The High T_c Superconductors: BCS or Not BCS?

- Does BCS theory work for the high temperature superconductors?
- We take a look at the electronic excitations using angle resolved photoemission spectroscopy (ARPES).

Outline

- Brief introduction to ARPES.
- The phase diagram: the underdoped and overdoped regions.
- Difference in behavior between these two regions.

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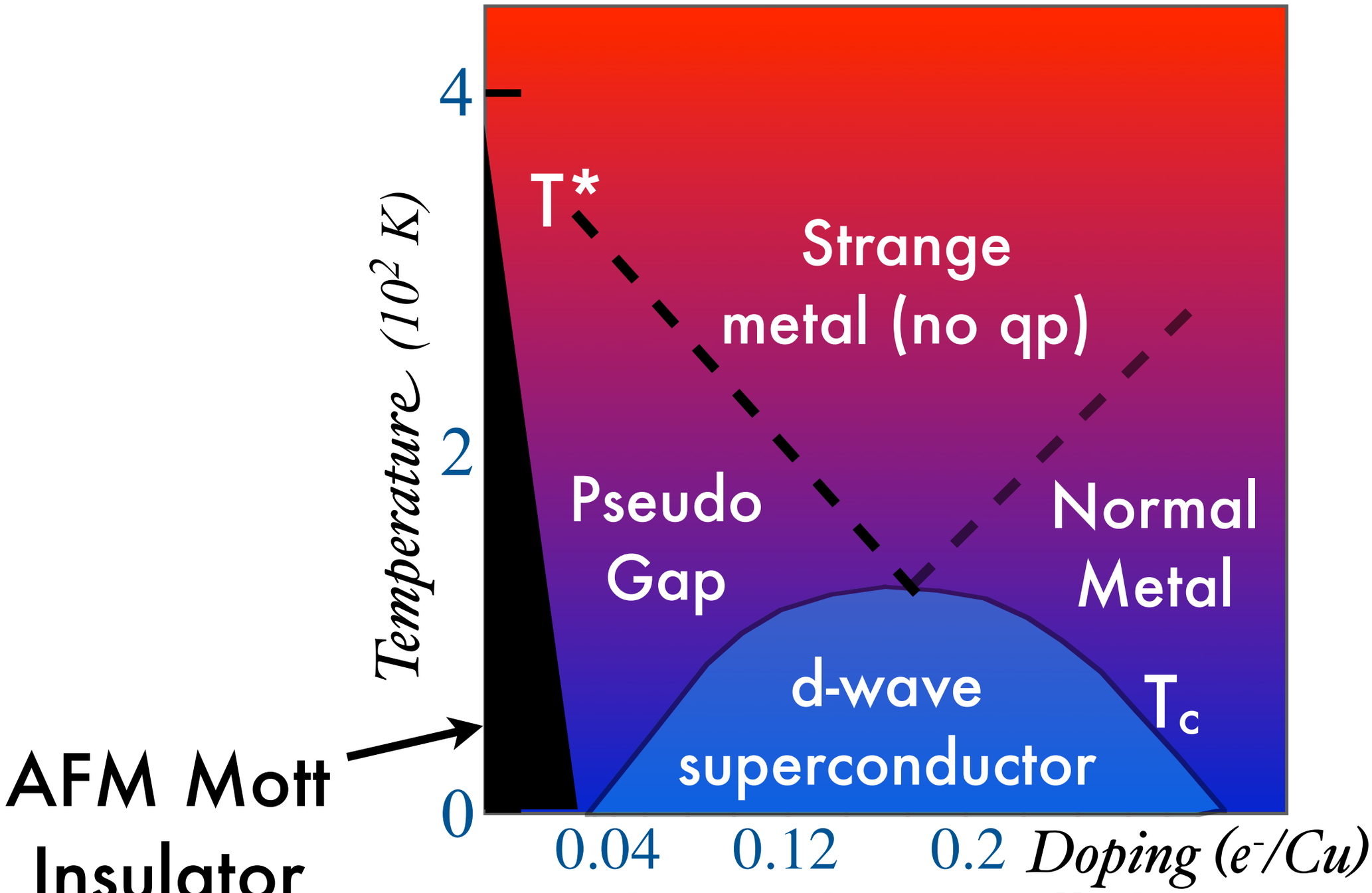
The high temperature superconductors

Schematic phase diagram

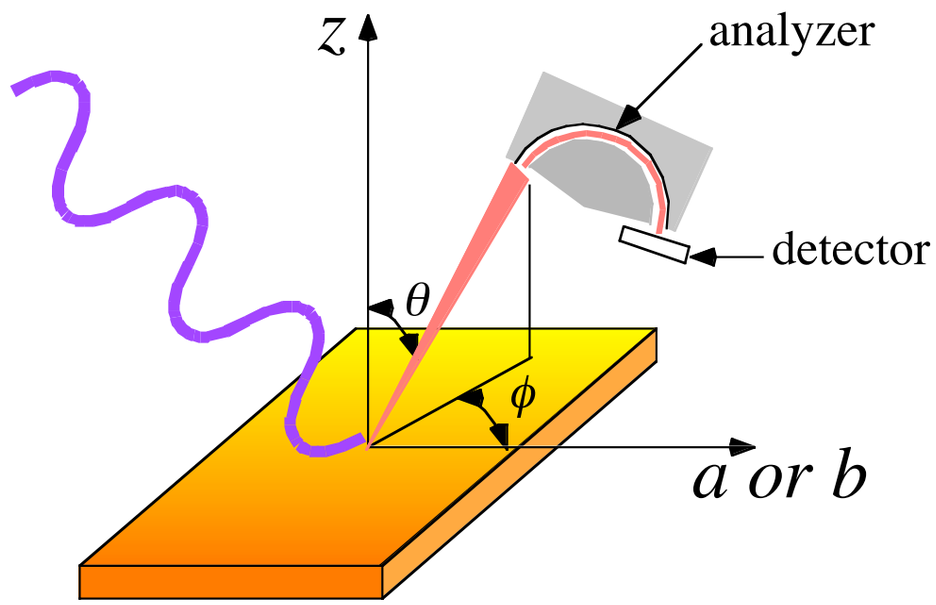


How do we know all this?

In large part from angle resolved photoemission

Angle resolved photoemission

Photons in - electrons out



$$\vec{k}^f_{//} = \vec{k}^i_{//} = \sqrt{\frac{2mE}{\hbar^2}} sin\theta$$

Why is ARPES important in the HTSC problem?

- Strong k-dependences in quantities of interest: SC gap; pseudogap; self-energy
- High temperature (Tc ~100K) & energy (Δ ~ 10's meV) scales
- High resolution
  δ k ~ 0.01 (2π/a)
  δω ~ 5 – 15 meV

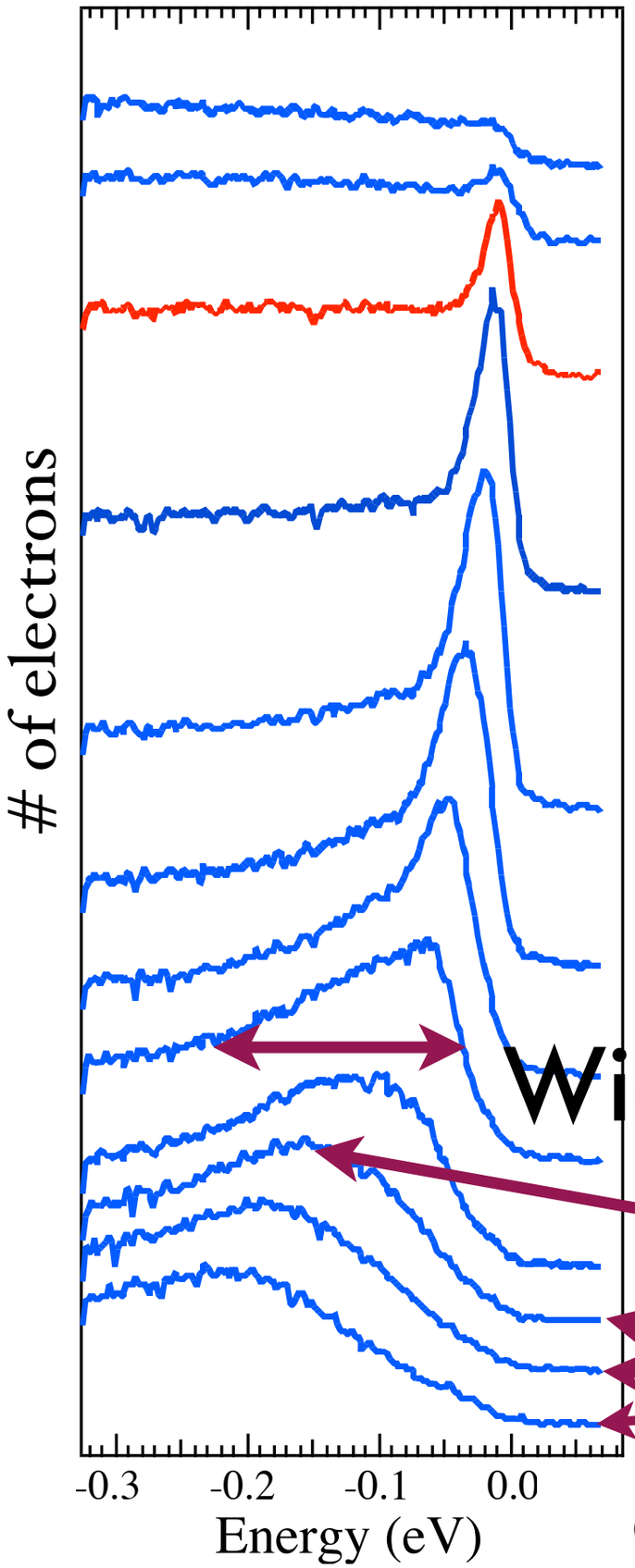
Reviews:

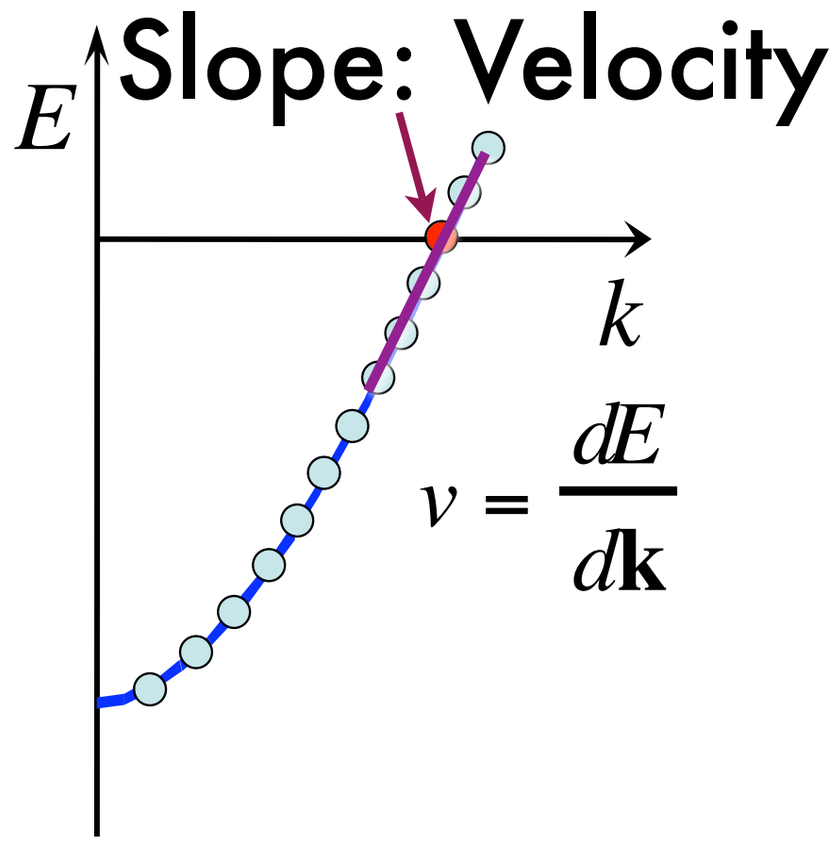
A. Damascelli, Z. Hussain and Z. X. Shen, Rev. Mod. Phys. *75*, 473 (2003).

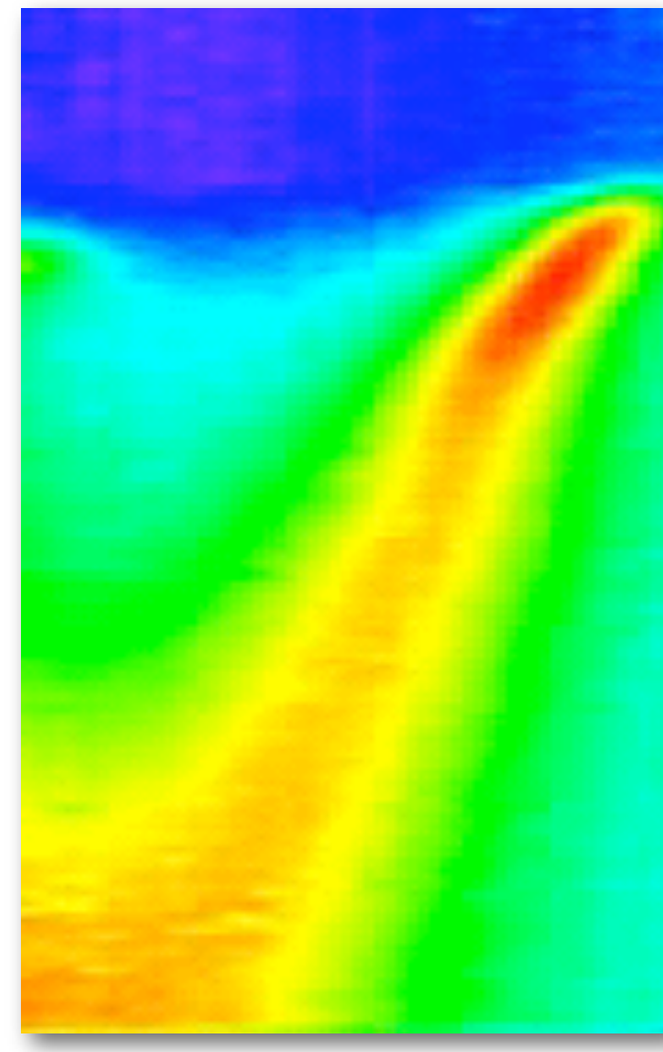
J. C. Campuzano, M. R. Norman and M. Randeria; in "*Physics of Conventional and Unconventional Superconductors*", edited by K. H. Bennemann and J. B. Ketterson, (Springer Verlag, 2004); cond-mat/0209476.

