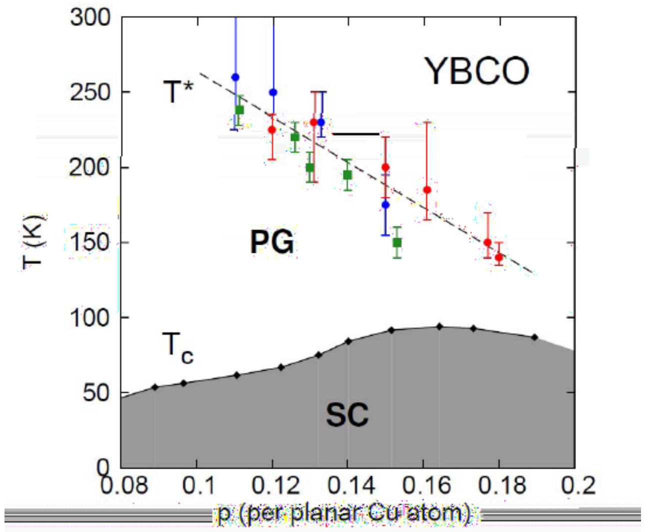
Difference between a & b axis responses strongly enhanced in pseudogap state

Anisotropy of Nernst



Unidirectional Incommensurate spin response



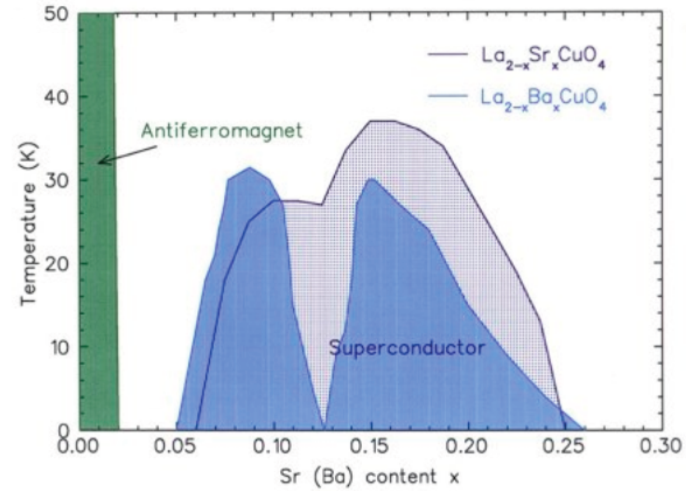


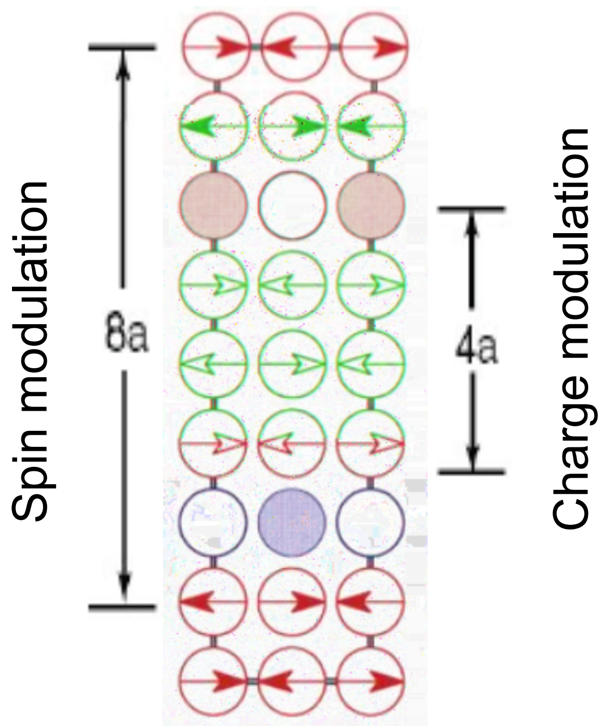
Review: A. Taillefer, Ann. Rev. Cond. Mat. Phys. (2010)

