Title: The strange â€œnormalâ€• state of high temperature superconductors, heavy fermion, and charge density wave materials.

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Abstract: In describing condensed matter, some well established paradigms have allowed much progress to be made in understanding and using materials. But in the last 15 - 20 years, new materials, such as heavy fermions, high temperature superconductors, and now charge density wave-supporting materials, have been shown to require new paradigms in describing them. While much progress has been achieved in that time, we still do not have a widely accepted theoretical description of the nature of their electronic excitations.

the strange "normal state" of high T_c superconductors, heavy fermion and charge density wave materials

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Funded by

NSF

U.S. DEPARTMENT OF ENERGY

Collaborators

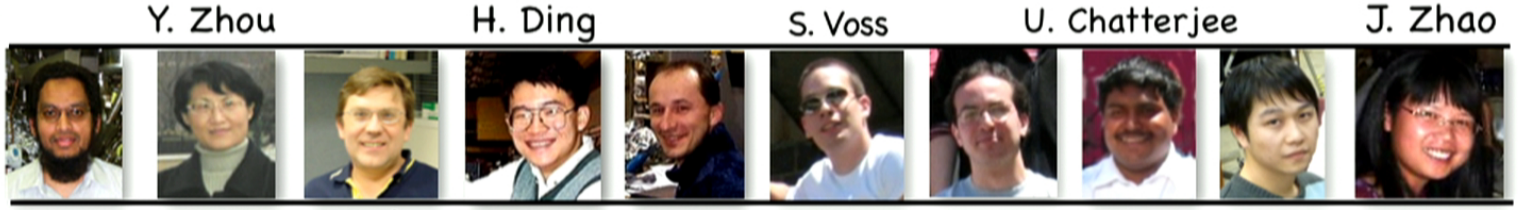
Students

Post-Doctoral Fellows

Senior Collaborators

Collaborators

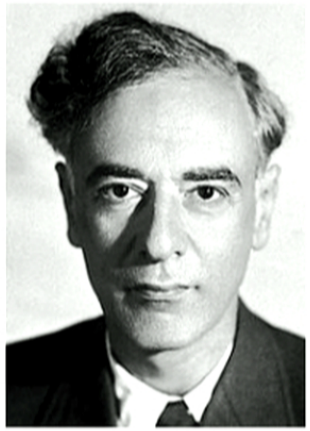
Students

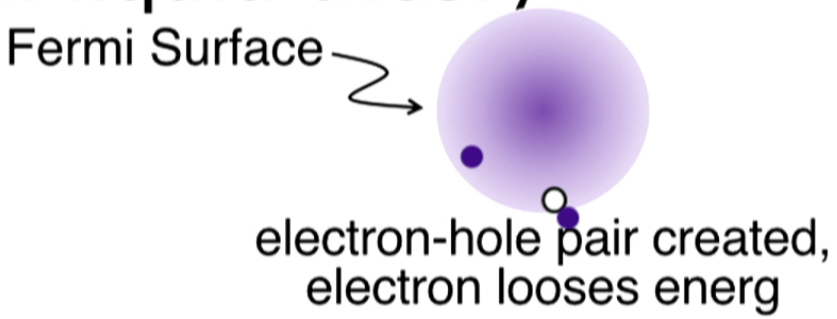


Post-Doctoral Fellows

Senior Co

Landau's Fermi liquid theory





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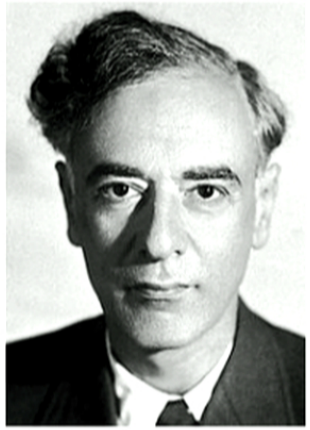
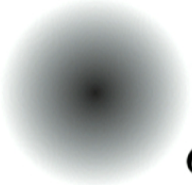


Fermi Surface

electron-hole pair created,
electron looses energ

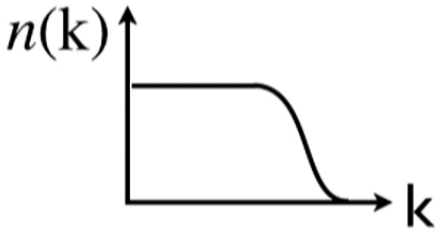
electron "dressed"
by excitations



$$m_e \to m^*$$

$$\epsilon \to \epsilon_0 + \Sigma(\omega, \mathbf{k})$$

Particles ⇨ quasi-paticles



⇨

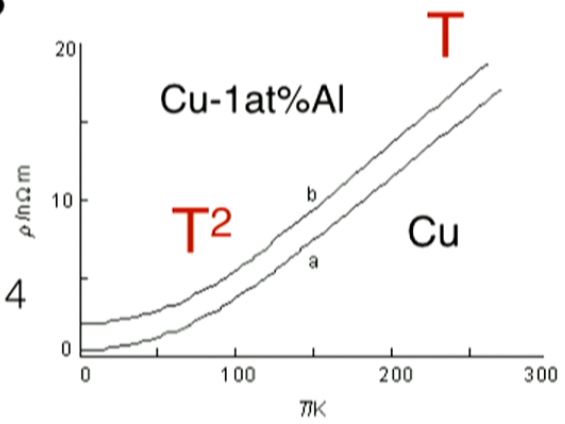
what do we mean by strange metals?

metals with properties very different from those of elemental metals

- RESISTIVITY

An excellent metallic conductor

www-sp.phy.cam.ac.uk/~wa14



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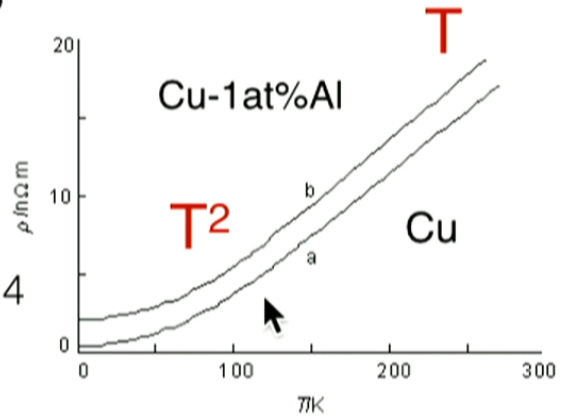
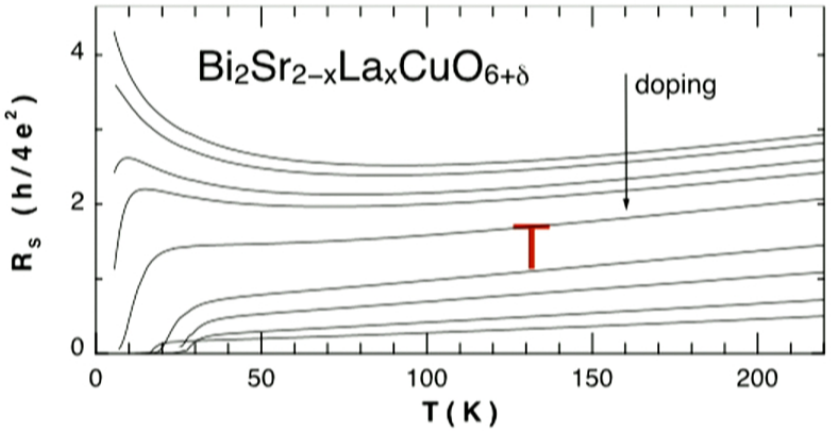
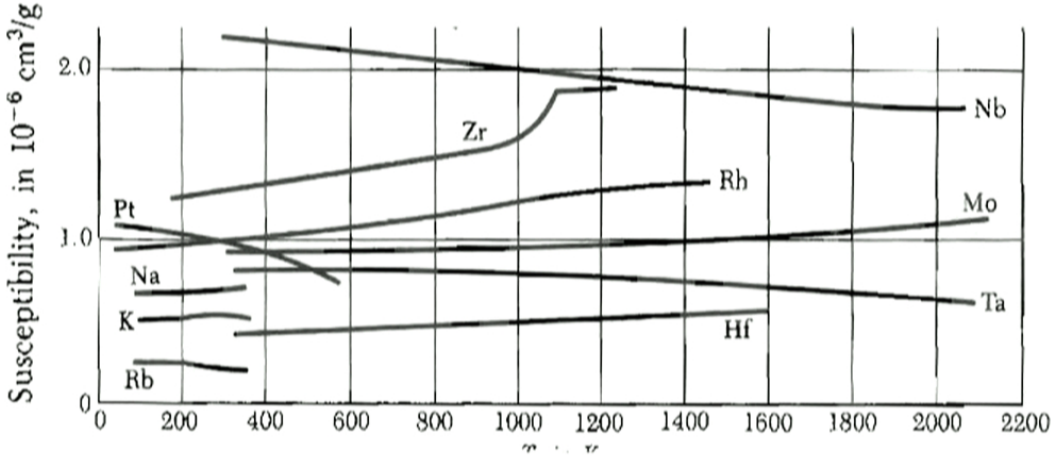
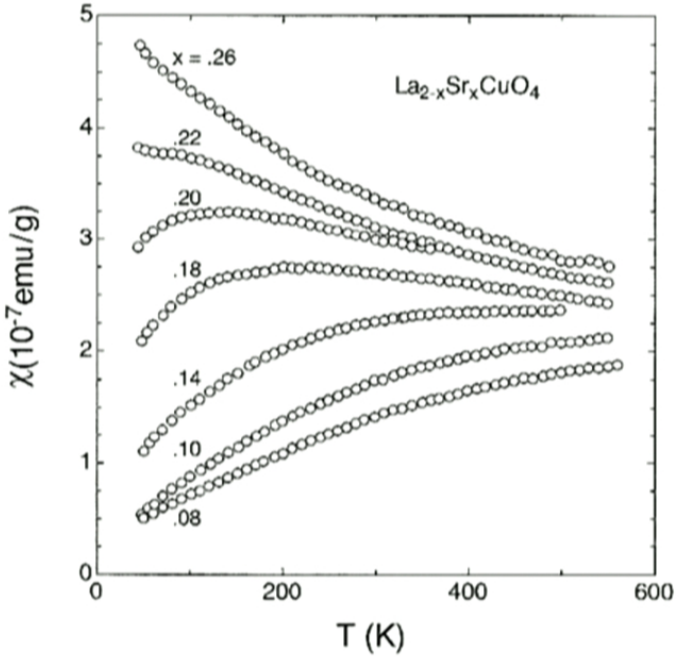