The ARPES spectra

It provides a fairly complete view of the excitations





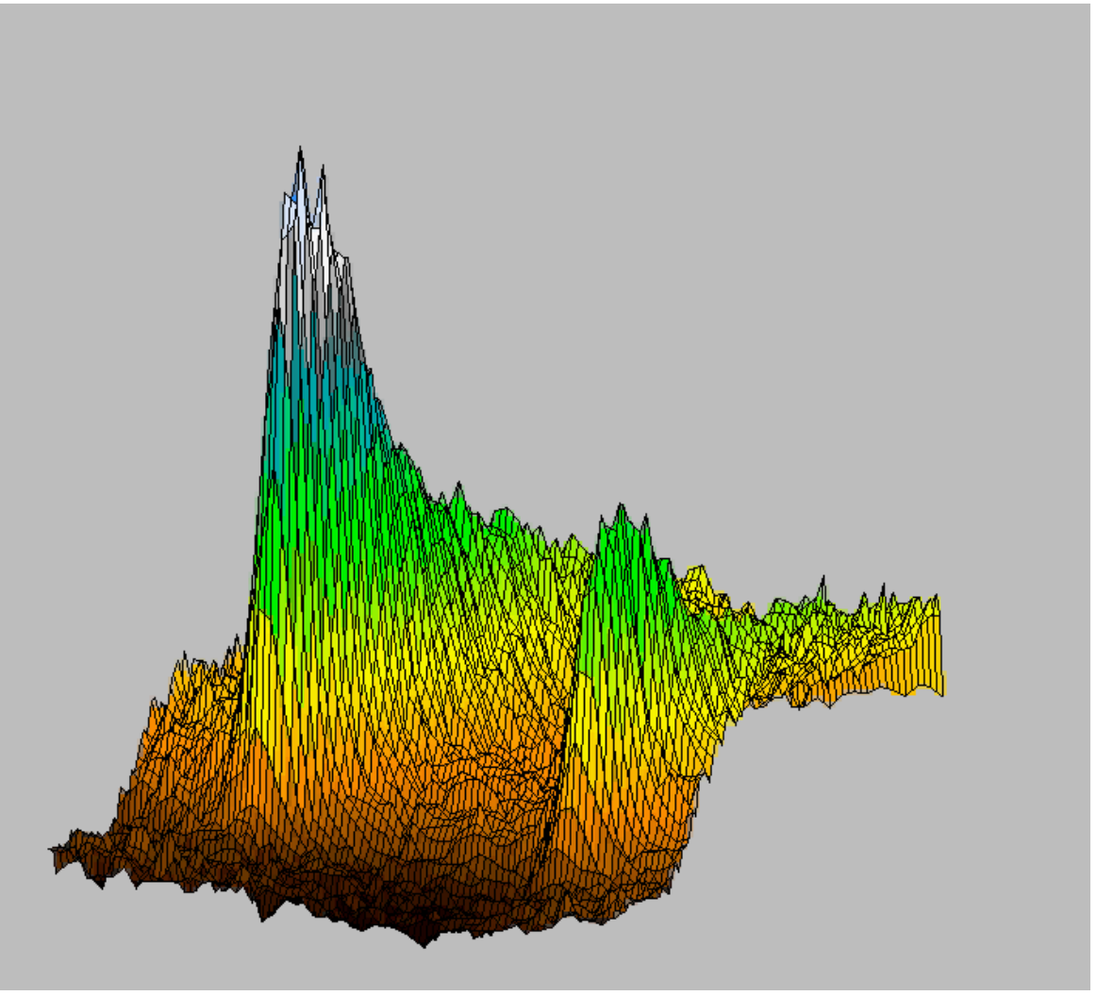


Width: 1/Lifetime

Position: Energy

Each spectrum corresponds to a particular k

ARPES measures the spectral function



$$A(\mathbf{k},\omega) = -\frac{1}{\pi}\,\Im m\, G_R$$

probability of adding or removing a particle from a many-body system

Randeria, et al., PRL 74 (95) 4951

Impulse approximation

$$I \propto \underbrace{\left\langle \psi_f \left| \vec{\mathbf{A}} \cdot \vec{\mathbf{p}} \right| \psi_i \right\rangle^2}_{\text{Depends on}} \underbrace{A(\mathbf{k},\omega)\, f(\omega)}_{\text{Depends on}}$$

Depends on
- $\mathbf{k}$
- polarization
- $h\nu$

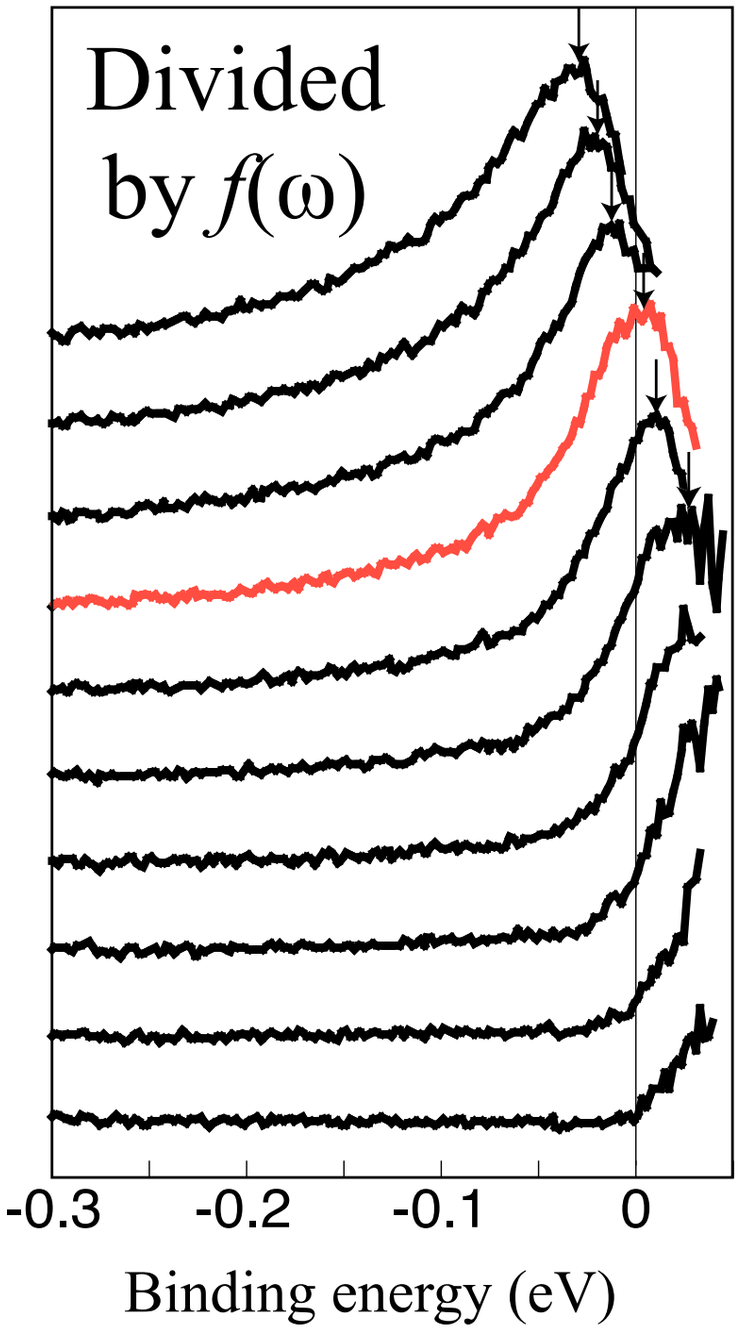
* selection rules

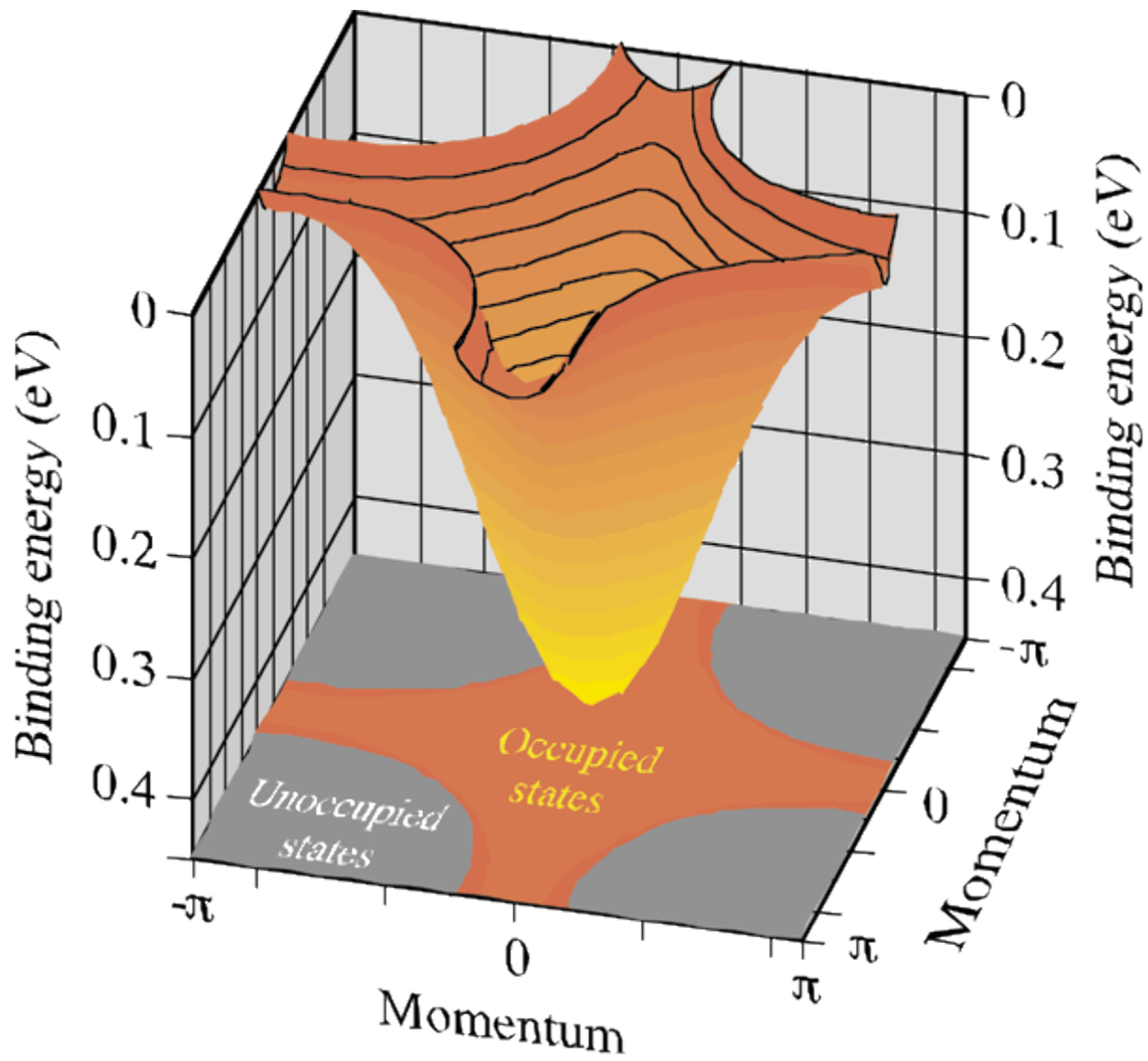
Depends on
- $\mathbf{k}$
- ω
- T

* sum rules

Eliminating the Fermi Function

$$\underline{I(\mathbf{k},\omega)} \propto A(\mathbf{k},\omega) f(\omega)$$



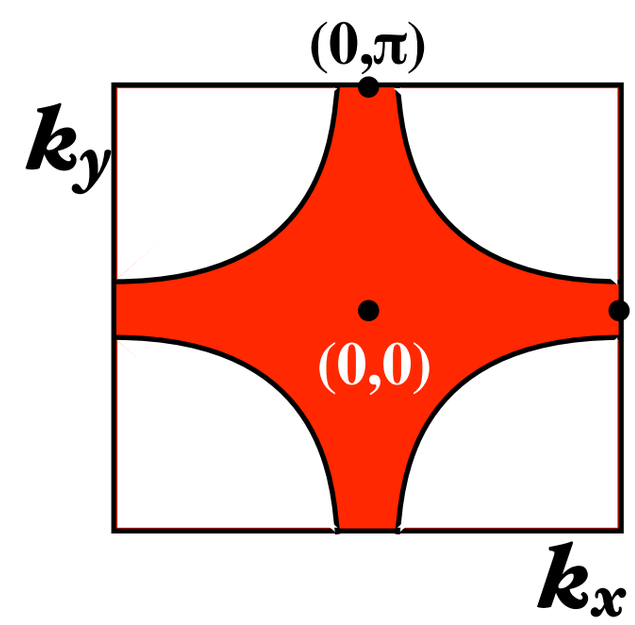


When all extraneous effects are removed, we are left with the single state crossing the Fermi energy