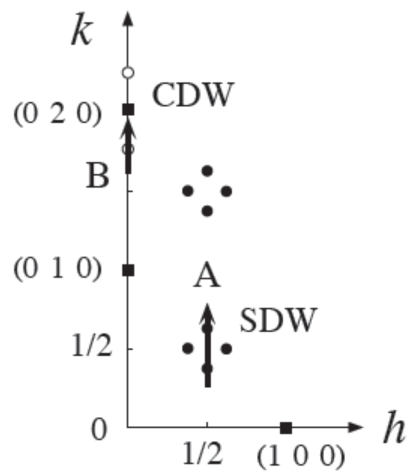
Broken Translation & Rotation: Stripes

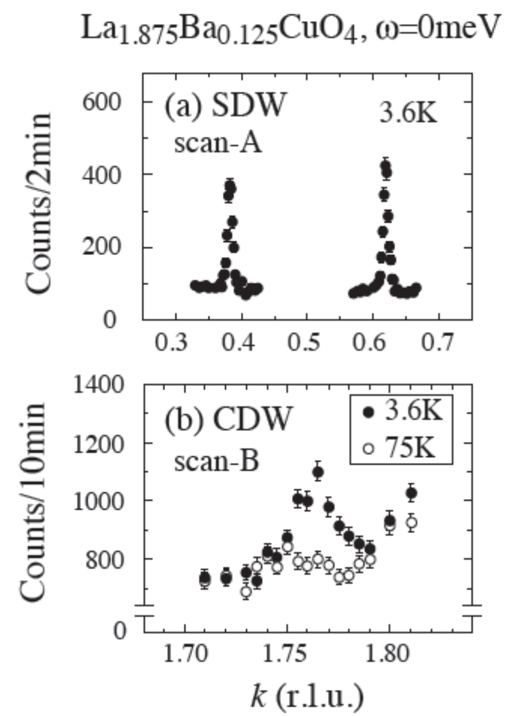
Nd:LSCO; LBCO (x=1/8)

Static stripes kill superconductivity









Review: J. Tranquada, AIP Conf. Proc. 1550, 114 (2013)
see S. Kivelon's lectures

Broken translation: Charge Density Wave

STM: checkerboard CDW -- Bi2212, Bi2201, Oxychlorides
vortex core – Bi2212

High field NMR – YBCO

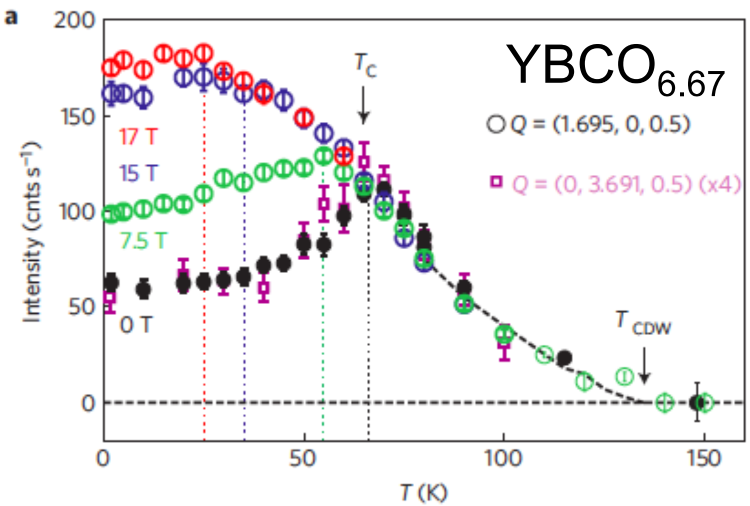
Xray diffraction – YBCO

REXS – YBCO, Bi2212

* Finite correlation length in H=0 (disorder or intrinsic?)