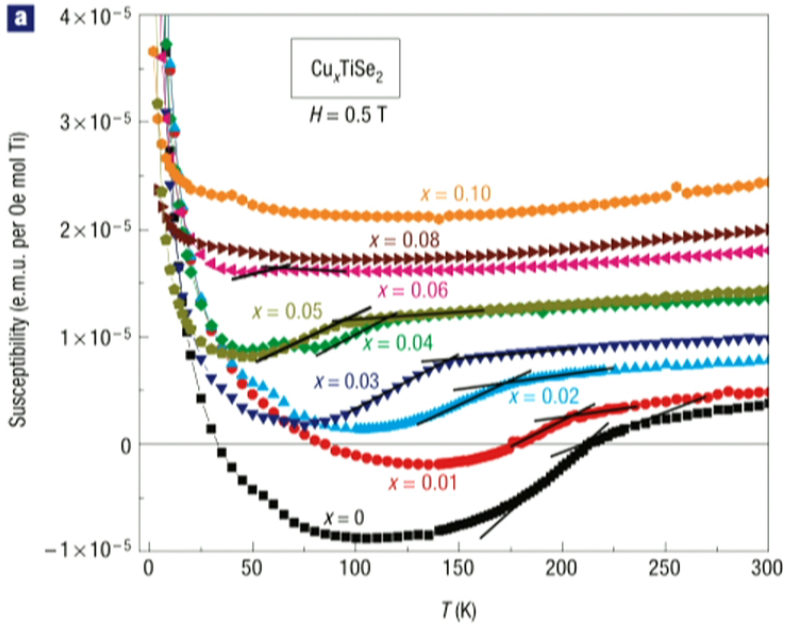
strange metals



- Magnetic
- susceptibility







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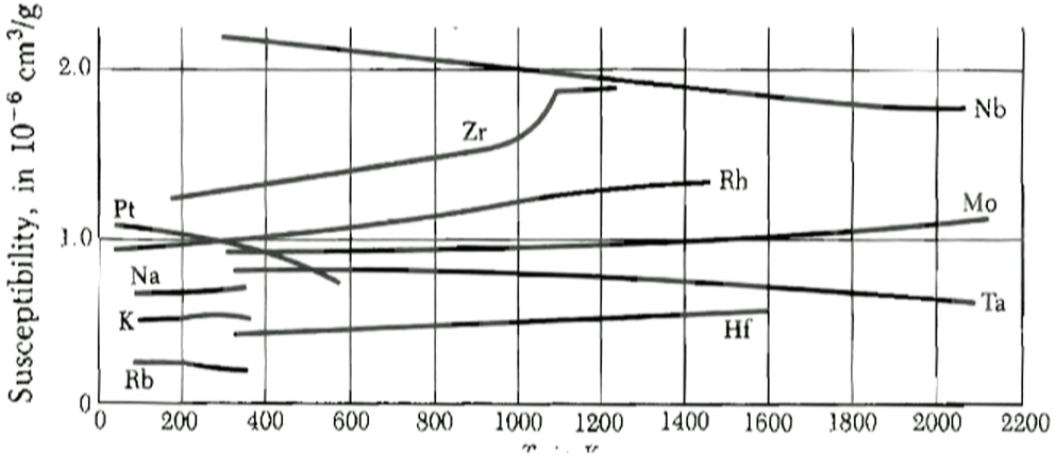
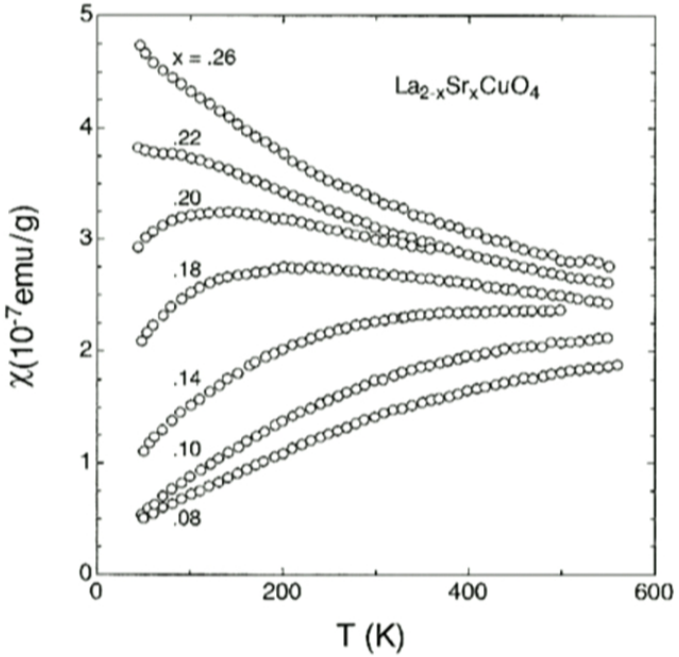
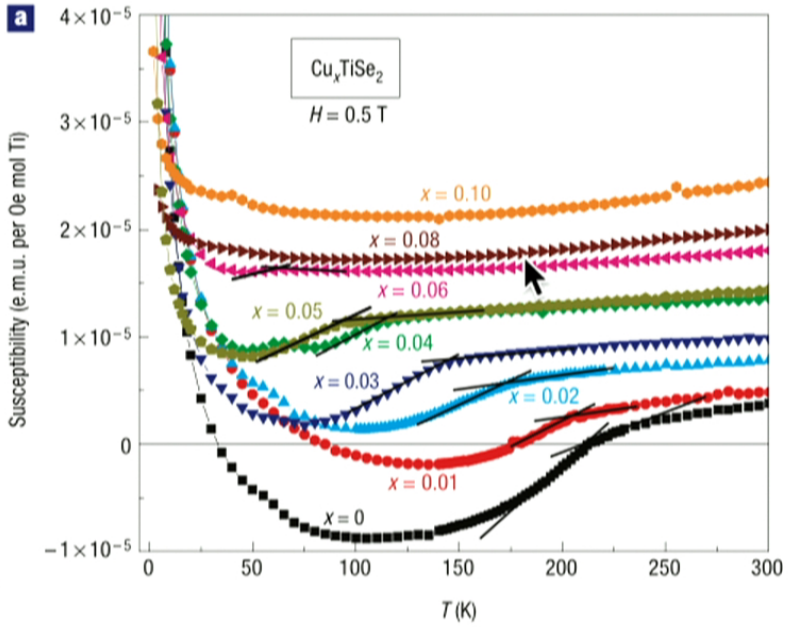
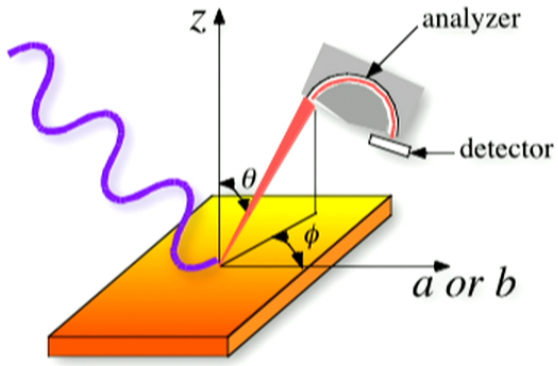


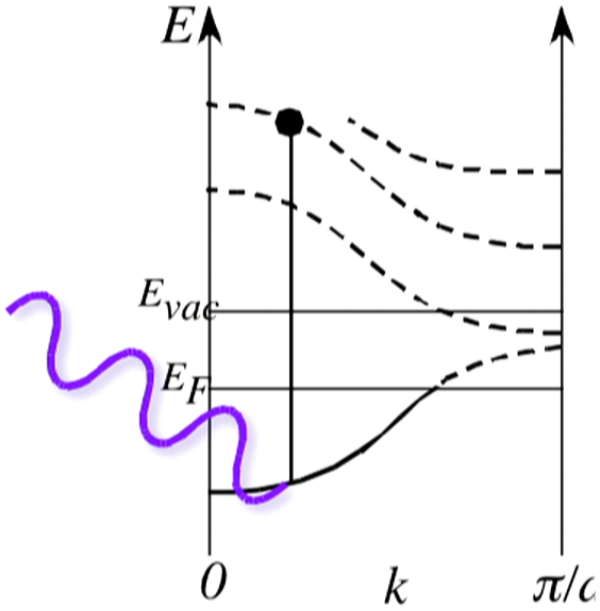




angle-resolved photoemission spectroscopy (ARPES)

Photons in - electrons out





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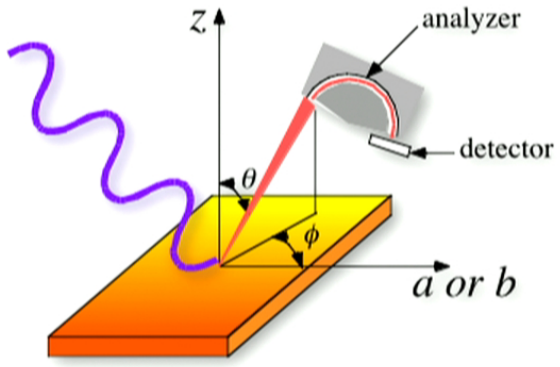
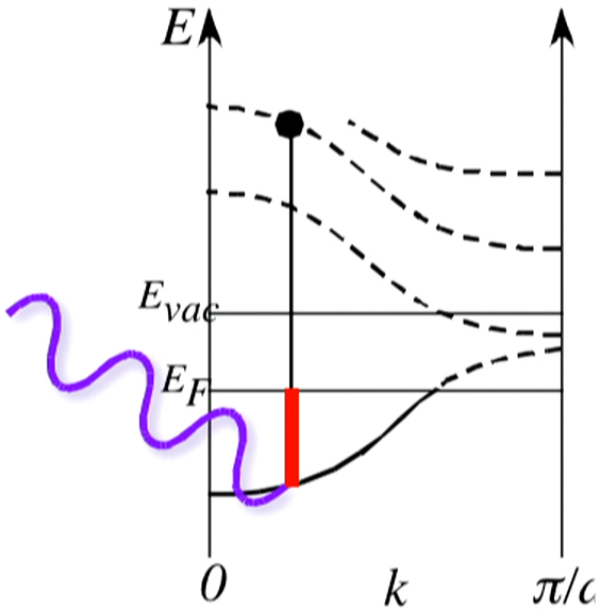
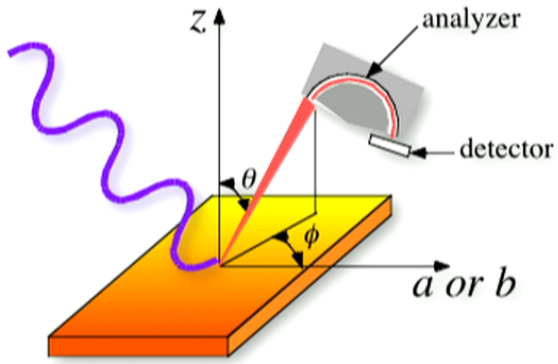