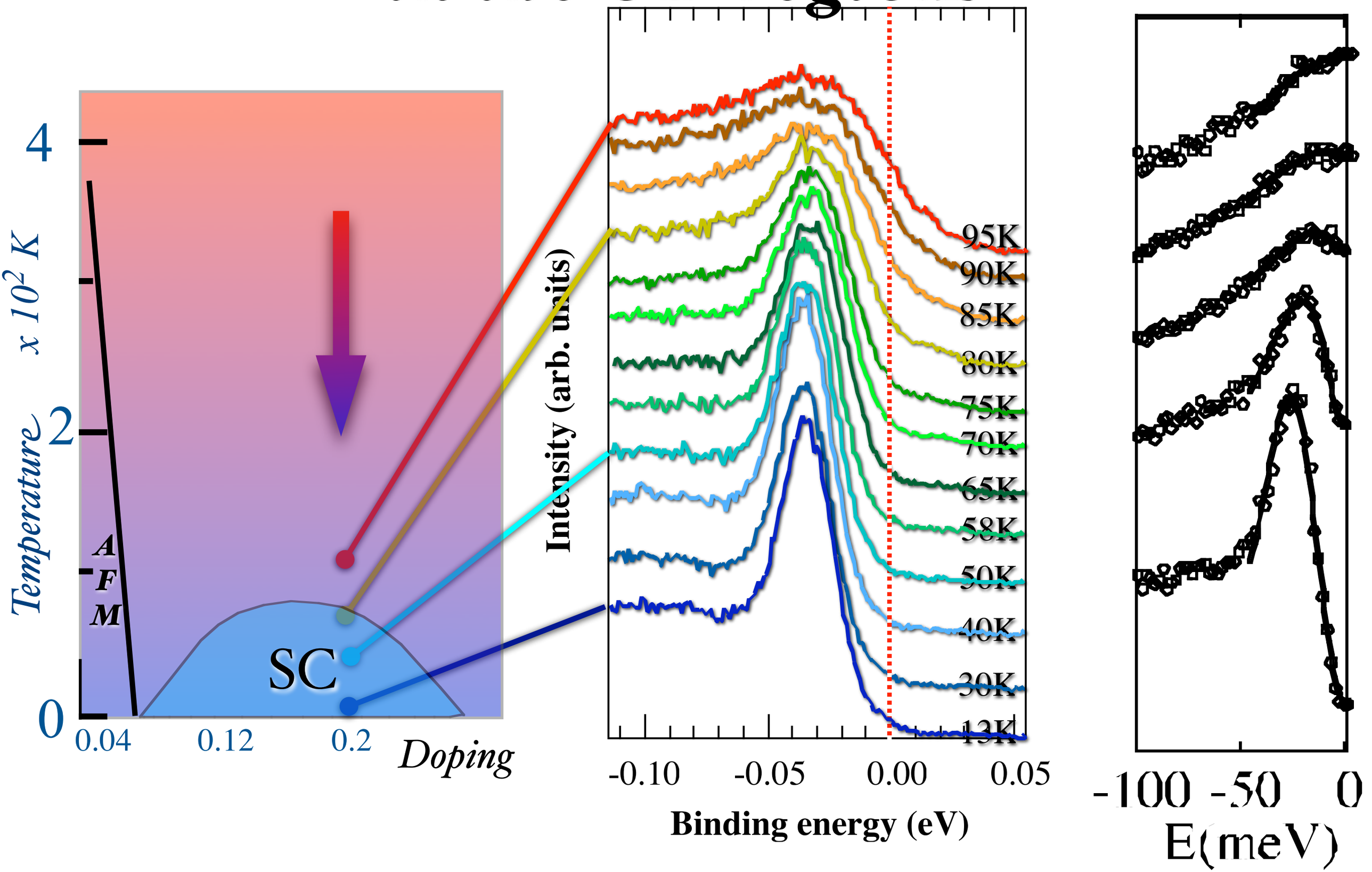
PRB 52 (1995) 615

Fermi surface

Campuzano, et al., PRL 64 (90) 2308



HTSCs: The Phase transition in the OD region



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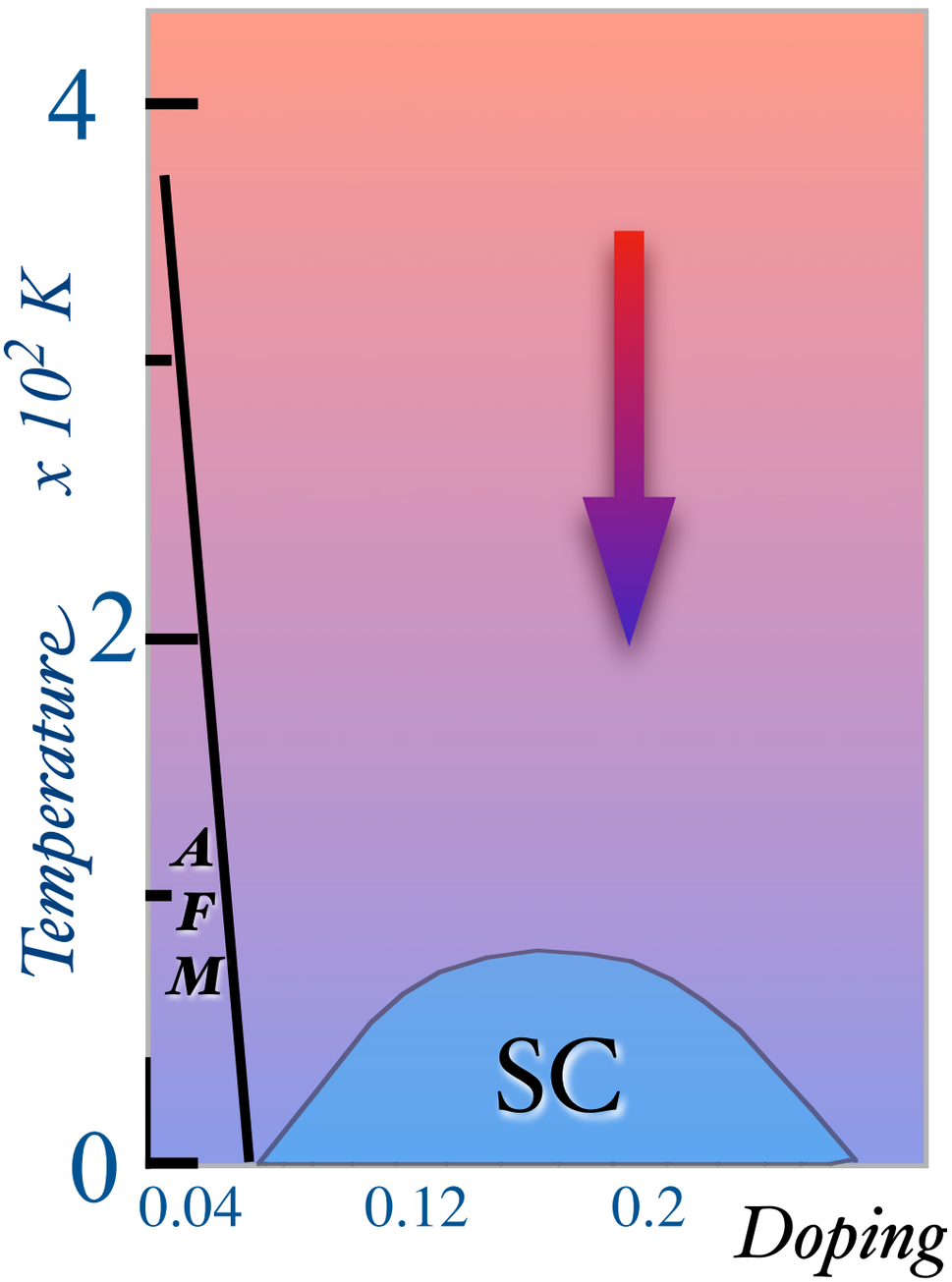
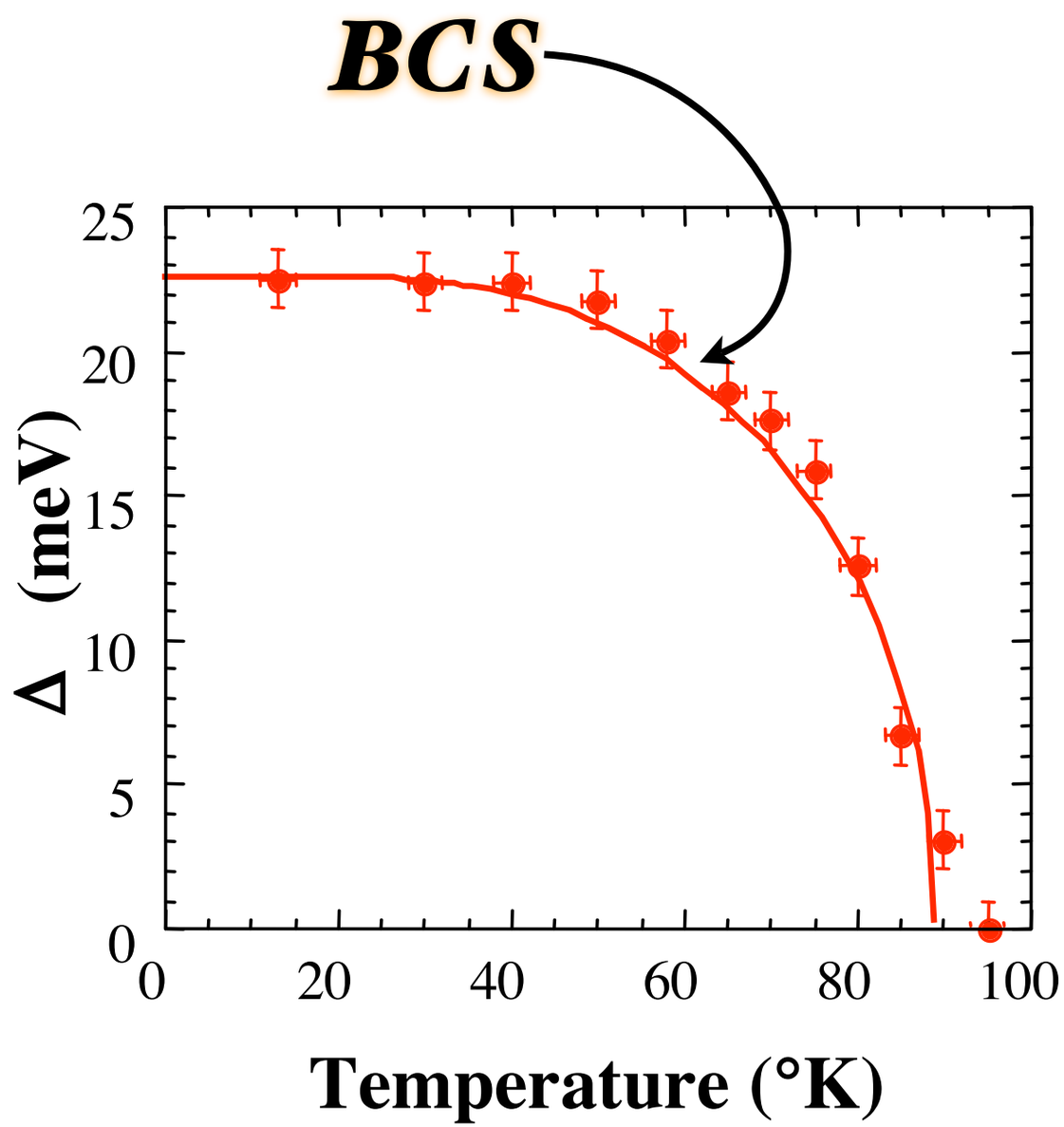
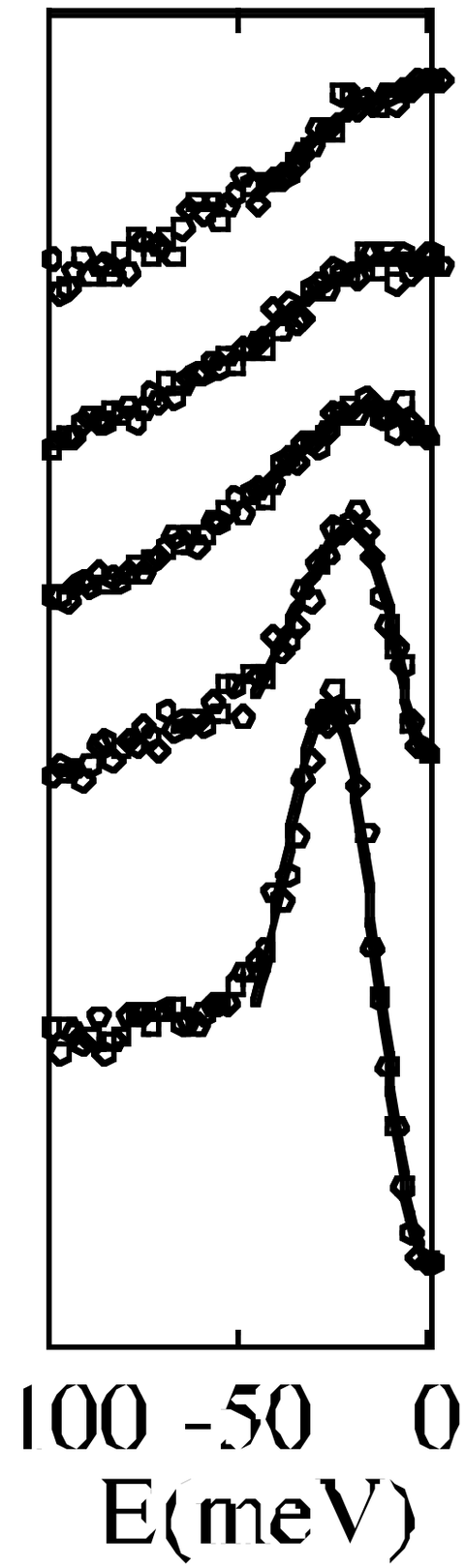


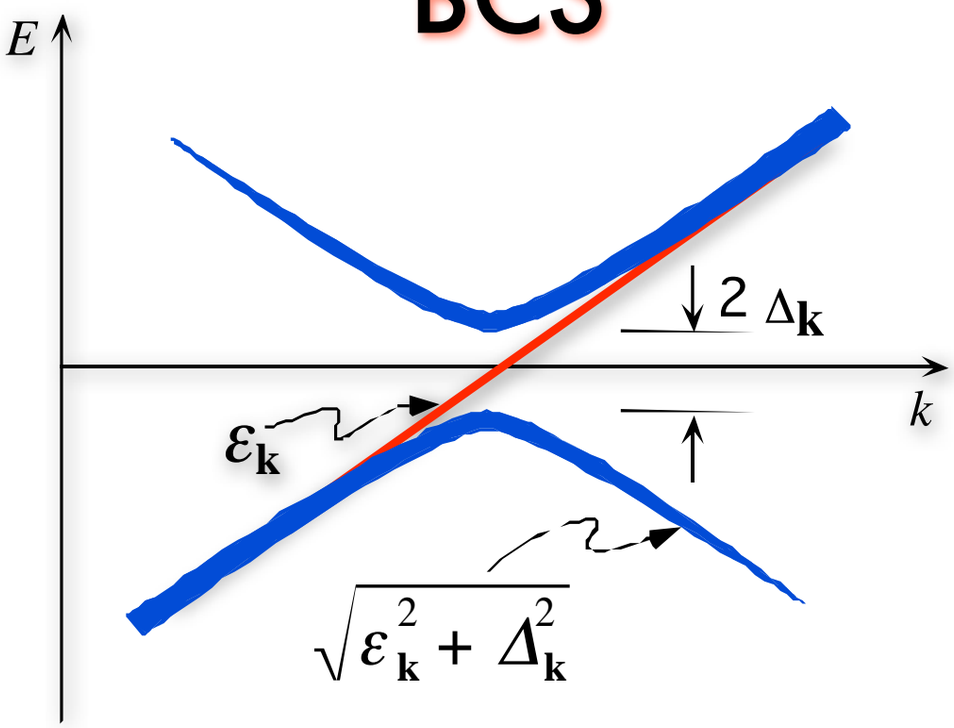




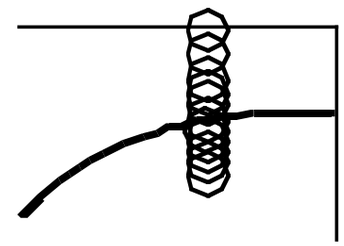
How do we know we are looking at Δ?