* Long range order in high fields:
Fermi surface reconstruction in Qtm Oscillations

Evidence for CDWs



UD YBCO (ortho-II, -III & -VIII)

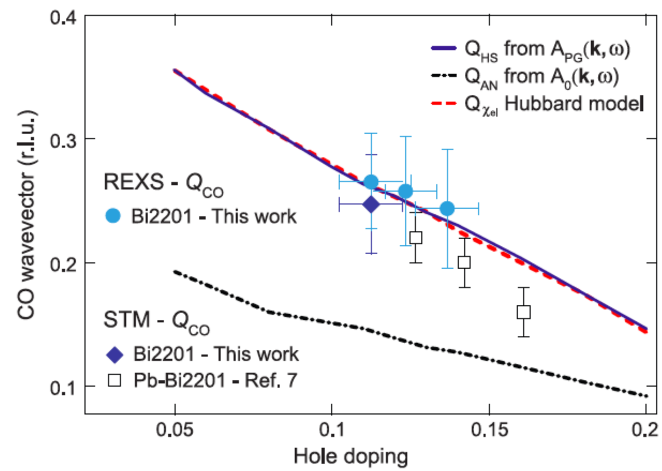
* Hard x-ray diffraction (100keV)
J.Chang et al., Nature Phys (2012)

Bi-directional CDW

$\boldsymbol{q_1} = (0.31, 0, 0.5)$
$\boldsymbol{q_2} = (0, 0.31, 0.5)$

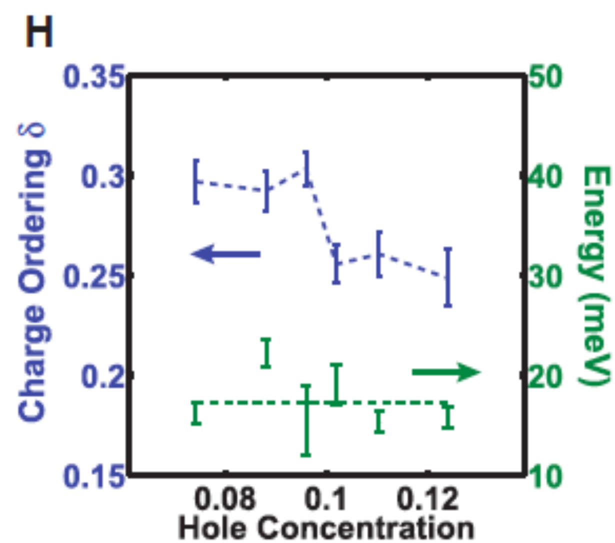
* Resonant elastic x-ray scattering
(soft xrays 930eV) YBCO
G.Ghiringhelli et al, Science (2012)

in-plane $\xi\ (\mathring{A}) \sim 60\ (\text{at } T_c)$



UD Bi2201
REXS
STM
ARPES
Comin…
Damascelli
Science
(2014)