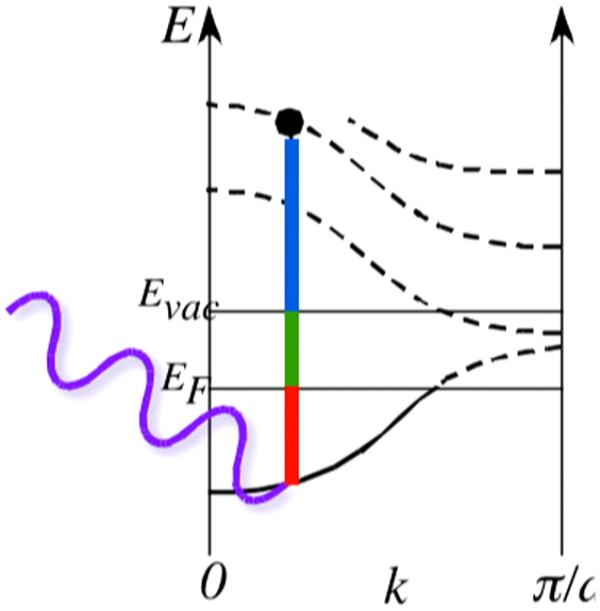


E_B

angle-resolved photoemission spectroscopy (ARPES)

Photons in - electrons out

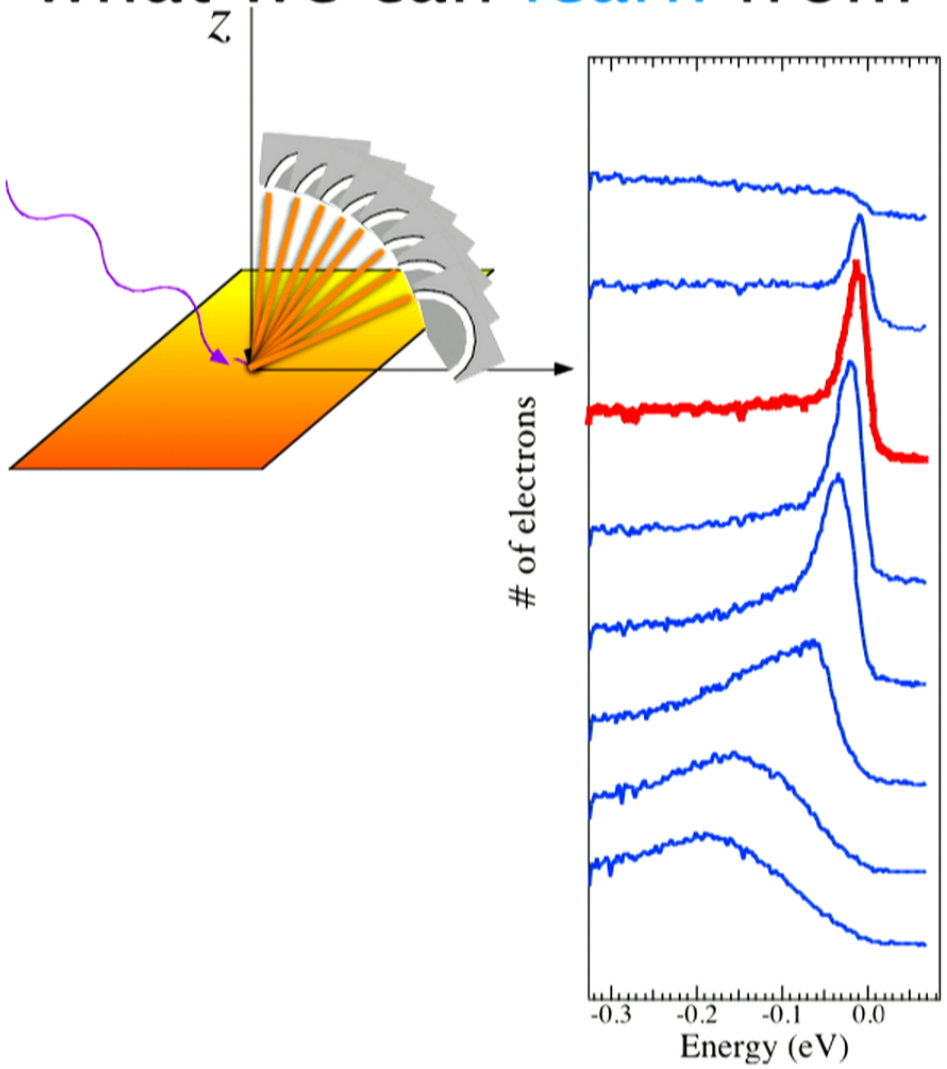




$$\vec{k}^{f}_{//} = \vec{k}^{i}_{//} = \sqrt{\frac{2mE}{\hbar^2}} sin\theta$$

$$E_B + \Phi + E_K = h\nu$$

what we can learn from ARPES spectra



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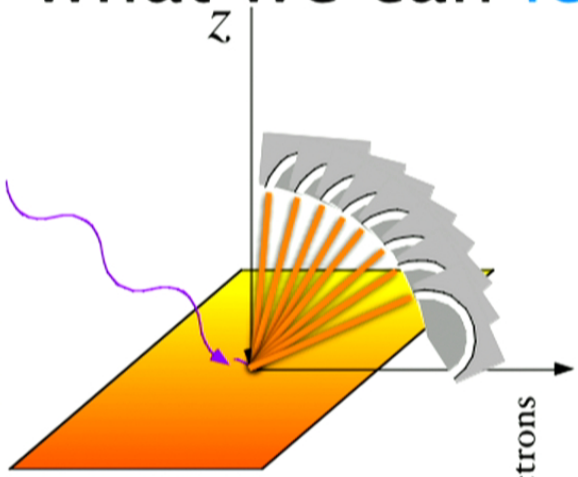
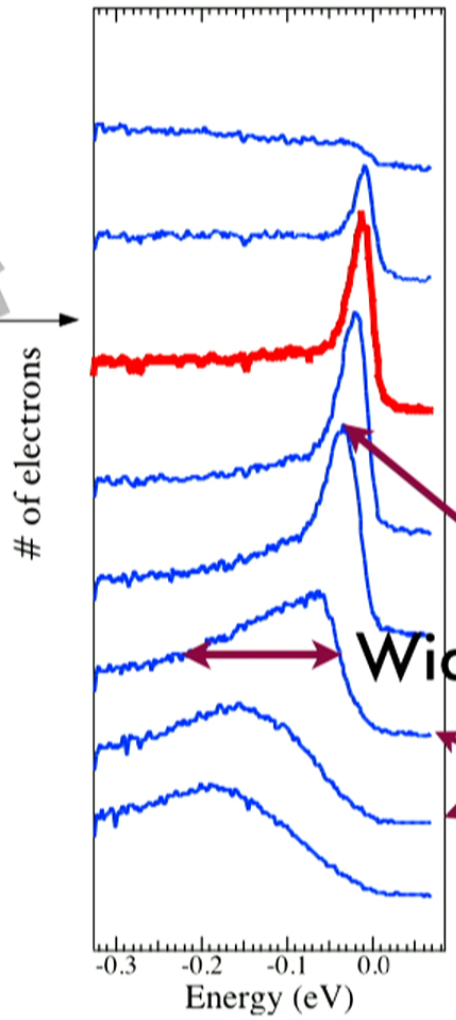
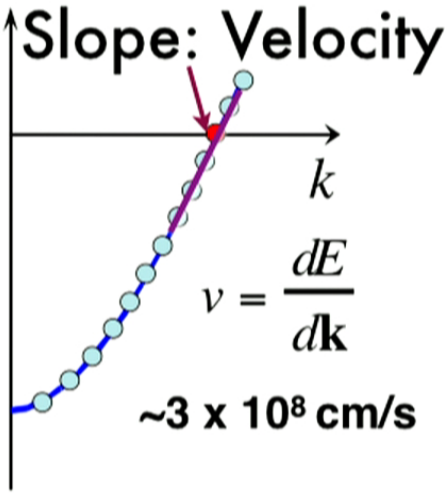




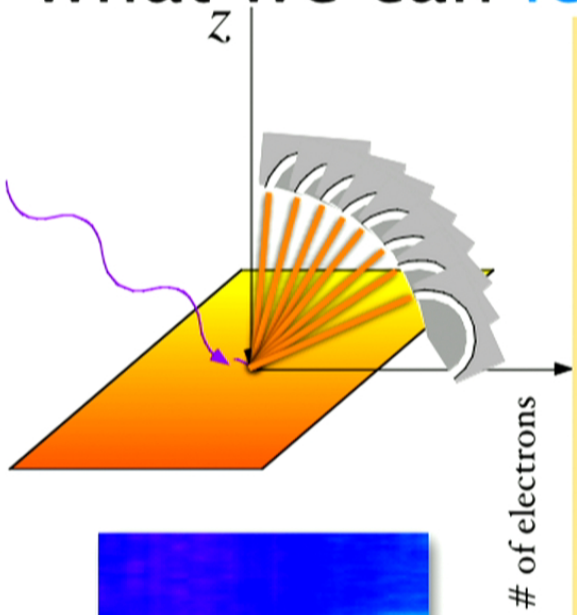


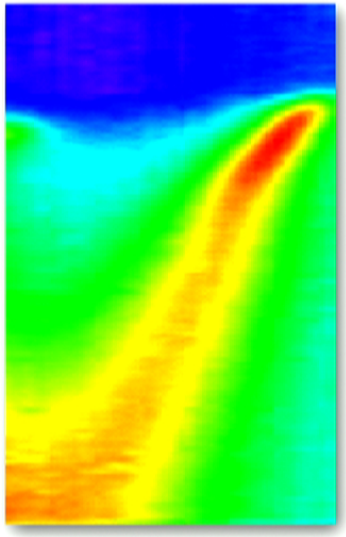
Position: Energy

Width: 1/Lifetime

Each spectrum corresponds to a particular k

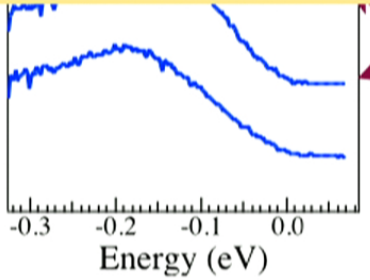
what we can learn from ARPES spectra





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
  δk ~ 0.003 (π/a)
  $\delta\omega$ ~ 1– 15 meV