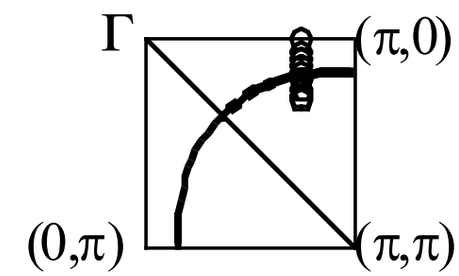
Particle-hole mixing

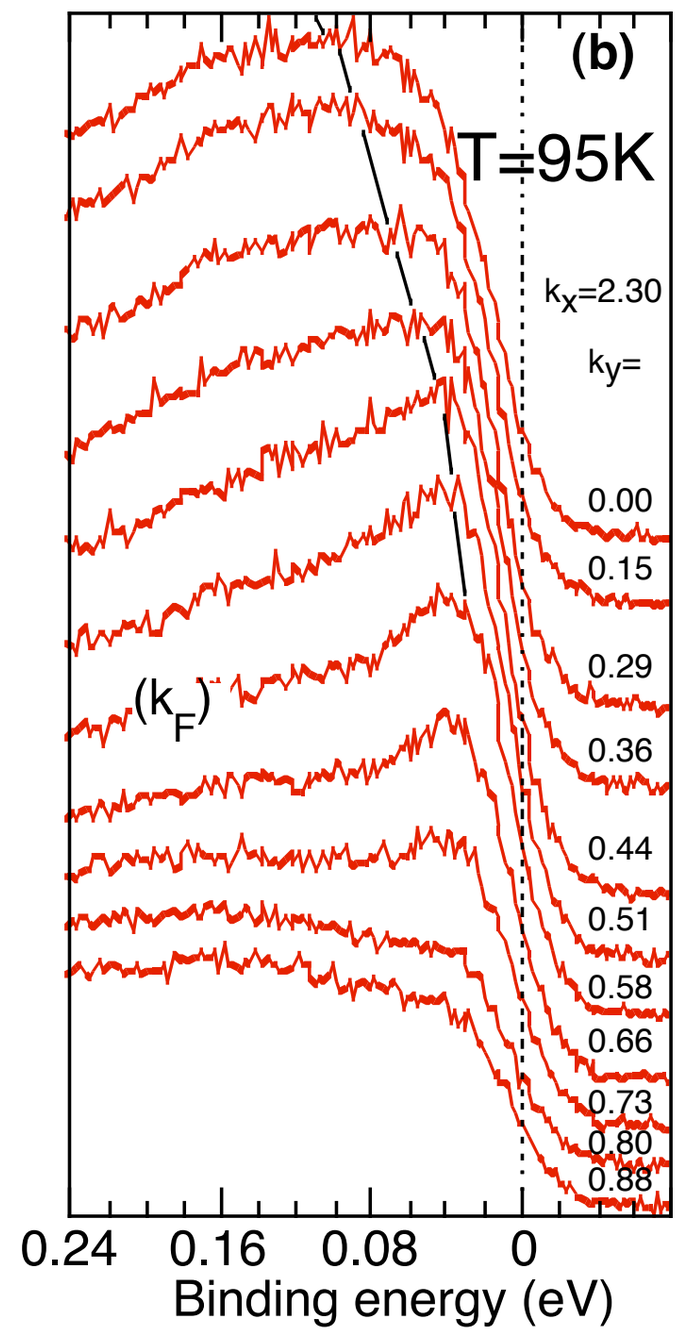
BCS

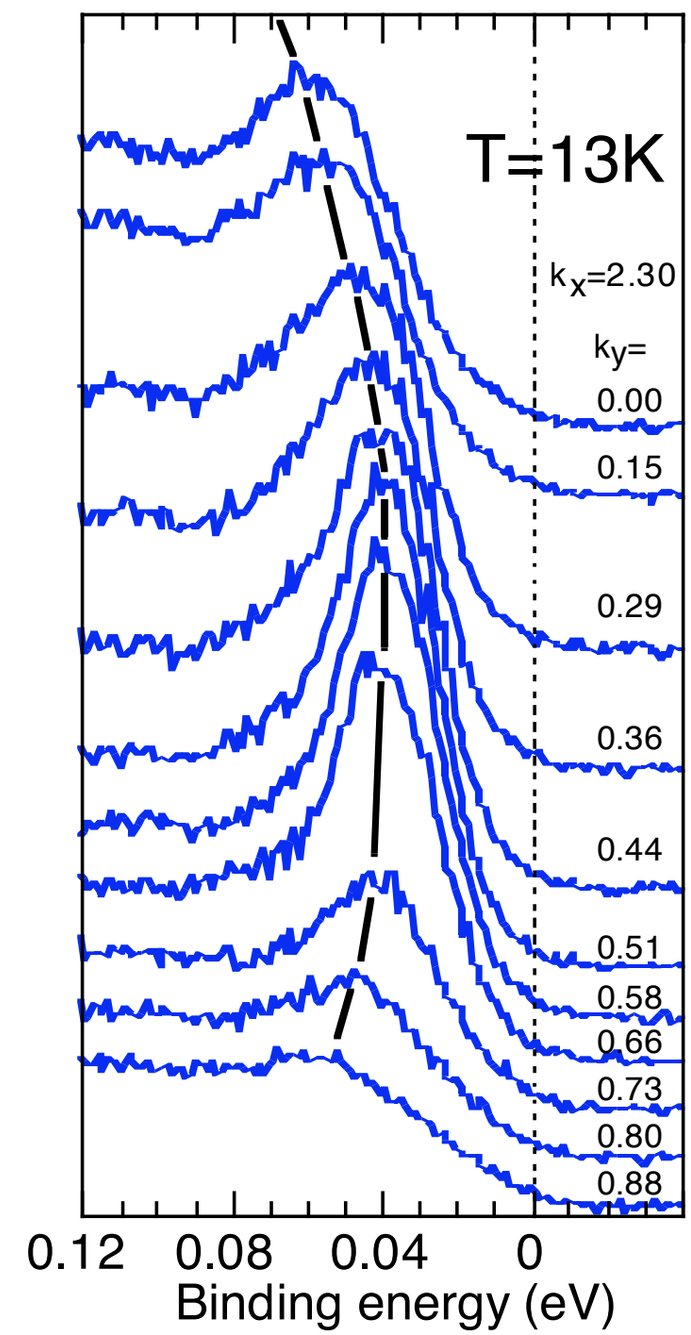


Campuzano, et al., PRB 53(96) R14797

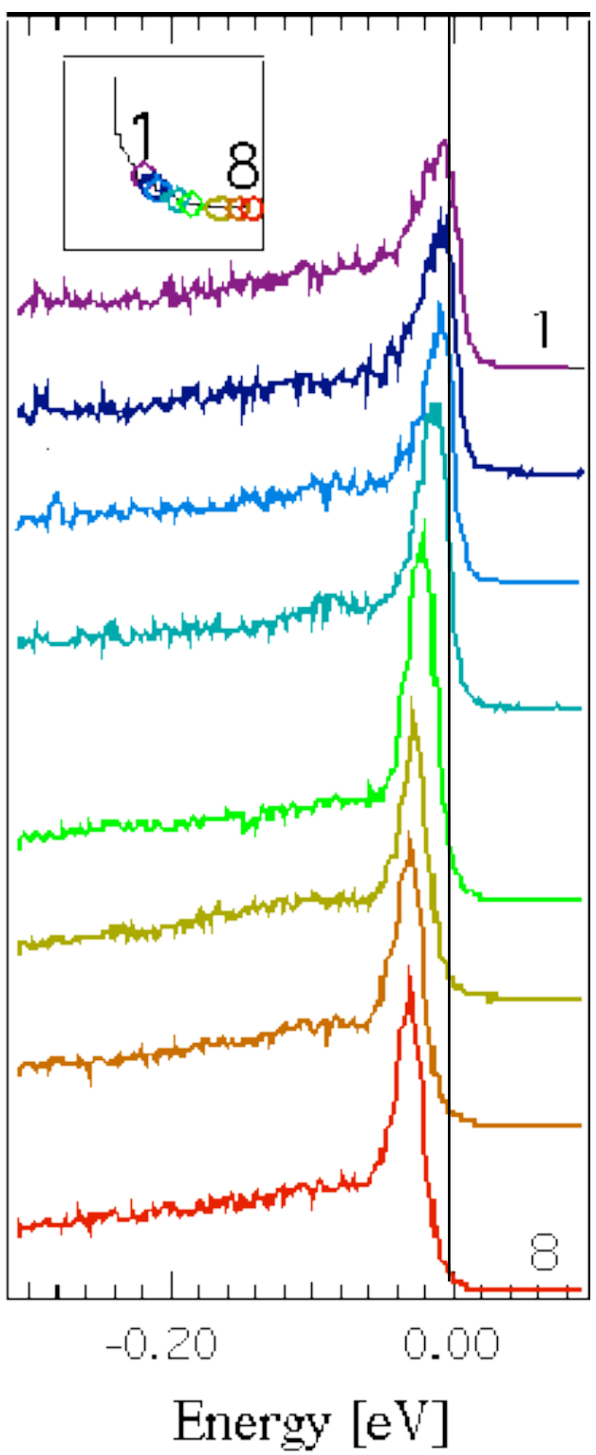


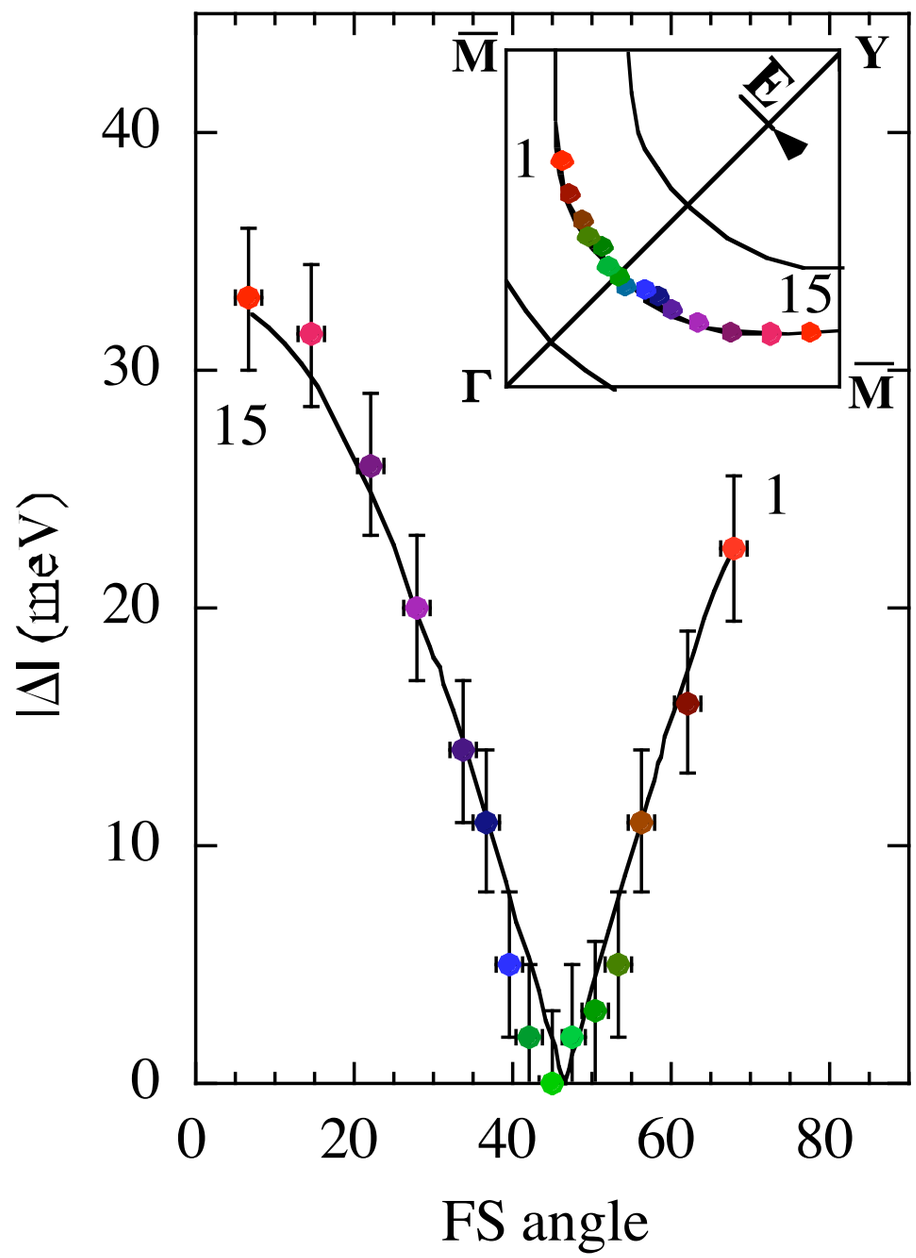






Shape of the superconducting gap

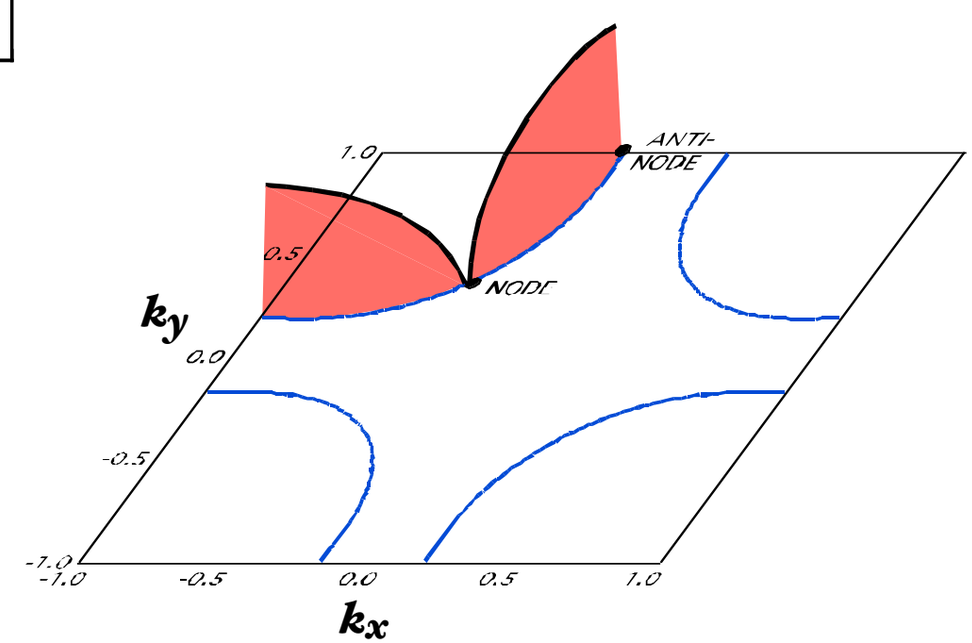




Shen, et al. PRL 70, 1553 (93)

Ding, et el., PRL 73, 3302 (94)

e- along diagonal to Cu-O bond not paired

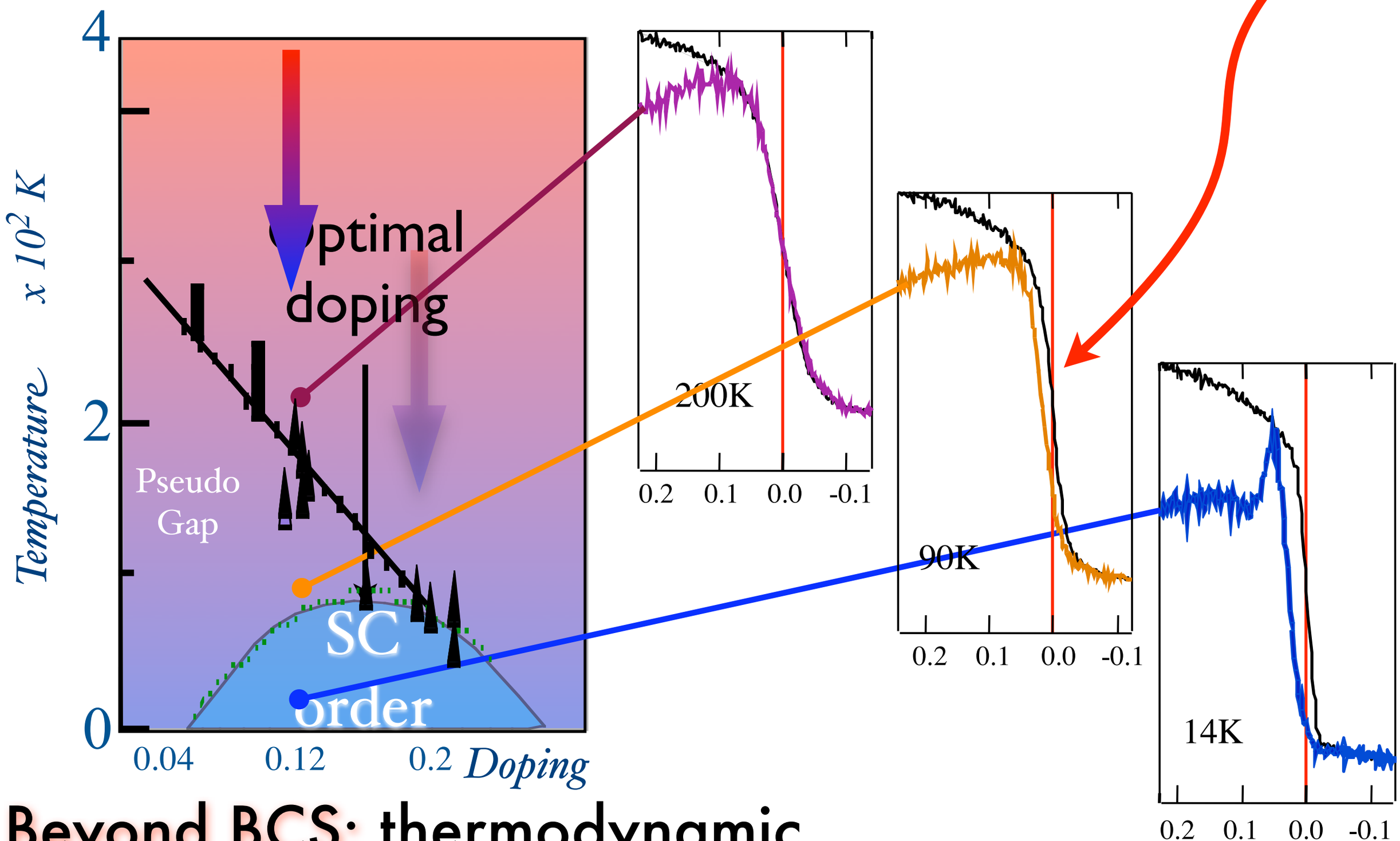


phase sensitive experiments

van Harlingen (1993, 95)