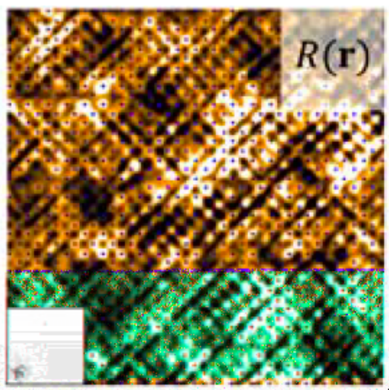
$\xi \sim 20 - 30\mathring{A}$

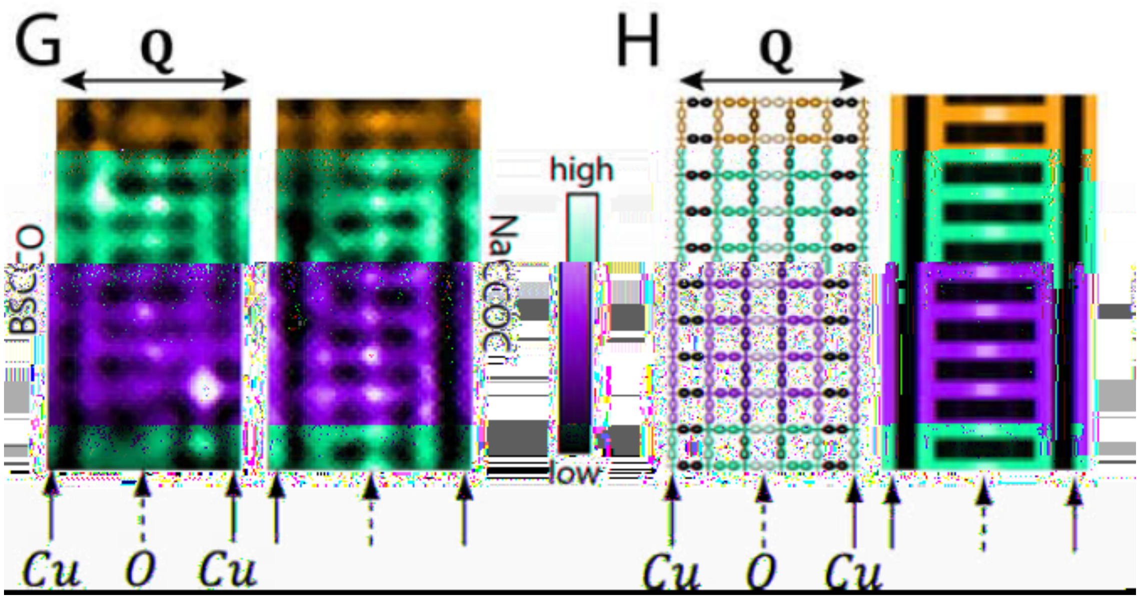


UD Bi2202
REXS
STM
Silva Neto
…Yazdani
Science
(2014)

STM → Nematic + Bond-centered CDW

Fujita ... Sachdev, Davis, arXiv1404.0362;





"d-wave" CDW

[Sachdev]

$$]c^{\dagger}_{r\alpha} c_{r'\alpha}[$$

$$(r + r')/2 \rightarrow \mathbf{Q}$$

CDW wavevector

$$(r - r')$$

→ Form factor for internal structure of CDW

Pseudogap: More questions; few definitive answers

Here are my thoughts:

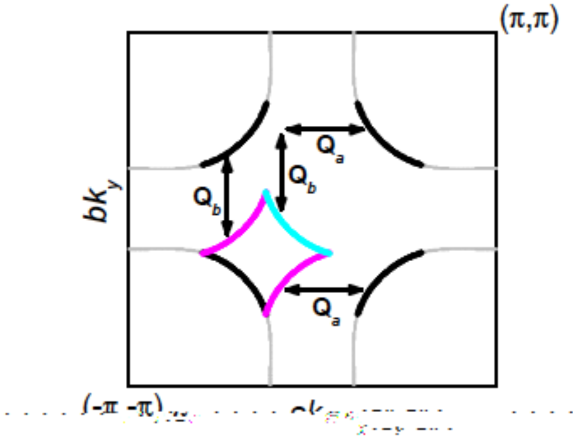
- What is responsible for the antinodal pseudogap ~ 60meV?

  -- proximity to Mott & spin pairing (RVB, DMFT)