Each spectrum corresponds to a particular k

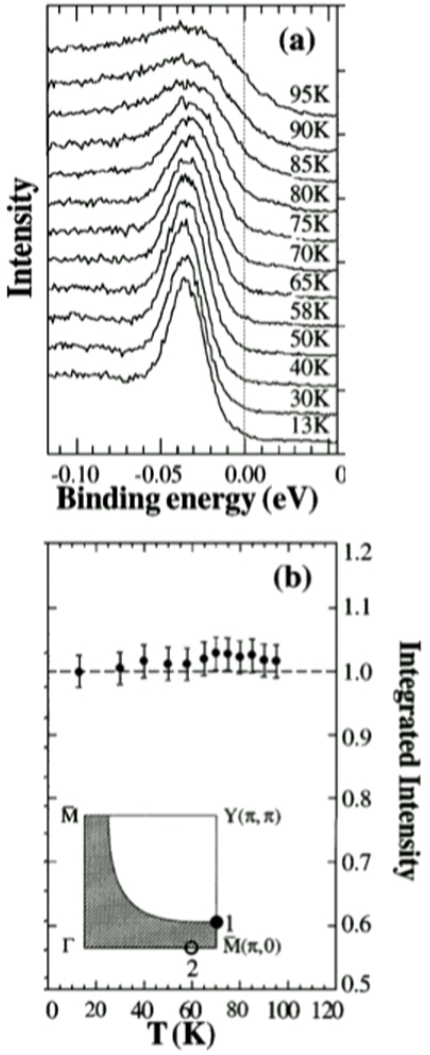
beyond band structure mapping

sum rules in ARPES

$$\int_{\infty}^{\infty} f(\omega,t)A(\mathbf{k},\omega,t) = n(\mathbf{k})$$

$$A(-\epsilon_{\mathbf{k}},-\omega) = A(\epsilon_{\mathbf{k}},\omega) \Longrightarrow n(\mathbf{k}) = const.$$

Impulse approximation



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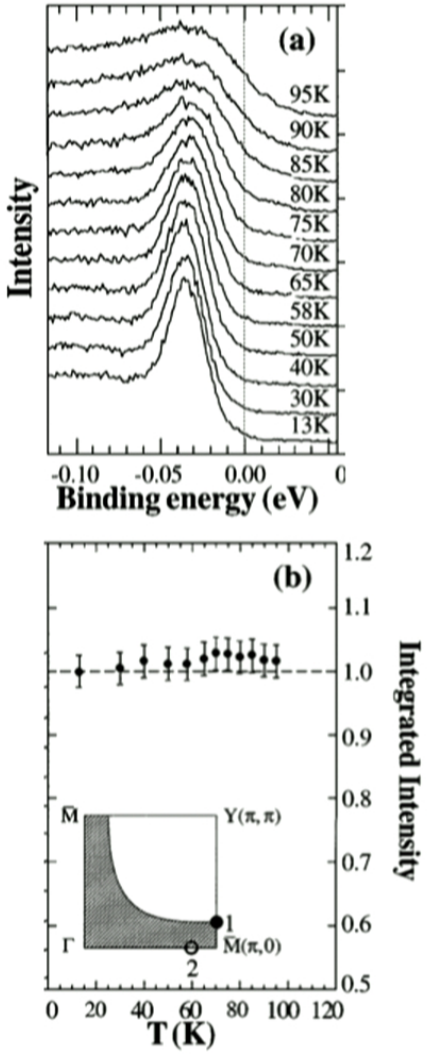
Impulse approximation

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



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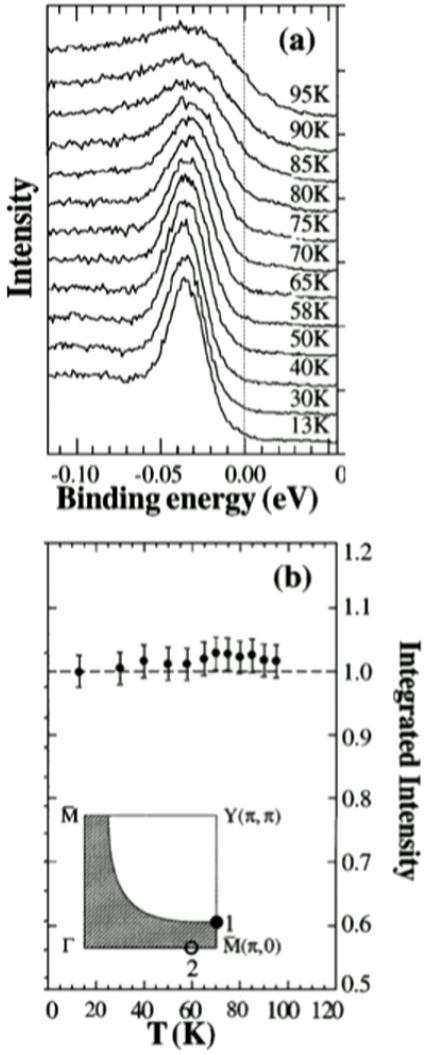
Impulse approximation

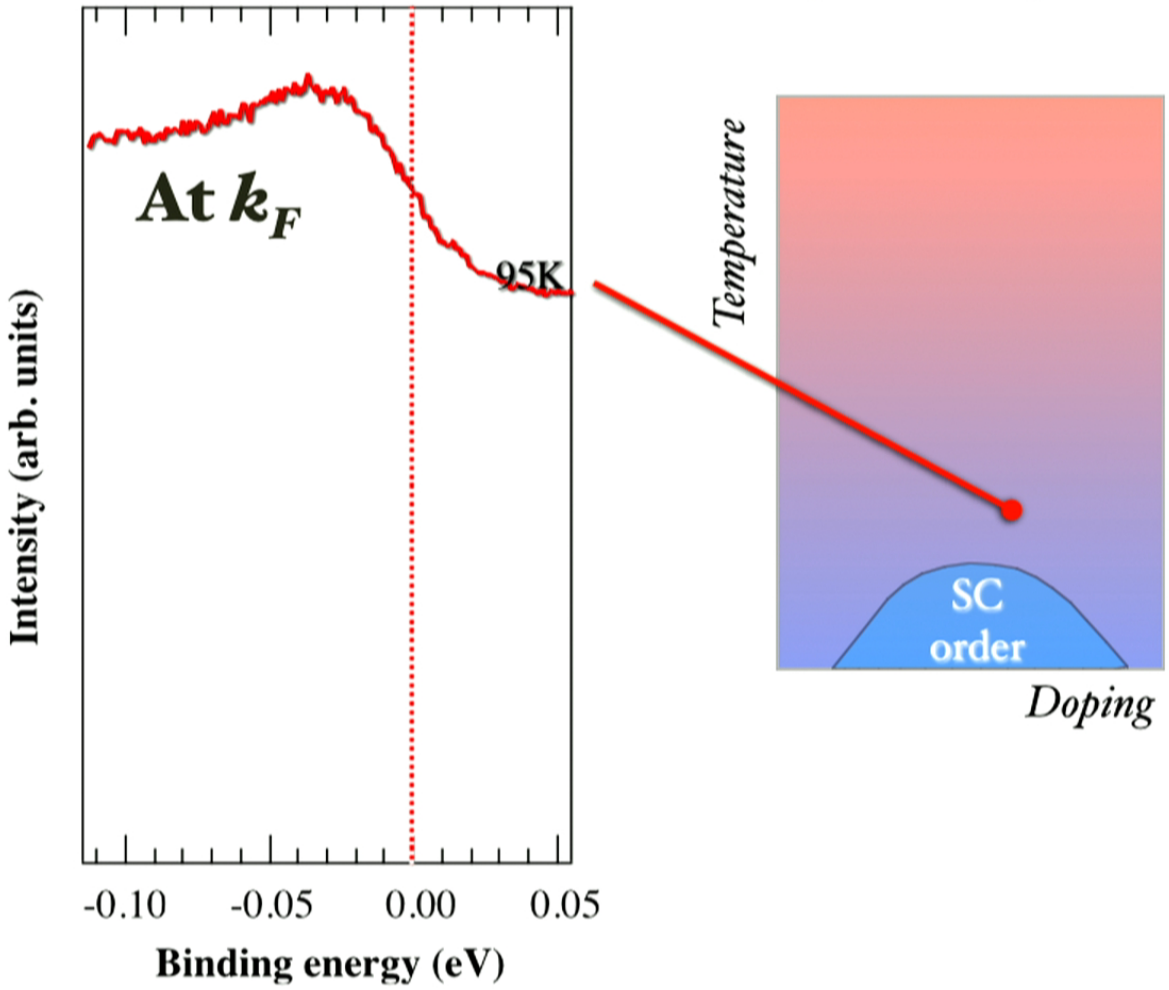
$$I \propto \left\langle \psi_f \left| \vec{\mathbf{A}} \cdot \vec{\mathbf{p}} \right| \psi_i \right\rangle^2 A(\mathbf{k},\omega) f(\omega)$$

i.e we directly measure the spectral function:

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



1st common feature: normal state excitations are not quasi-particles



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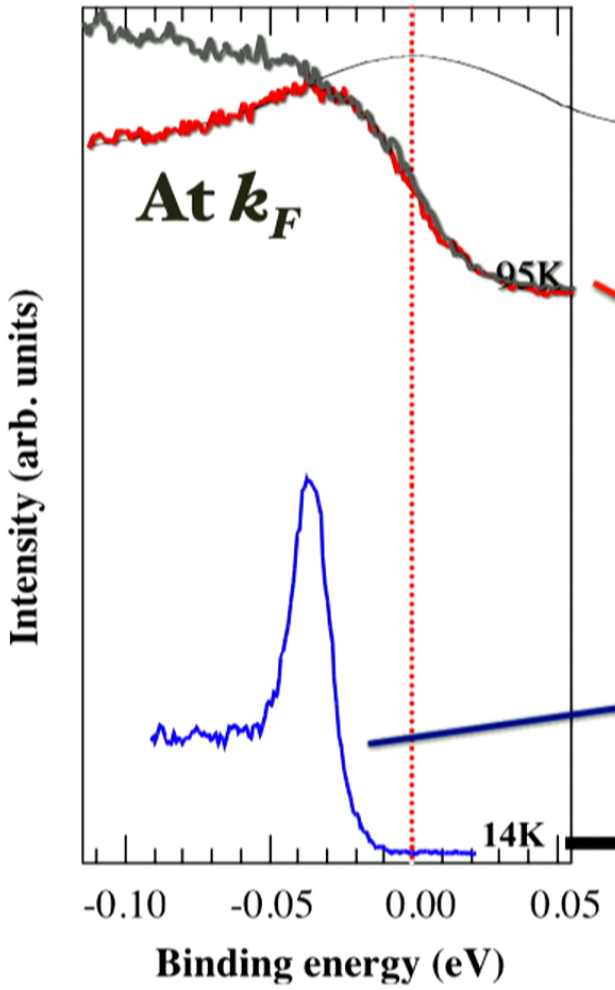
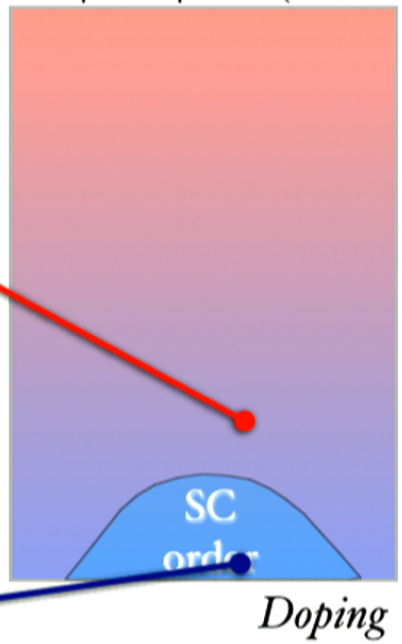