Tsuei & Kirtley (1994, 95)

Pseudogap: Supression of spectral weight at E_F

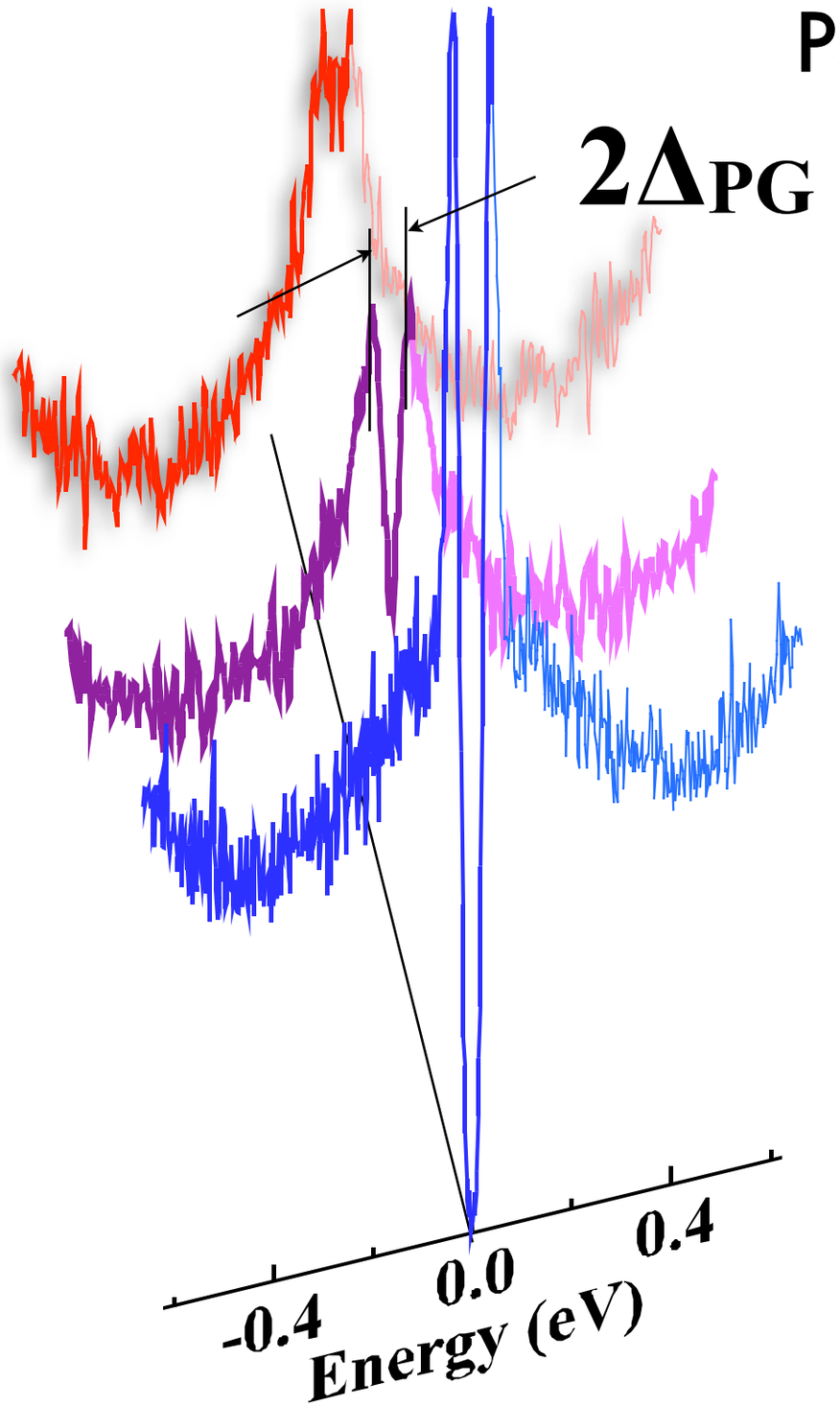


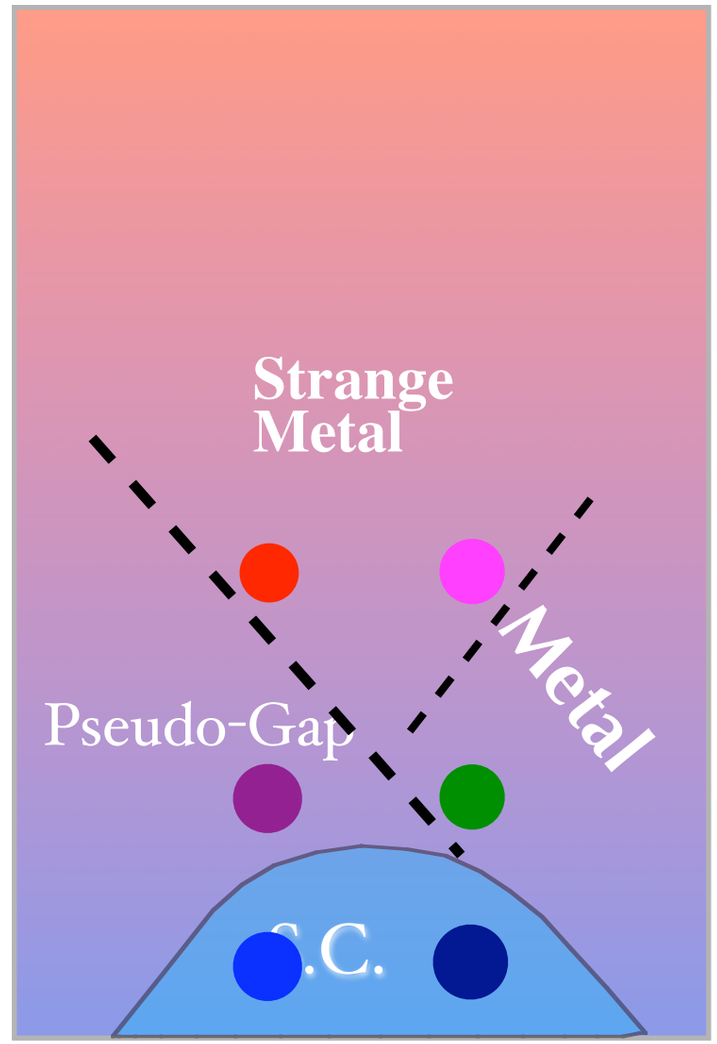
Beyond BCS: thermodynamic transition NOT mean field

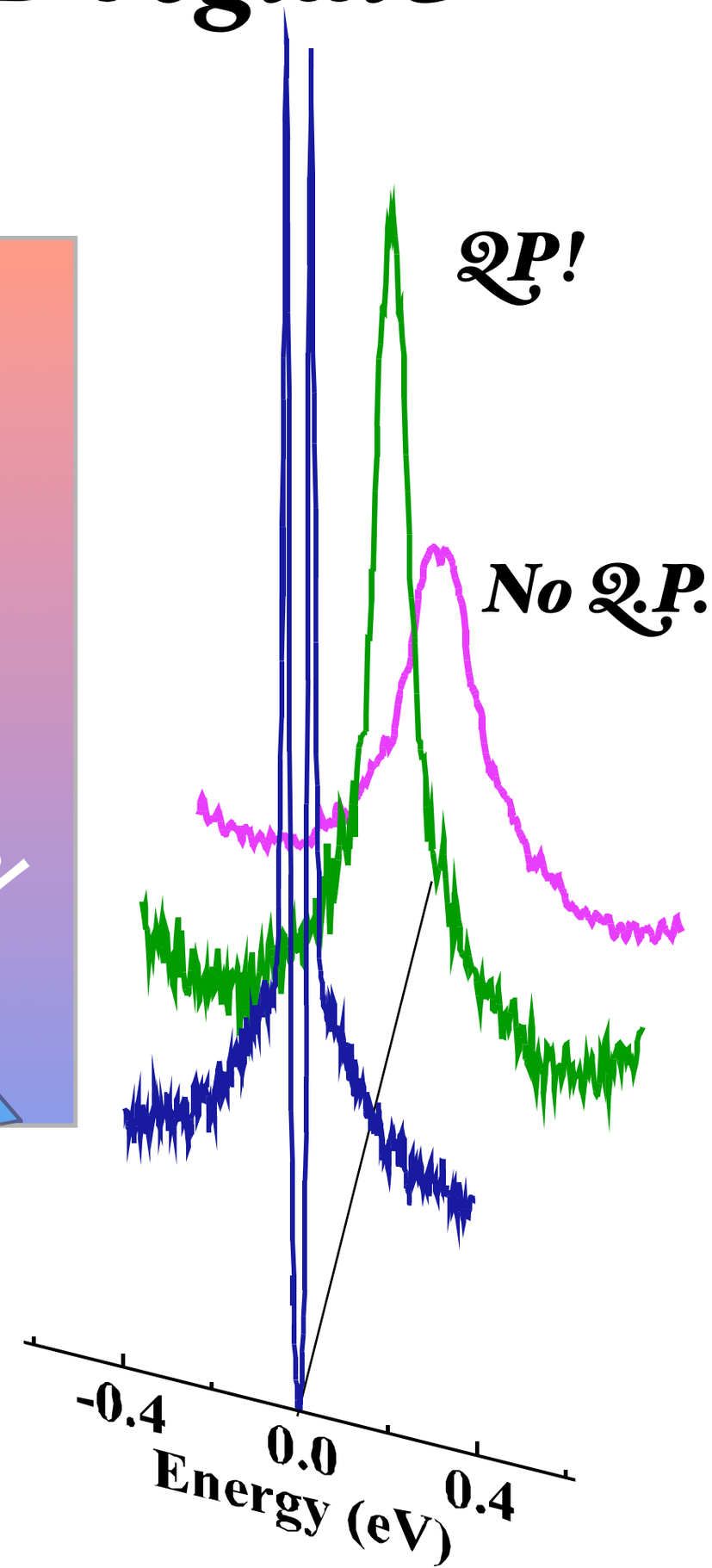
Ding, et al., Nature 382, 51 (96)
Loeser, et al. Science 273, 325 (96)