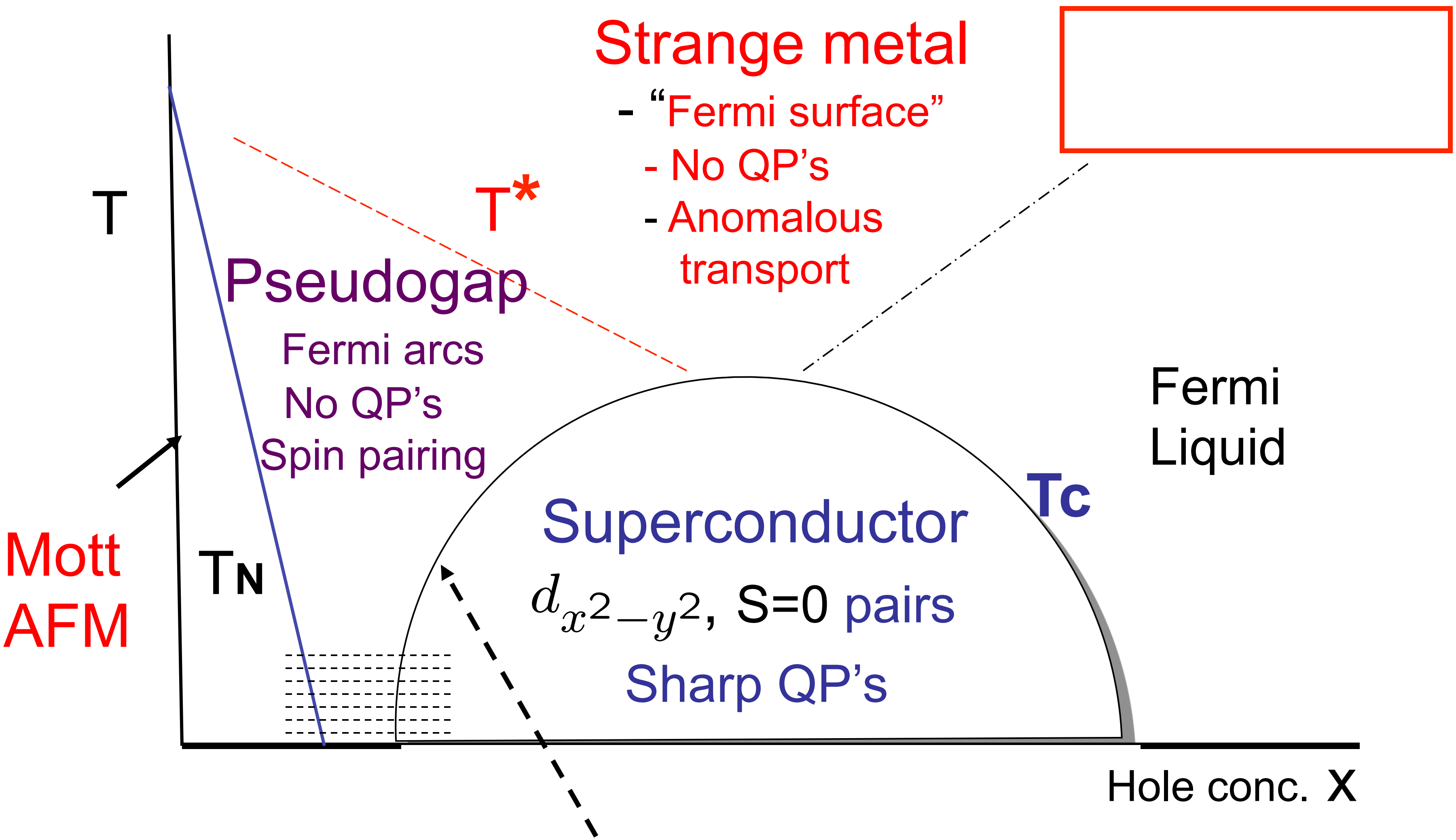
  -- competing orders are not the cause of the pseudogap but rather competing instabilities in the PG state

- Broken translational symmetry required by quantum oscillations

  -- bidirectional CDW order stabilized in a field ←→ FS reconstruction seems the best proposal



Harrison & Sebastian, PRL (2011)


Strange metal
- "Fermi surface"
- No QP's
- Anomalous transport
T
T*
Pseudogap
Fermi arcs
No QP's
Spin pairing
Mott
AFM
T_N
Superconductor
$d_{x^2-y^2}$, S=0 pairs
Sharp QP's
Tc
Fermi
Liquid
Hole conc. X