$$I(\omega) = |M|^2 A(\vec{k}, \omega) f(\omega)$$

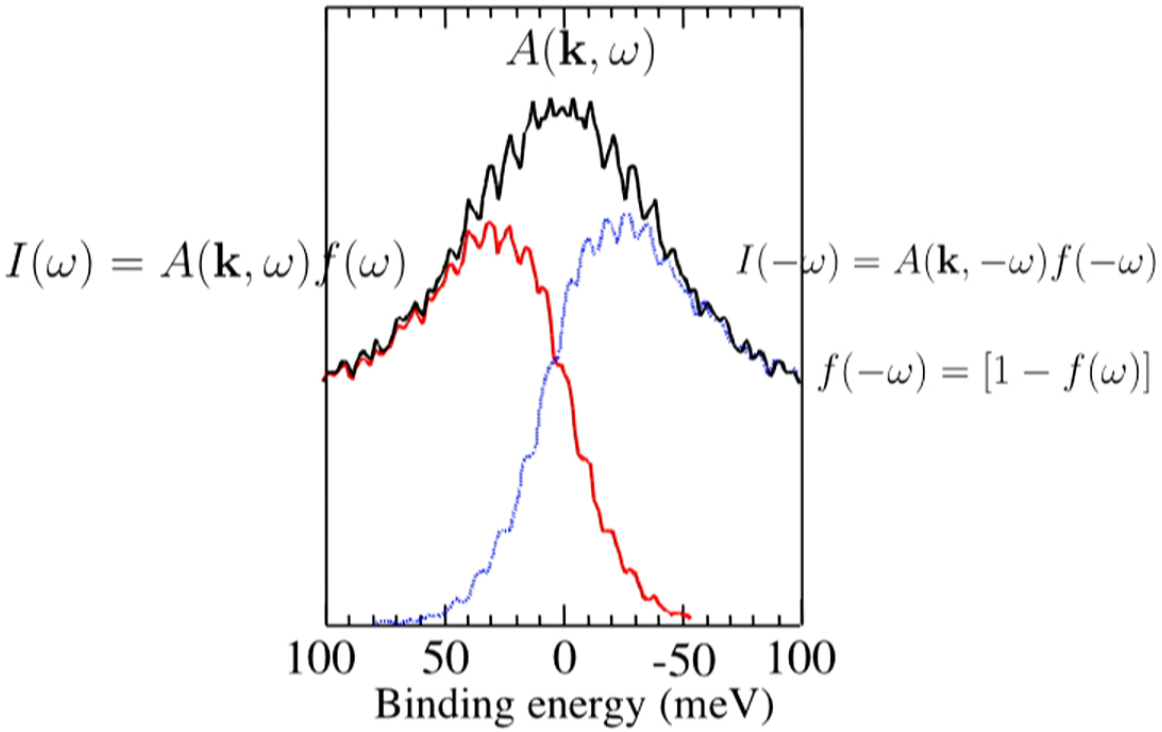


Now, long-lived excitations (quasiparticles) below Tc

Phys. Rev. Lett. **74** (95) 4951

A trick: symmetrization

Nature **392** (1988) 157



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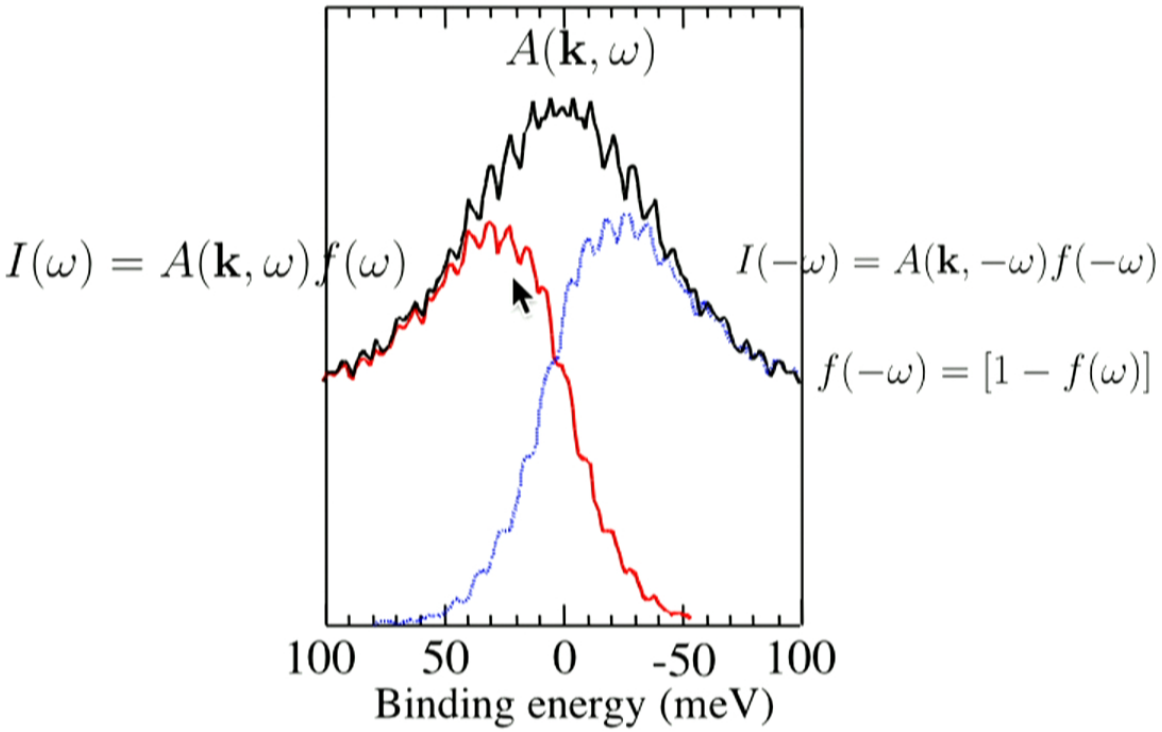
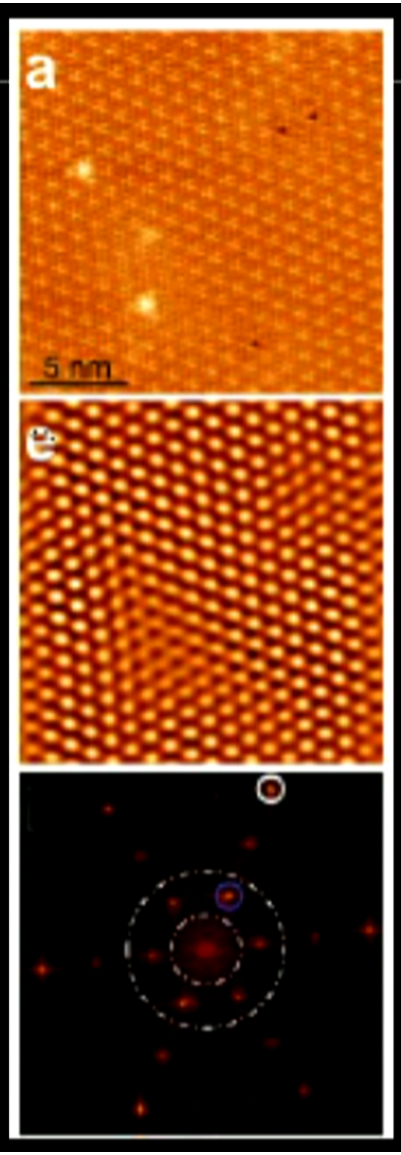
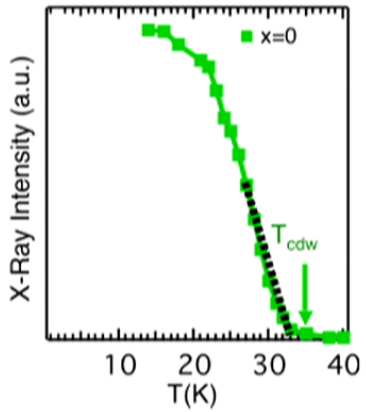