Contrast the UD and OD regime

Pseudogap same as SC gap



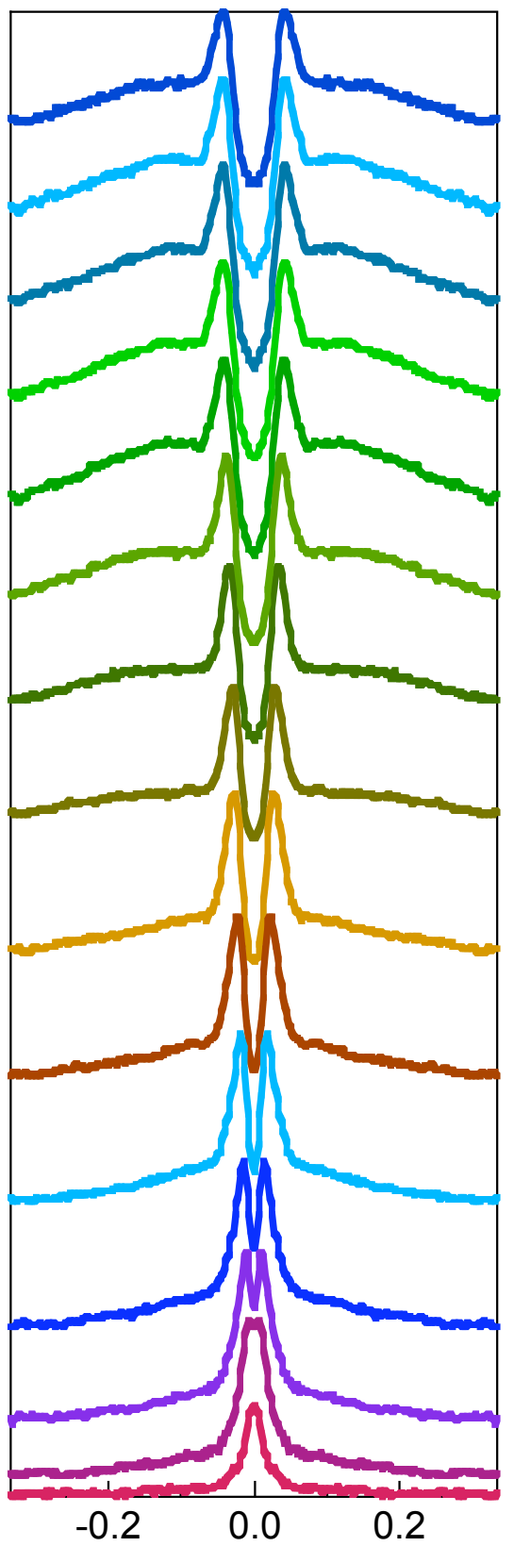


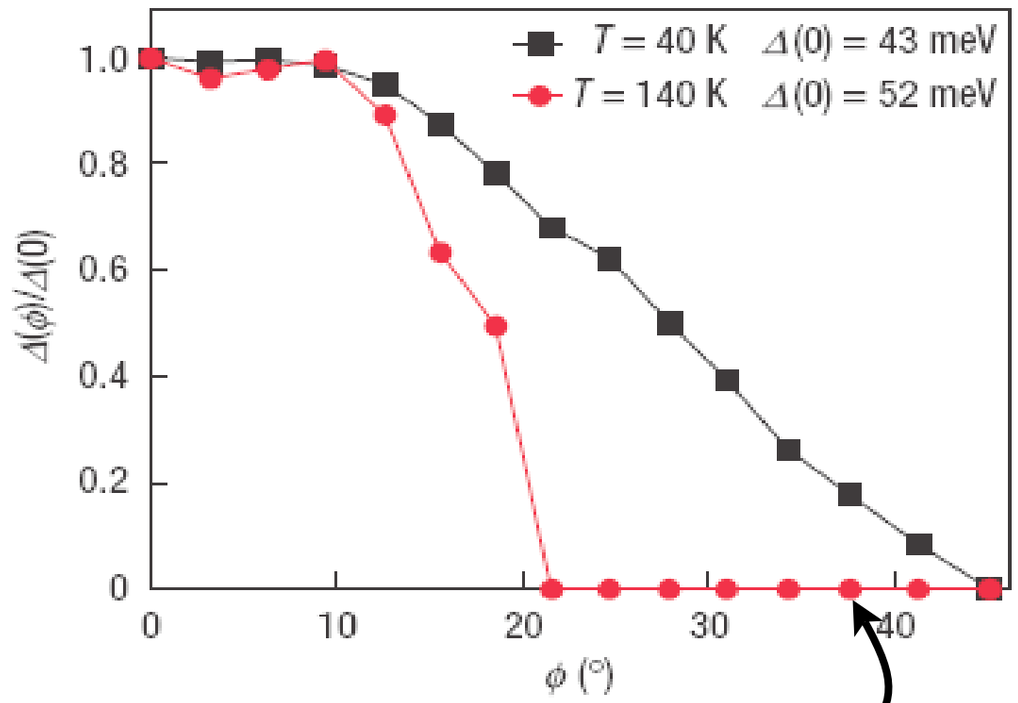


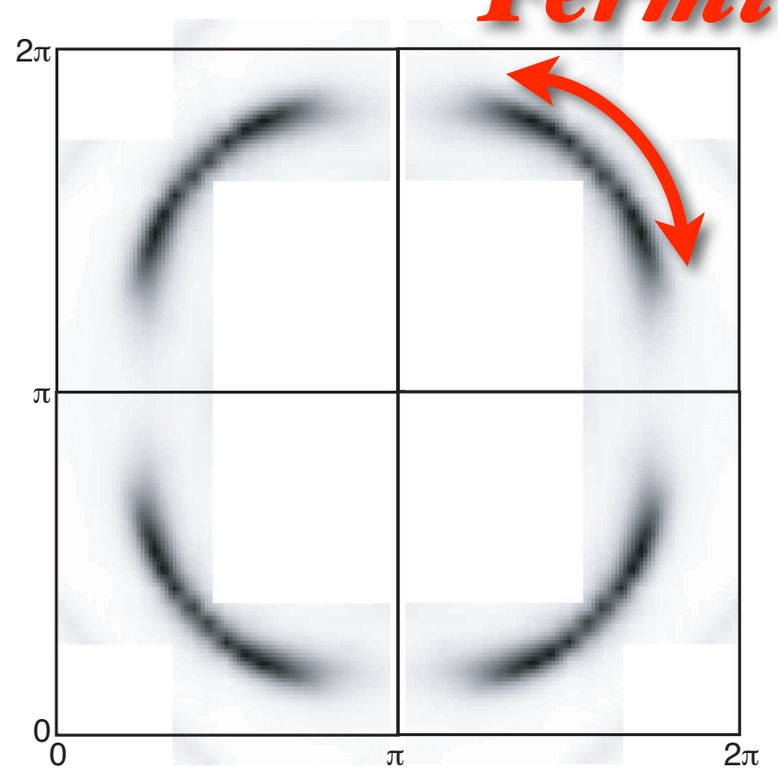
Beyond BCS: SC state does NOT arise from a Fermi liquid

Pseudogap leaves behind Fermi arcs

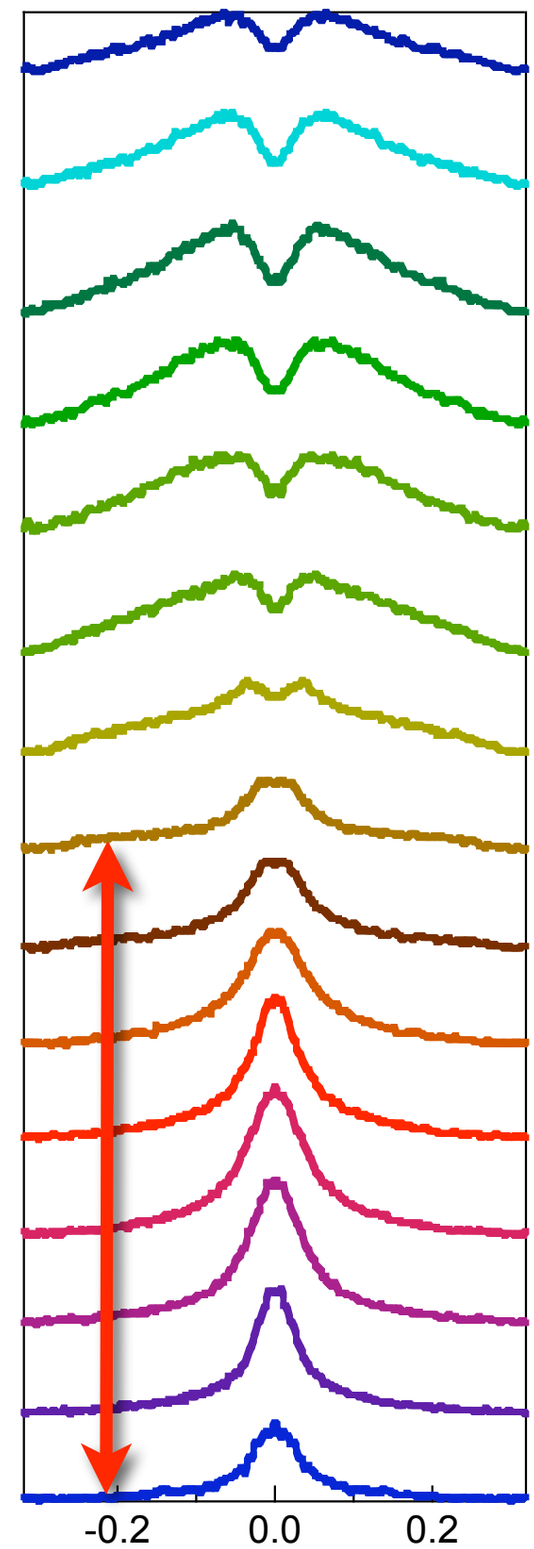
SC state







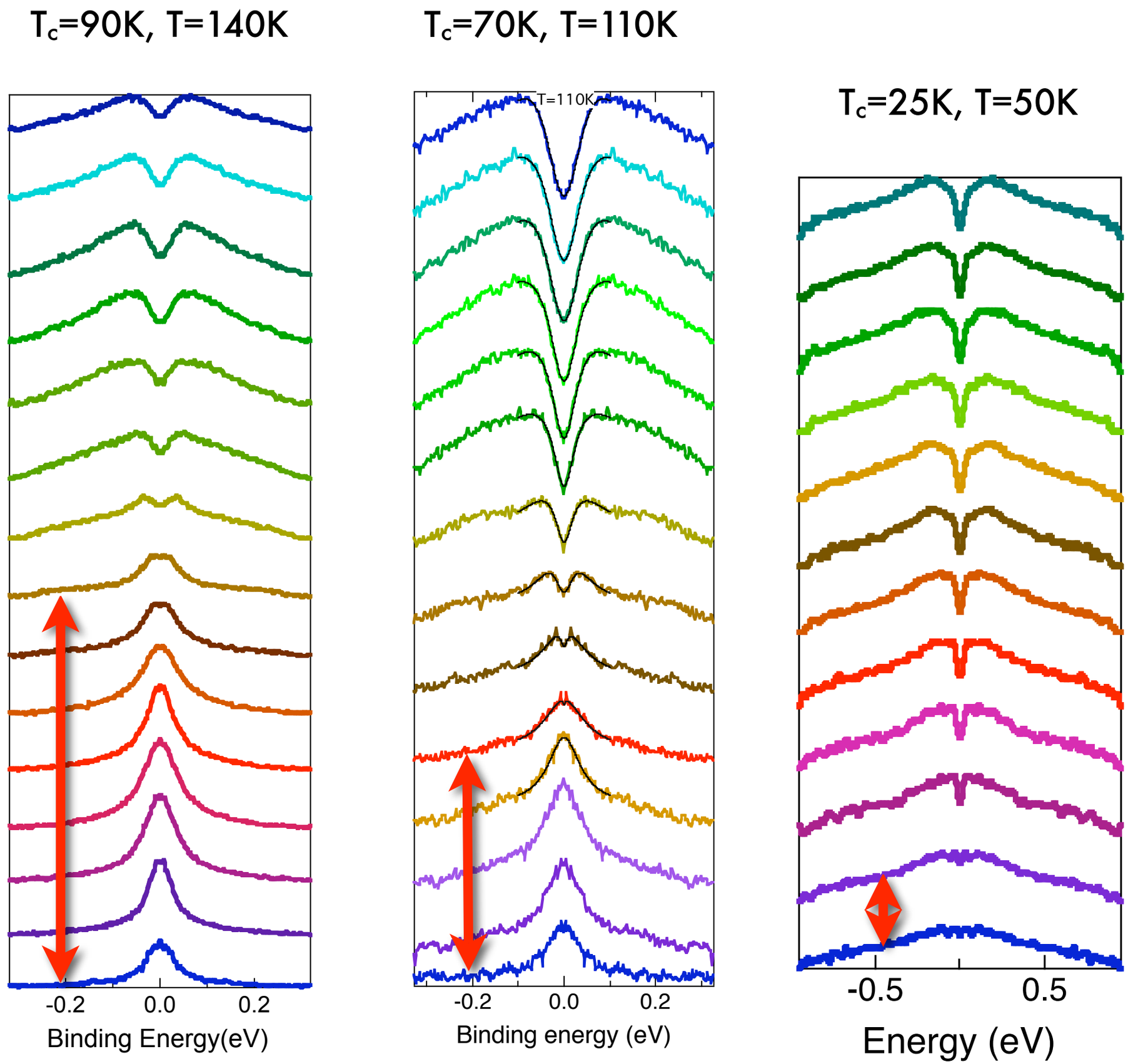
PG state



Norman, et al., Nature 392 (98) 157

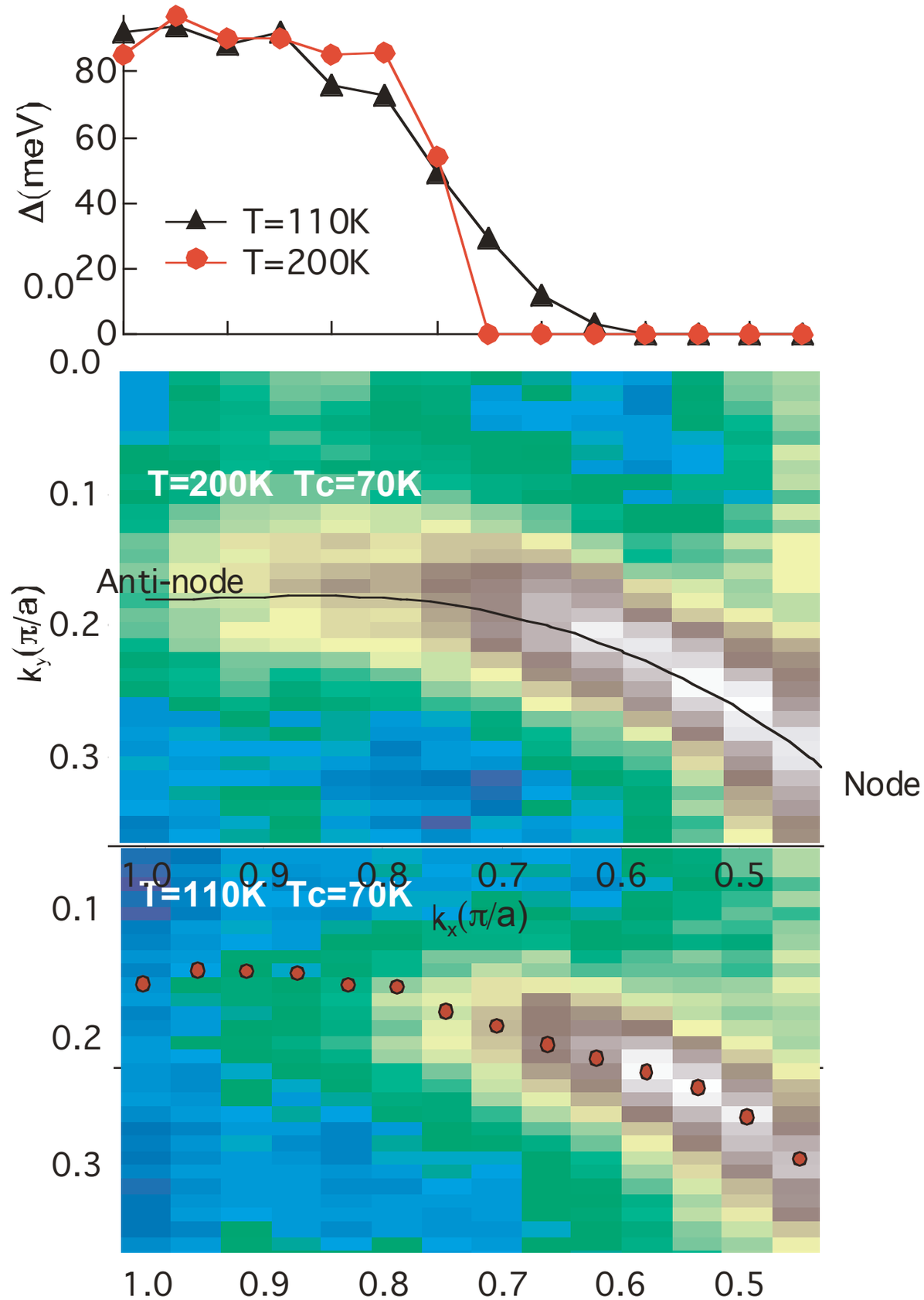
Scaling properties of the Fermi arcs

As the doping decreases, the Fermi arcs get shorter!



Scaling properties of the Fermi arcs

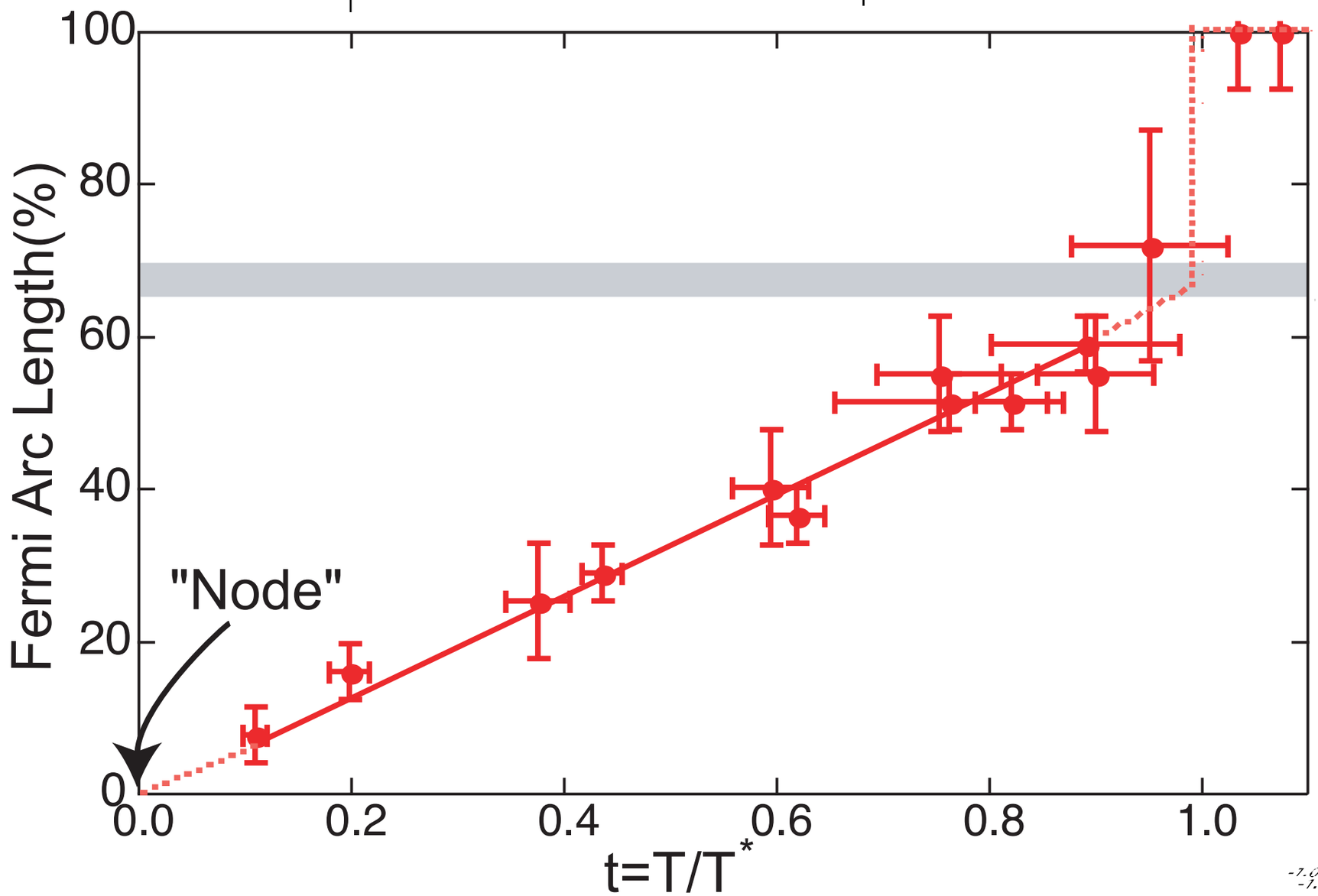
As the temperature decreases, the arcs also get shorter!