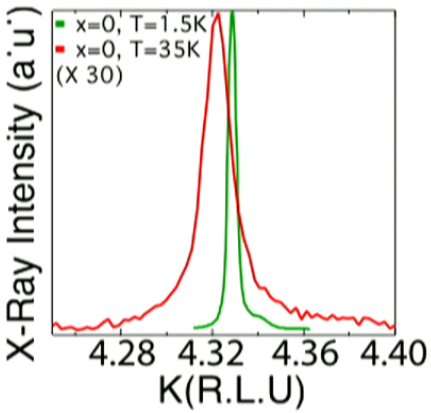
charge density wave: $NbSe_2$

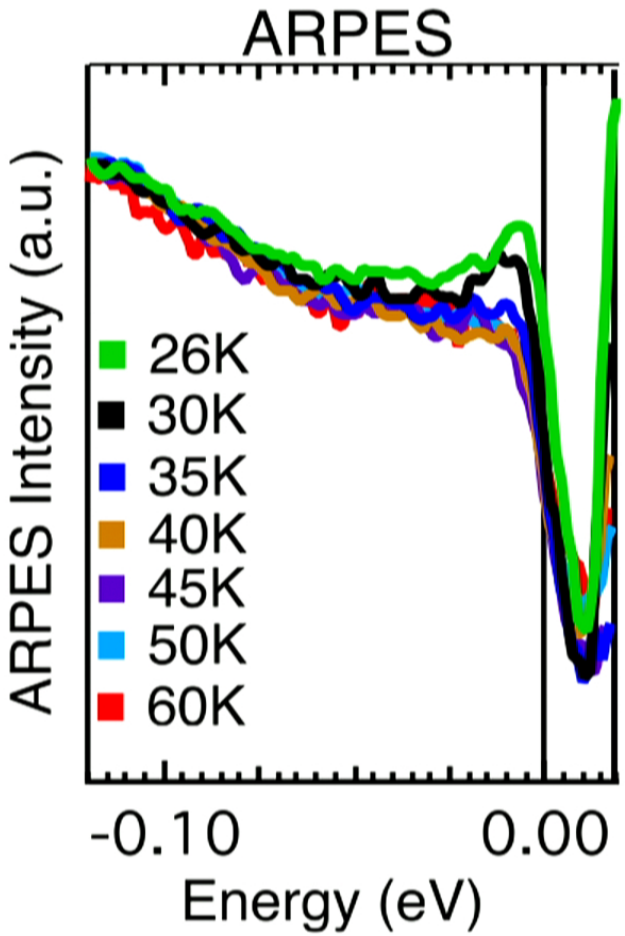


1st common feature:
absence of q.p. in the normal state

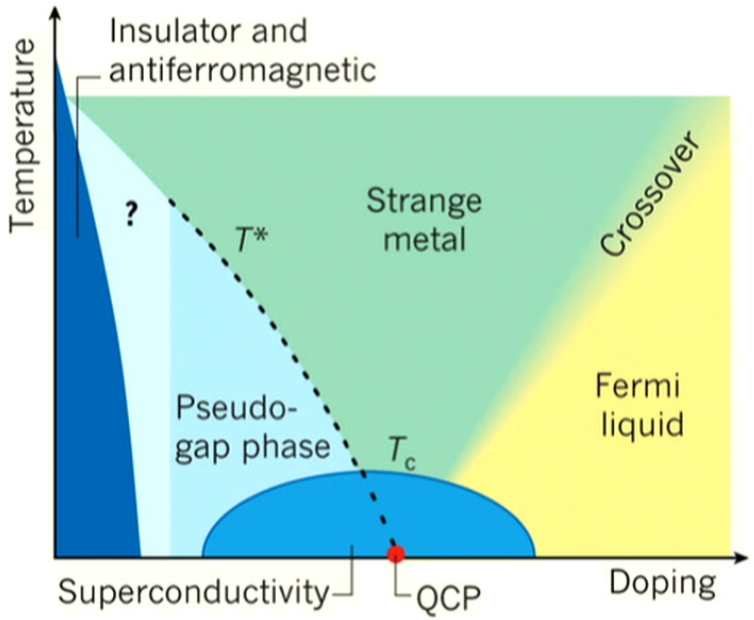
X-Ray diffraction





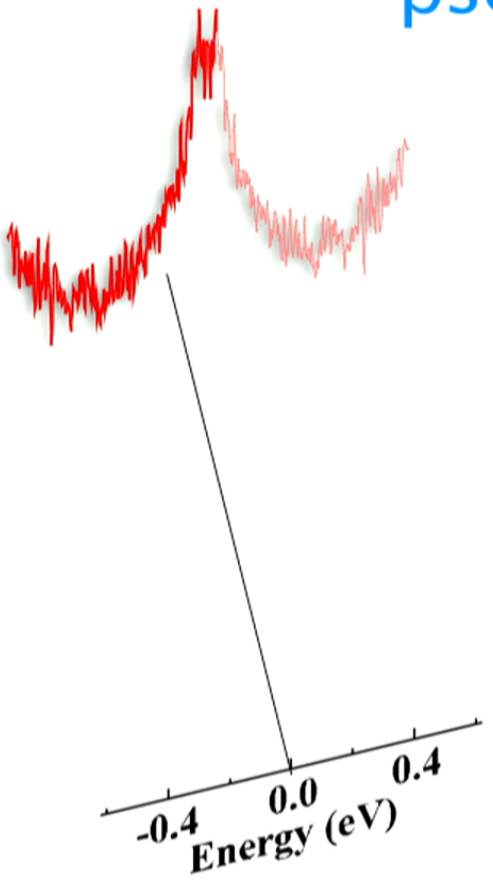


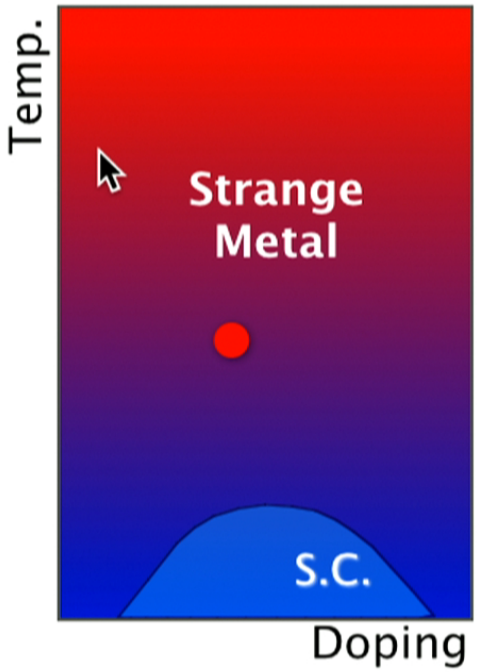
2nd common feature:
the pseudogap



HTSC schematic

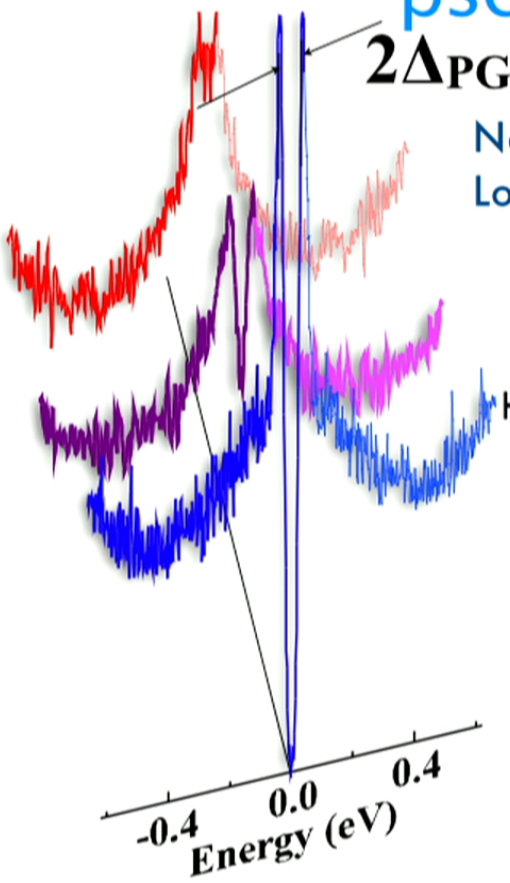
2nd common feature
pseudogap in the normal state



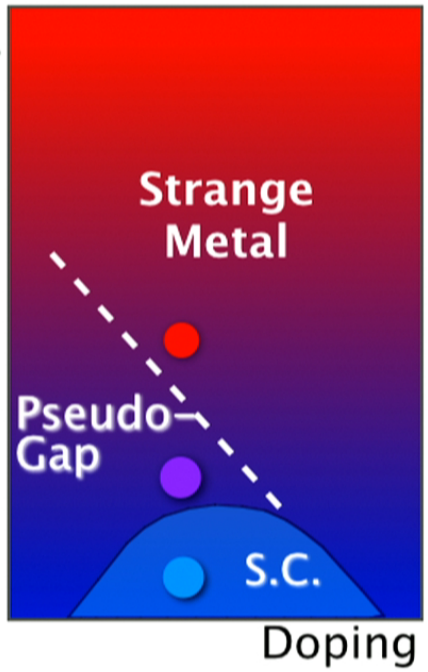


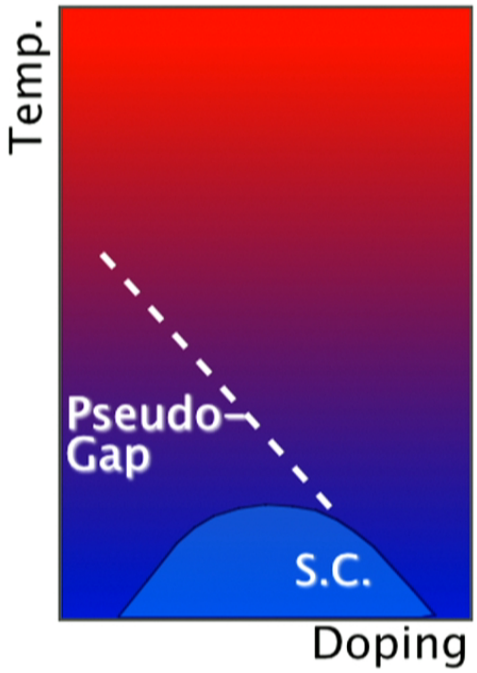
2nd common feature

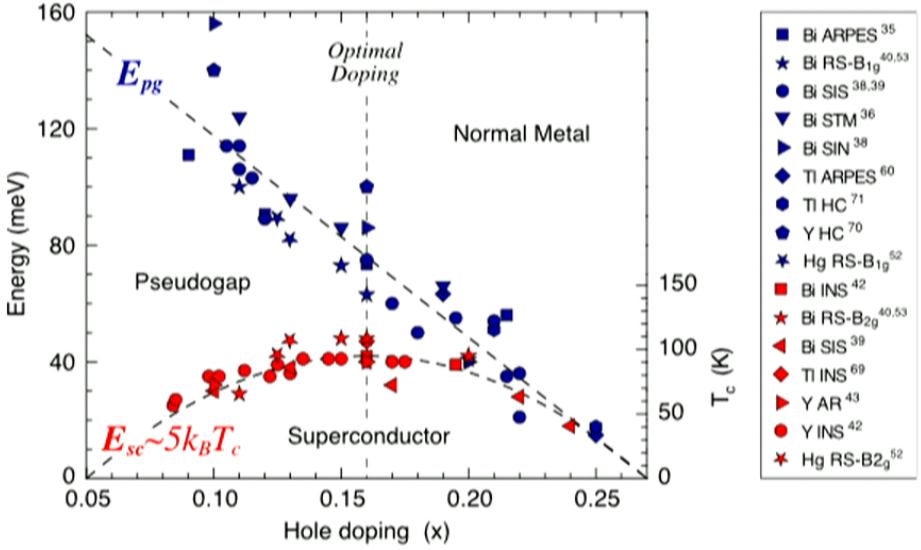
pseudogap in the normal state



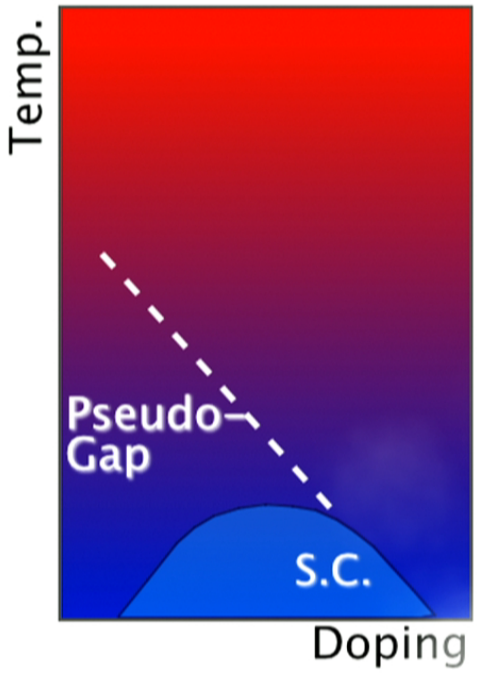
Nature 382, 51 (96)
Loeser, et al. Science 273, 325 (96)



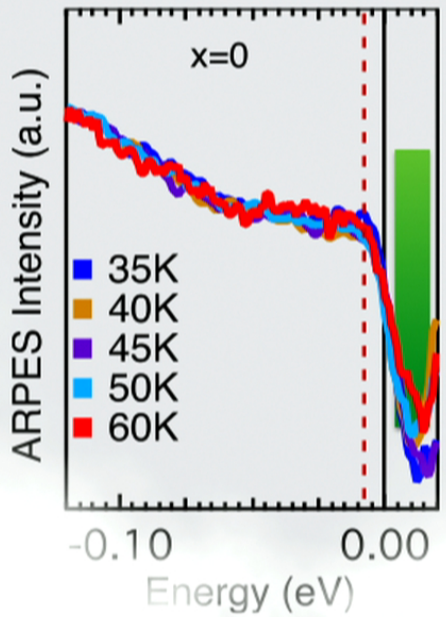




Hüfner, Damascelli & Sawatzki
Rep. Prog. Phys. **71** (2008) 062501



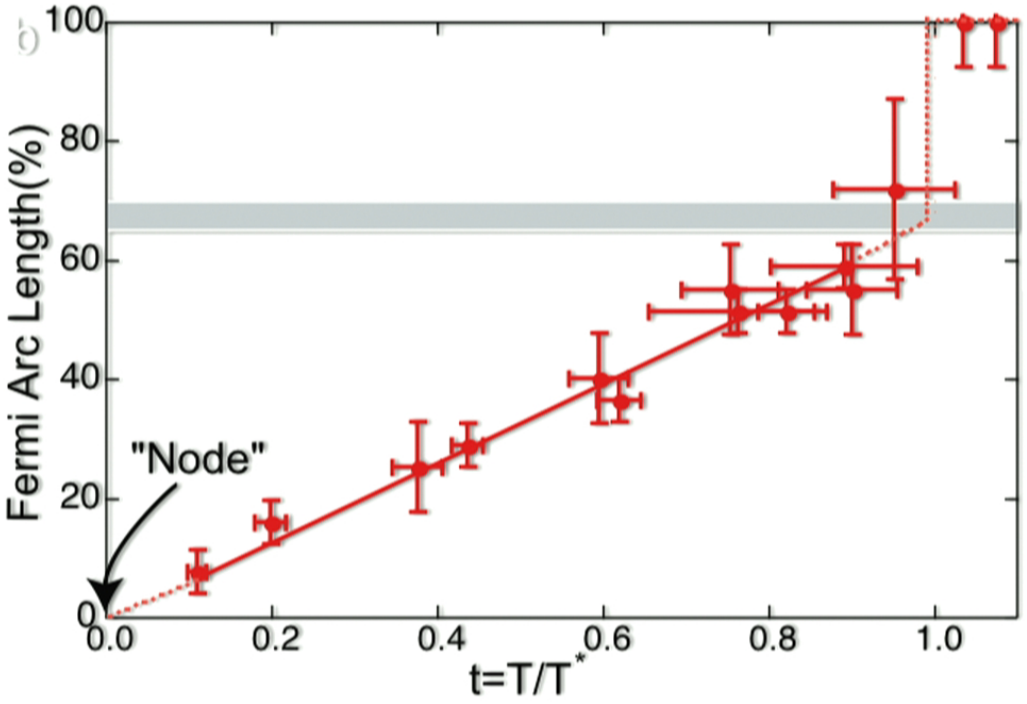
is there a PG in the CDW normal state?

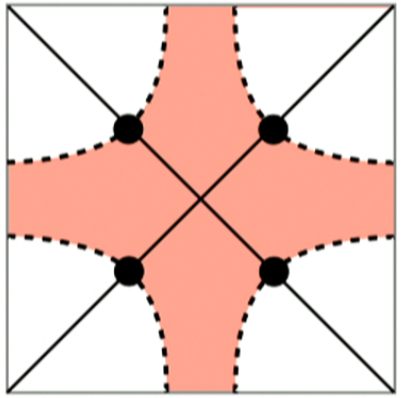


scaling of the Fermi arcs

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

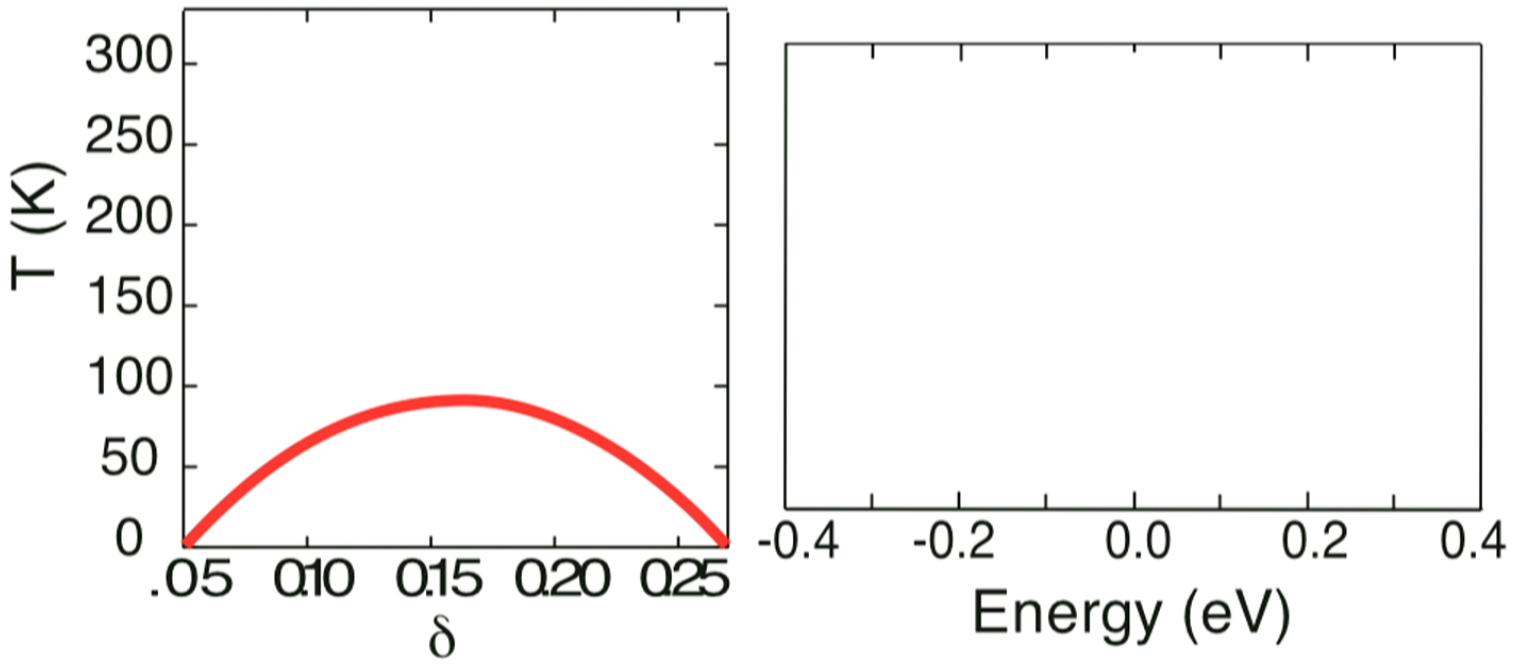
Nature Physics, 2, 447 (06)





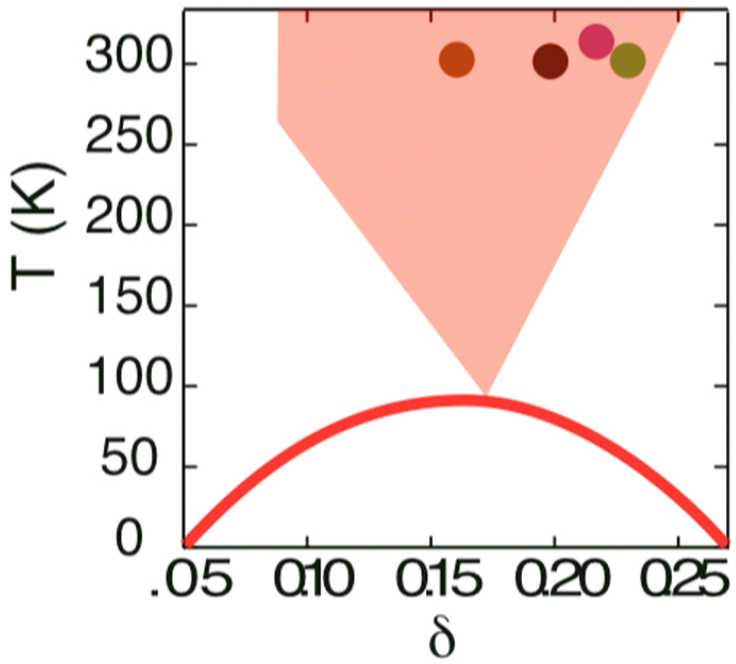
Results suggest that at T=0, the pseudogap would have a Fermi surface with only 4 points - A nodal liquid?

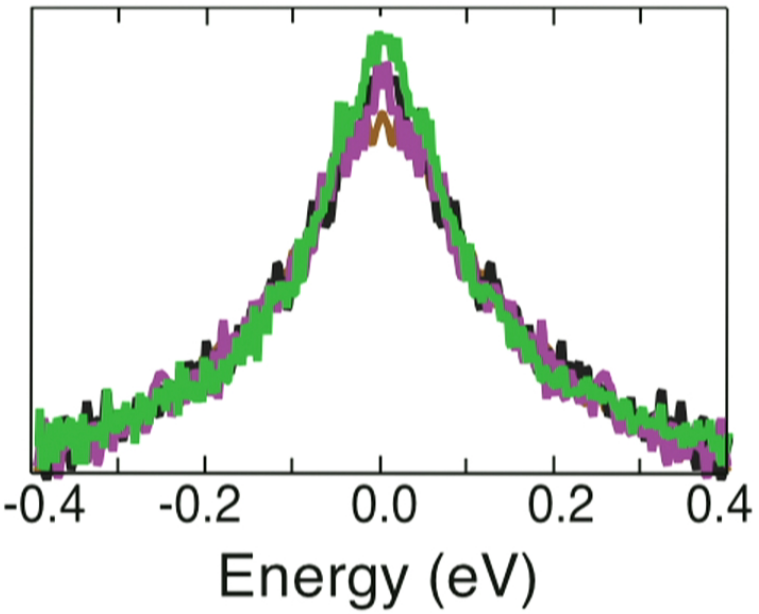
the strange spectral function of the strange metal