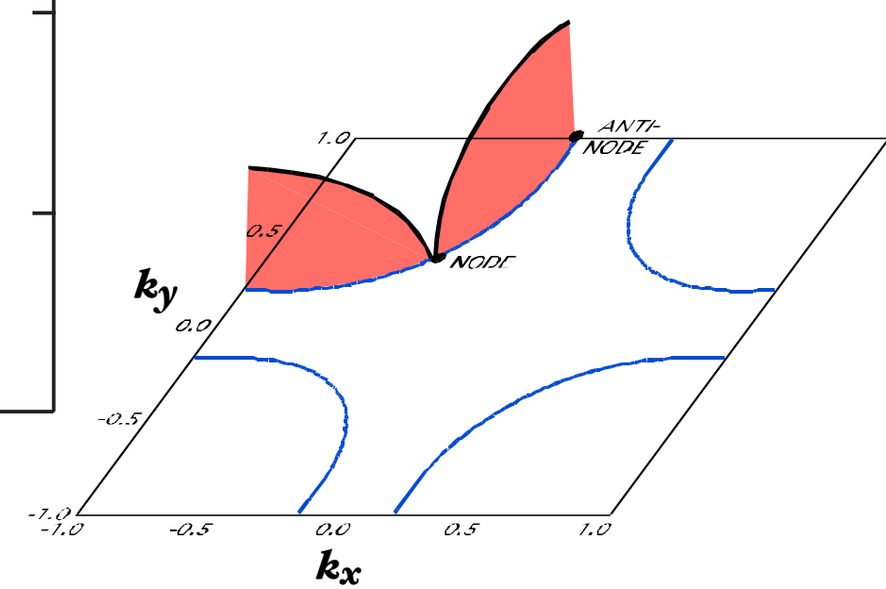


Scaling of the Fermi arcs

$t = T/T^*(x)$

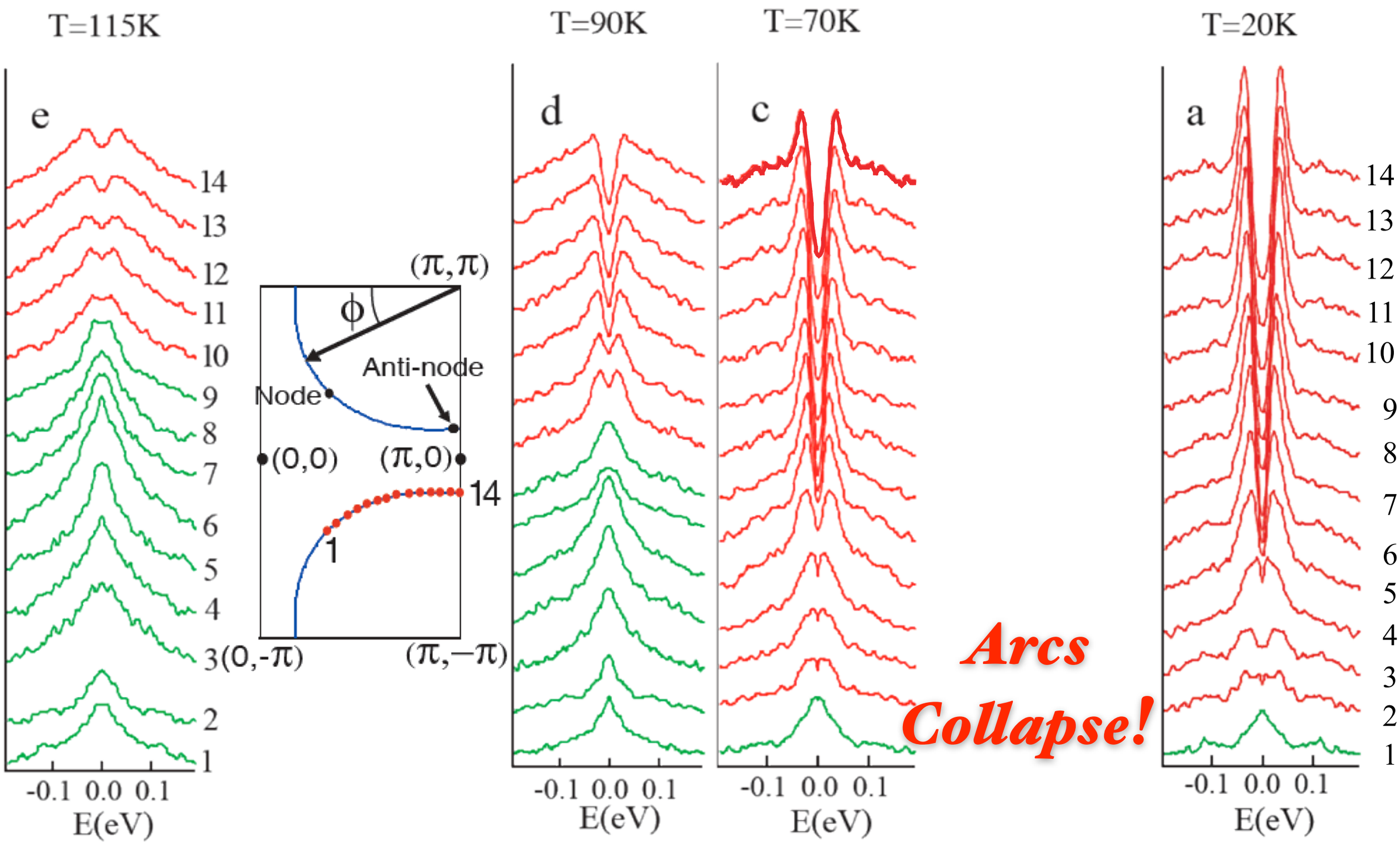
Kanigel, et al. Nature Physics, 2, 447 (06)





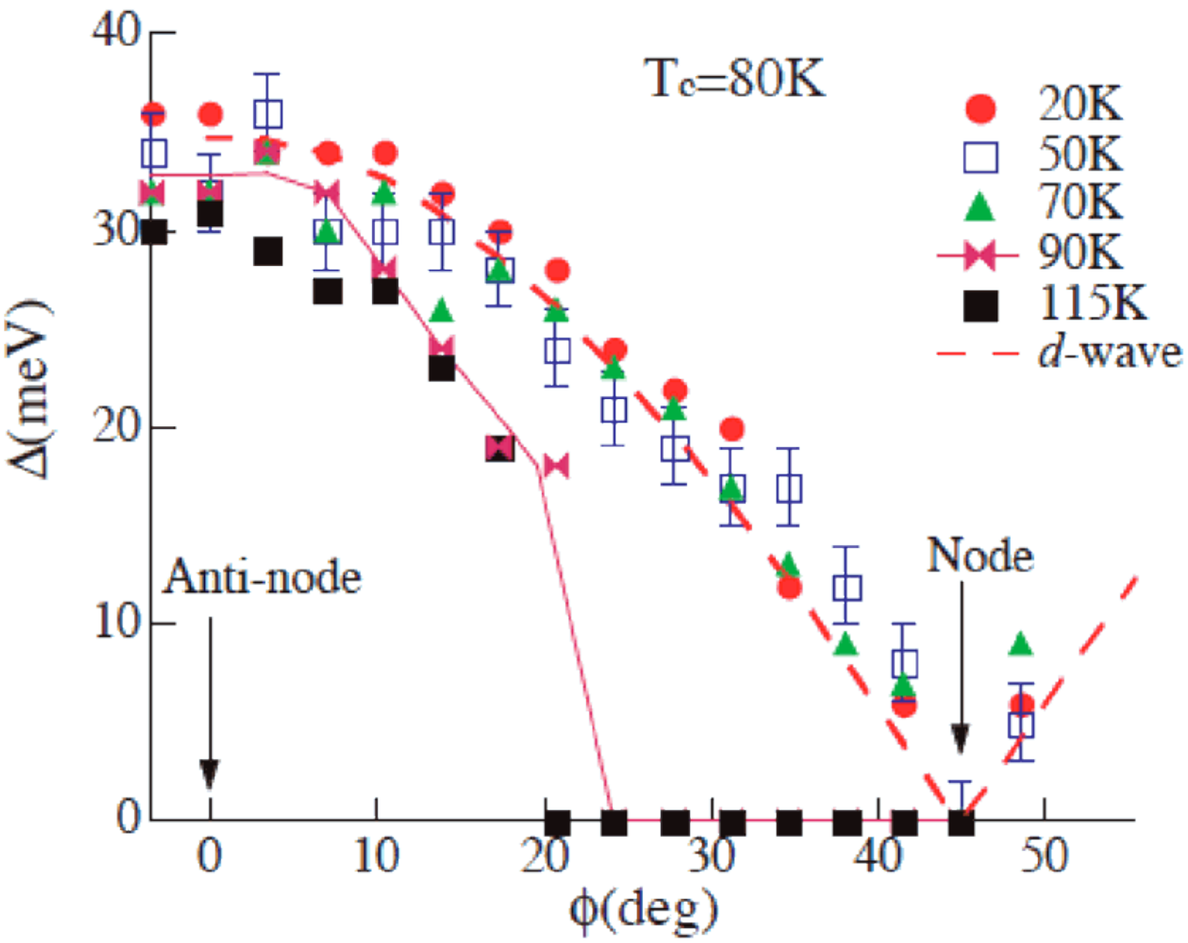
<u>If</u> you could go down to T=0 in the PG state, it would have four point nodes, just like a d-wave SC, but its NOT a SC!

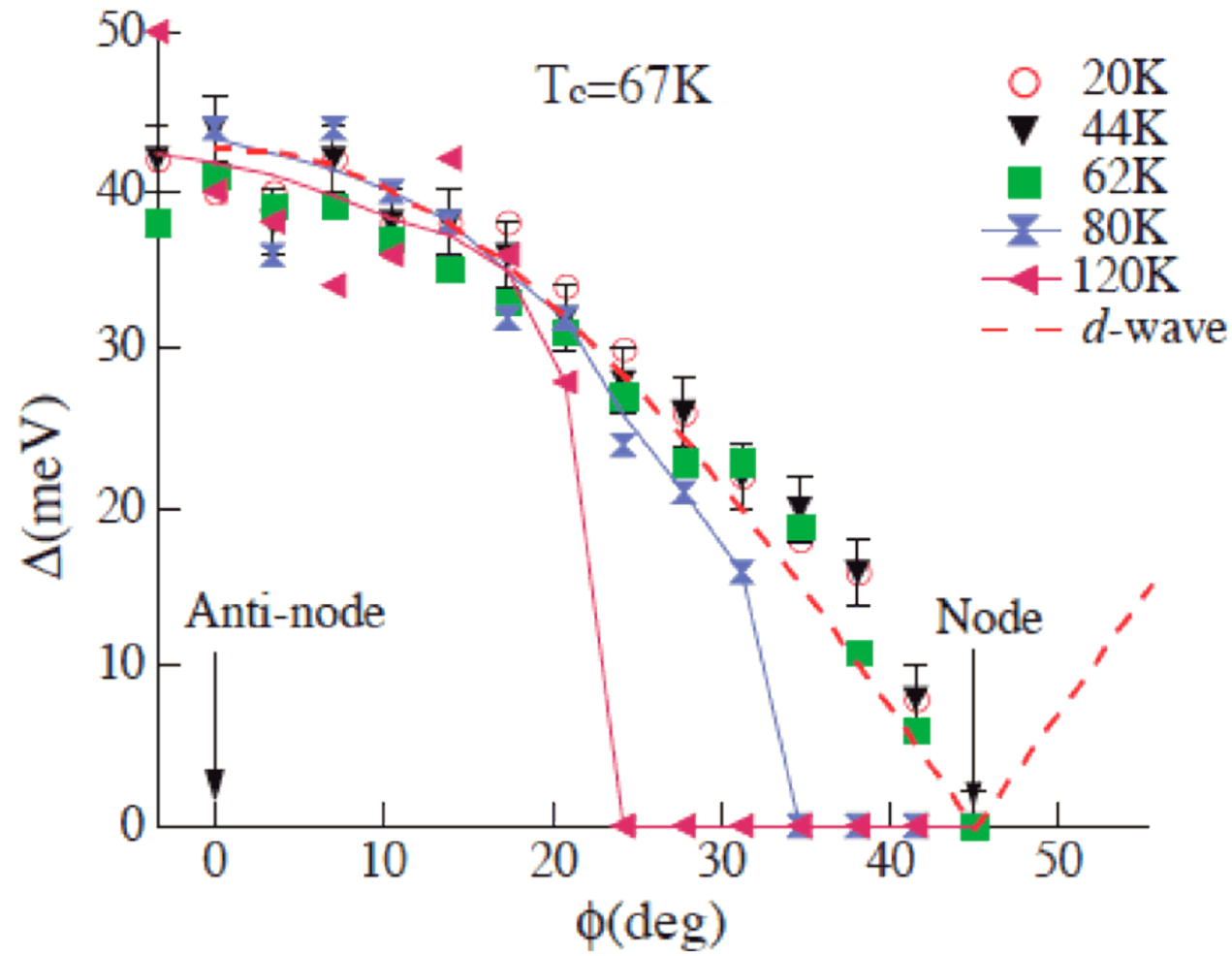
Are the Fermi arcs just a T-effect?



Beyond BCS: Δ shows NO T-dependence

Temperature evolution of Δ

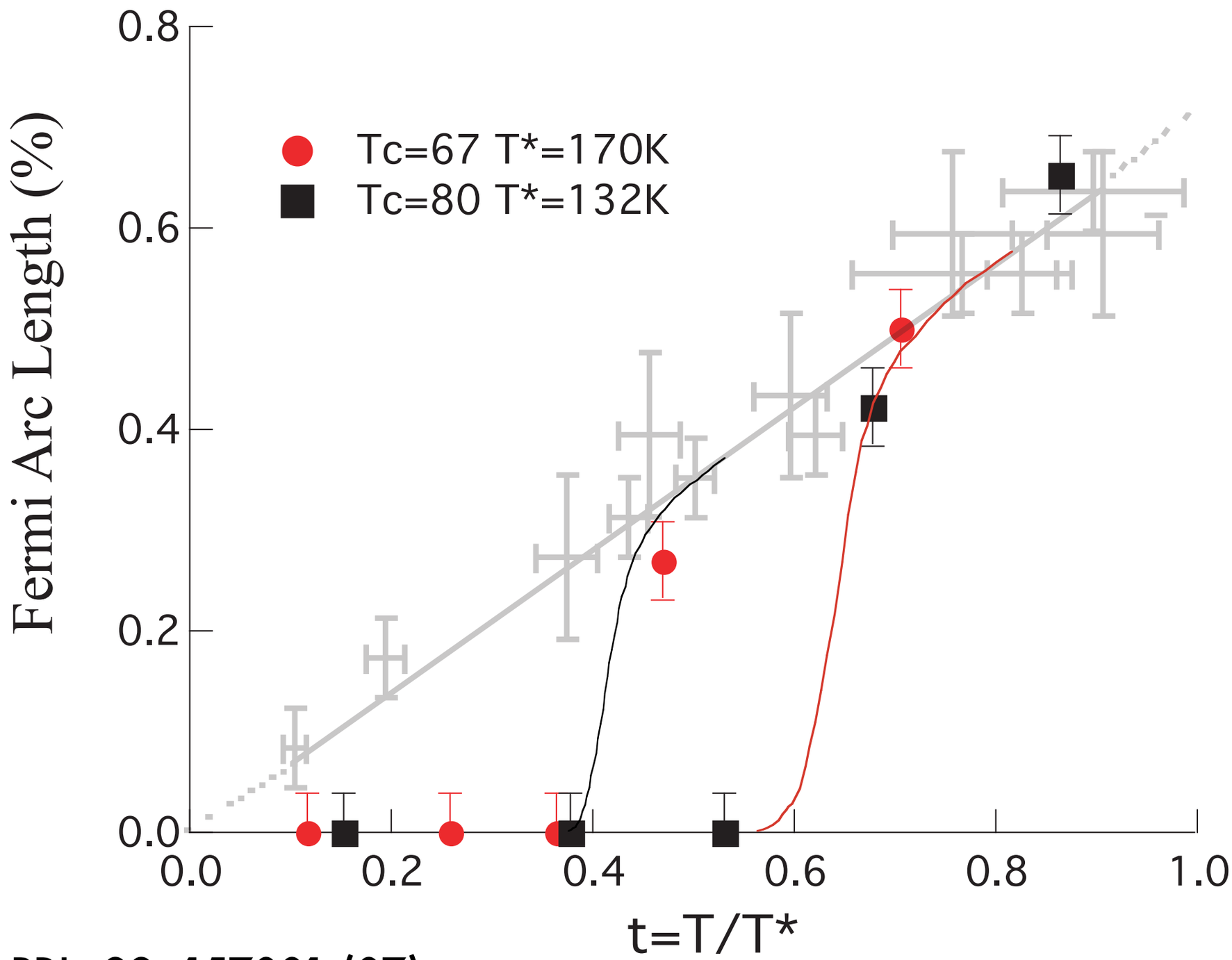




Kanigel, et al., PRL 99 (07) 157001

Beyond BCS: NO relation between the gap and tbe order parameter!

Fermi arc collapse controlled by transition width

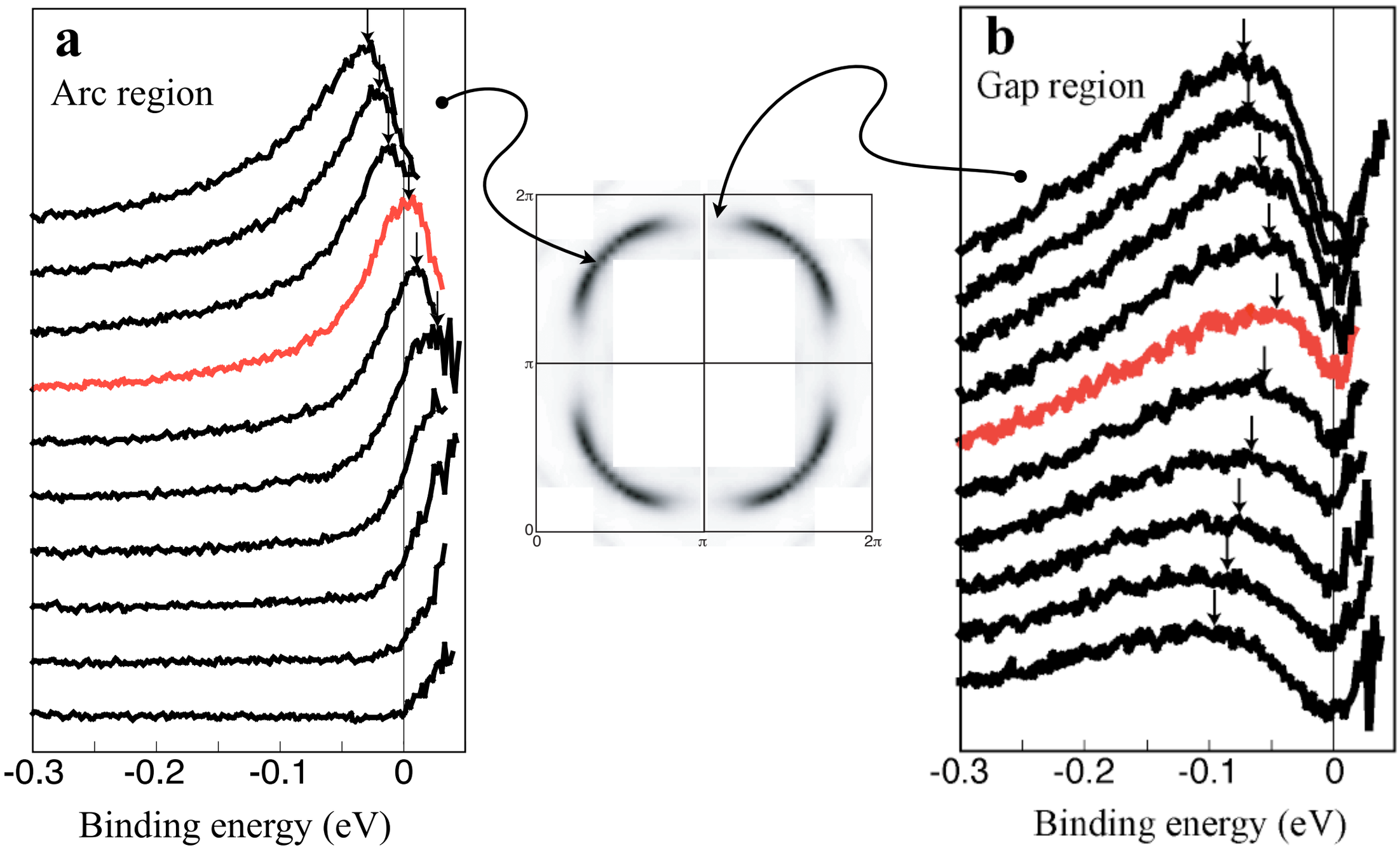


Kanigel, et al., PRL, 99, 157001 (07)

Pseudogap in parts like a metal and in other parts akin to a SC, but no LRO

Metal

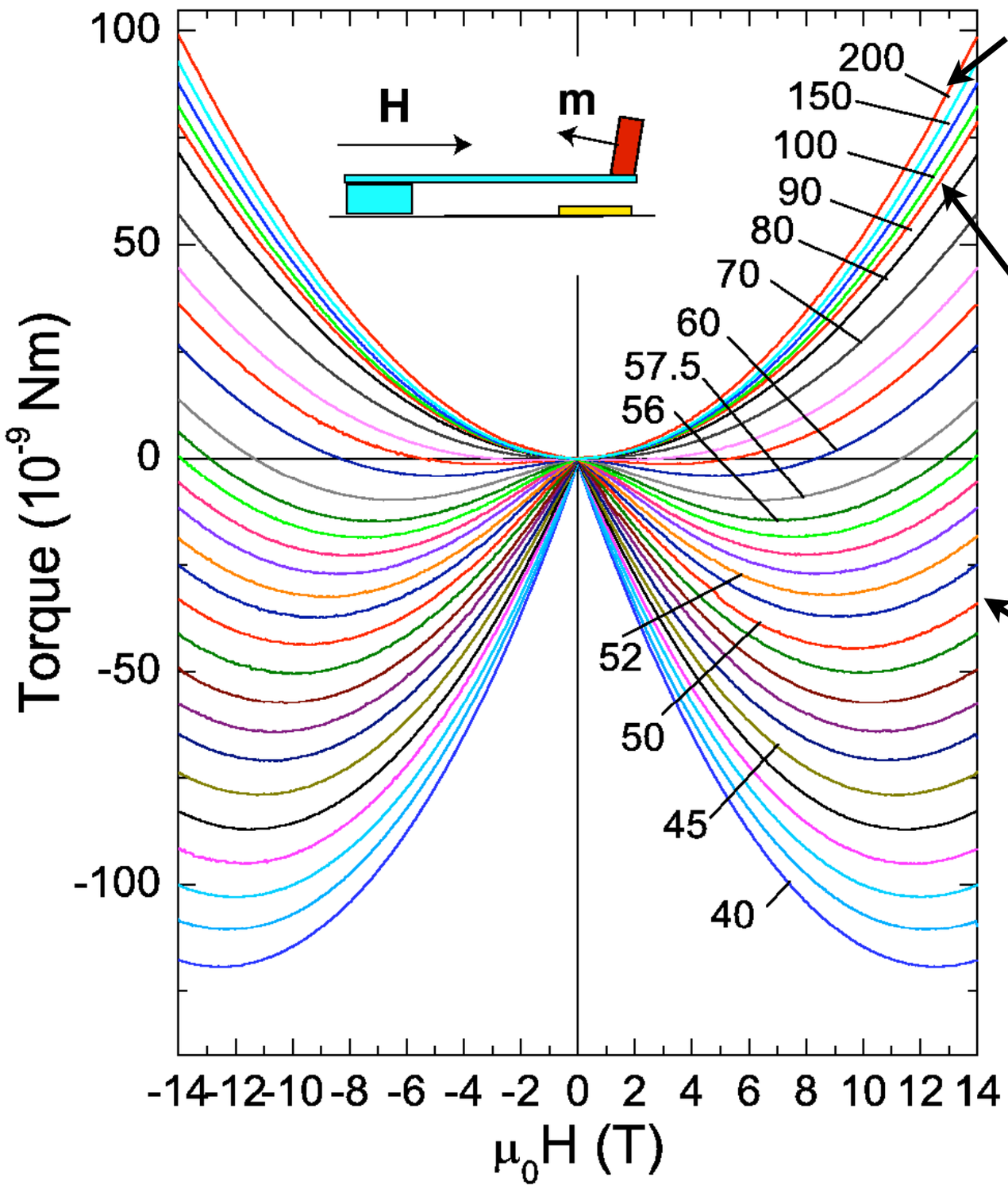
Superconductor



Fluctuating Diamagnetism in the PG phase

Wang, et al., PRL 95, 247002 (05)

Underdoped
Bi 2212



Parabolic behavior at highest *T* due to

$$\Delta \chi H_z$$

Less than parabolic due to diamagnetism

T_c

Properties of the pseudogap

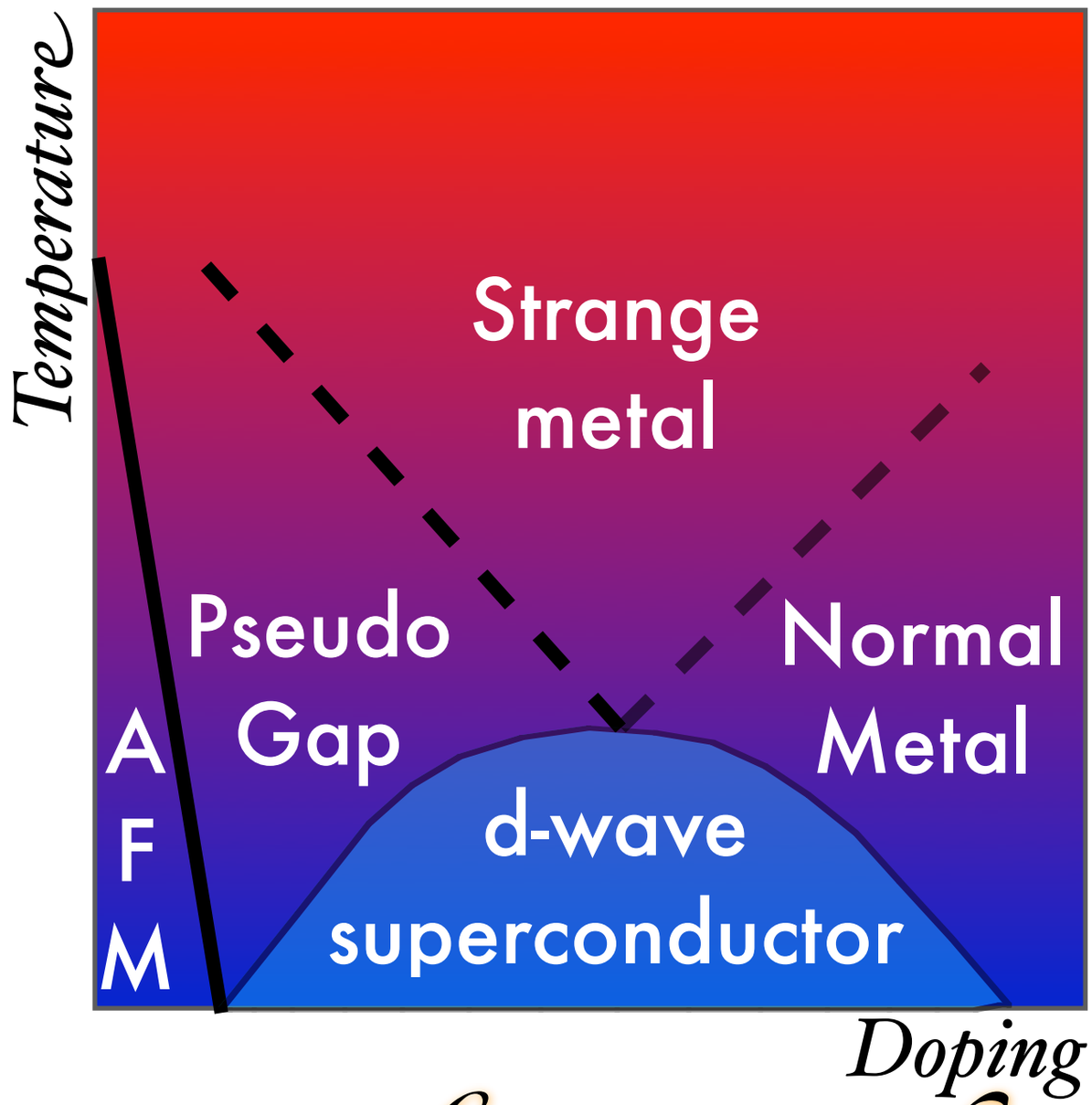
- PG same magnitude as Δ.
- Anisotropy is T-dependent, leading to disconnected Fermi arcs below T*
- PG at same k_F of the SC gap and of the normal state
- Fermi arc collapses below T_c.
- There is fluctuating diamagnetism in the PG

$\Rightarrow$ PG is a precursor to the SC gap

Summary: What ARPES tells us

Phase diagram exhibits the failure of three paradigms of 20th Century Solid State Physics!

Band theory fails for the x=0 parent insulator



Landau's Fermi liquid theory fails for the strange metal and pseudogap regimes

BCS fails for the Unconventional SC for x<optimal

Thank you for your attention