the strange spectral function of the strange metal

spectra near 300K vs. δ





the strange spectral function of the strange metal

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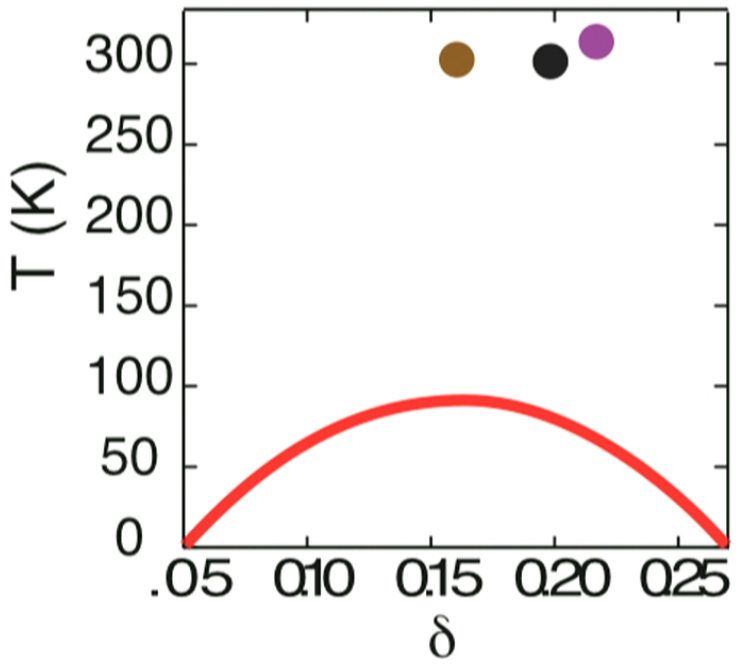
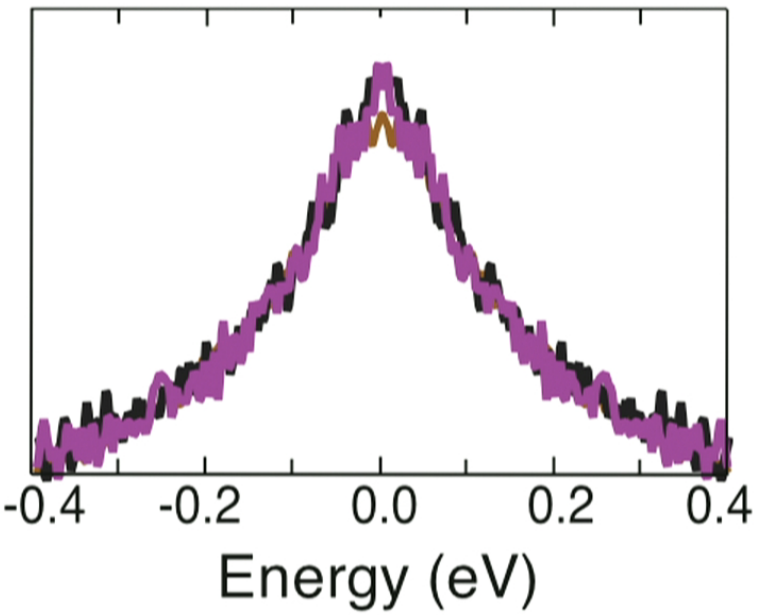
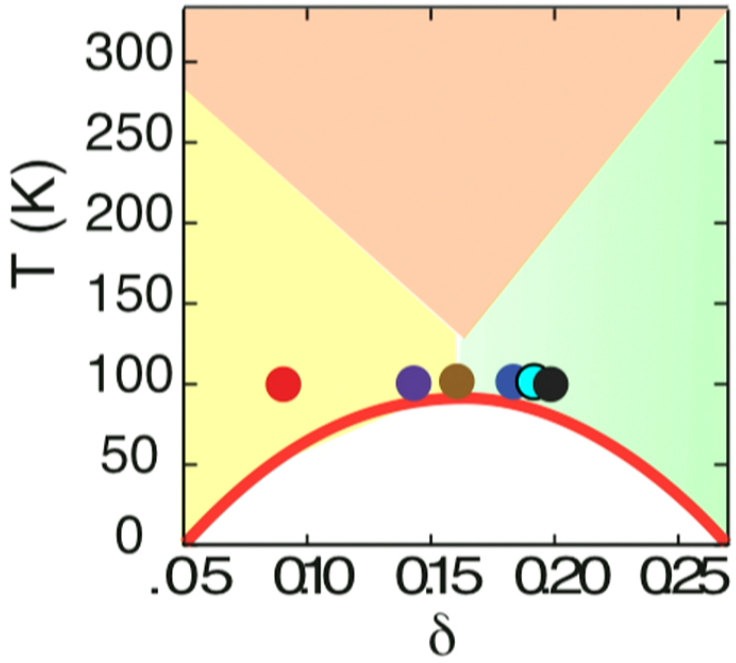
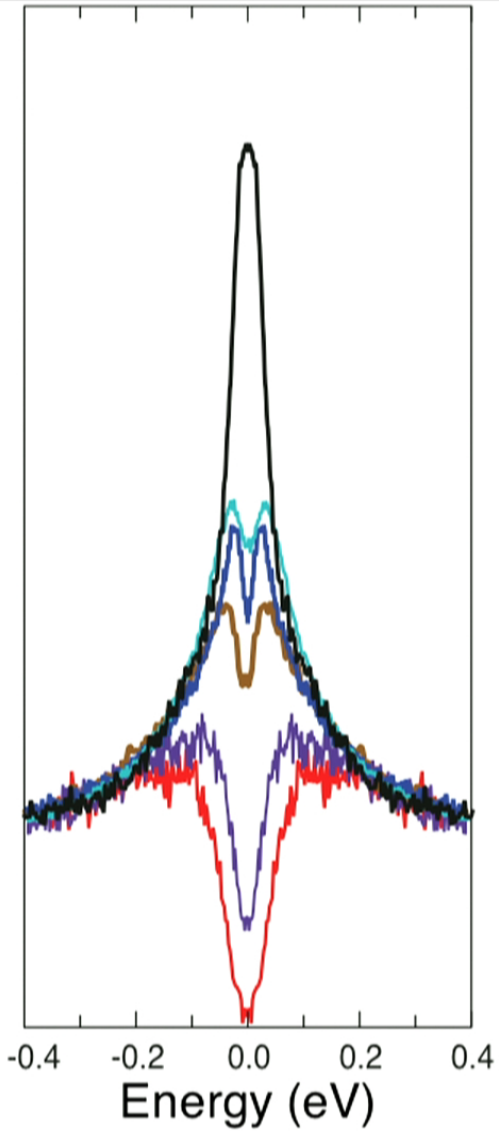




more interesting at ~100K





the essence of the problem

The Resonating Valence Bond State in La_2CuO_4 and Superconductivity

P. W. ANDERSON

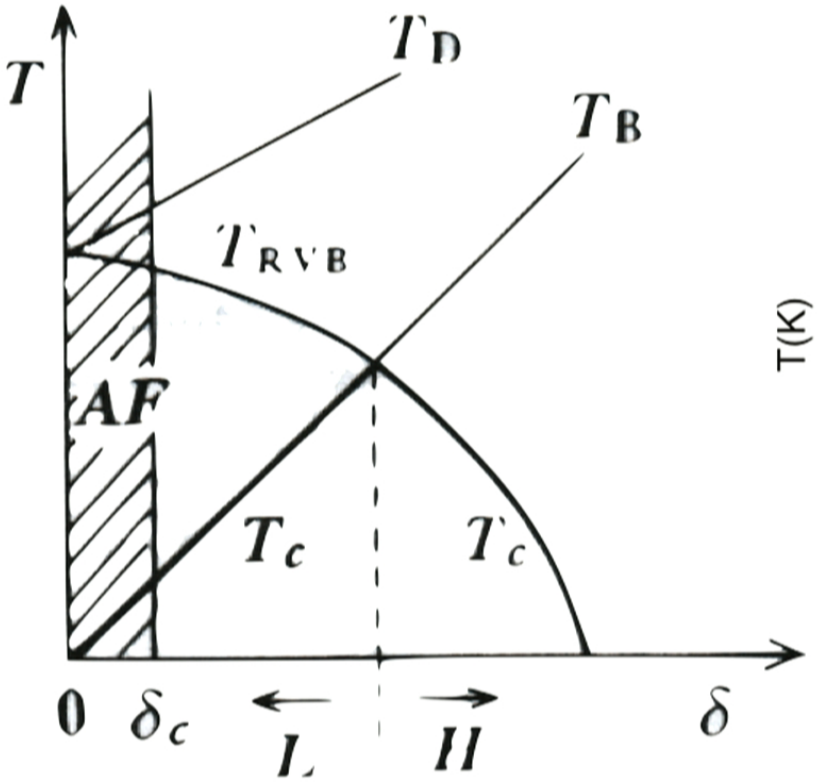
SCIENCE, VOL. 235 6 MARCH 1987 1196

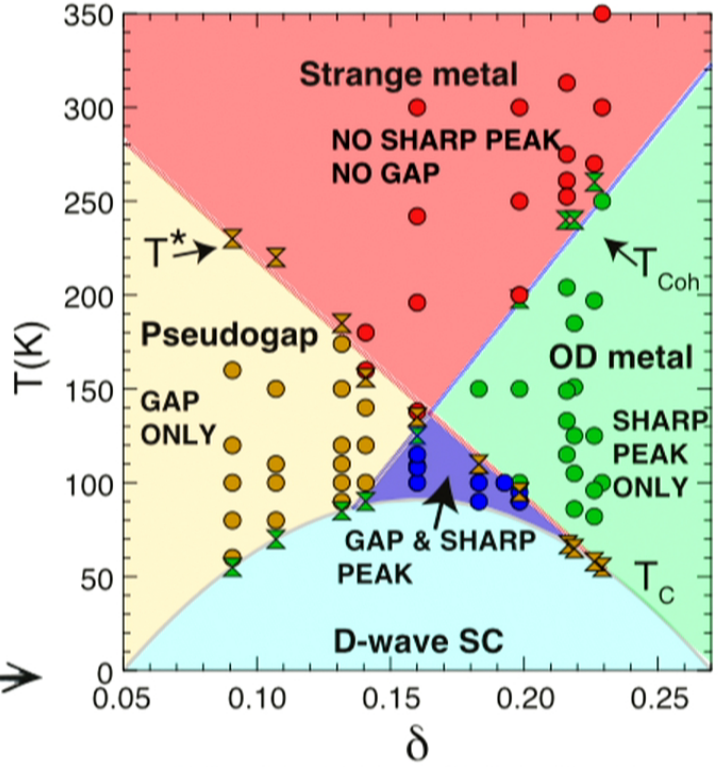
A single pair of electrons in a mobile valence bond along a lattice vector τ may be written

$$b_\tau^+ \Psi_0 = \frac{1}{\sqrt{N}} \left(\sum_j c_j^{+\uparrow} \; c_{j+\tau\downarrow} \right) \Psi_0 =$$

$$\frac{1}{\sqrt{N}} \left(\sum_k c_{k\uparrow}^+ \; c_{-k\downarrow}^+ \; \exp i \, (k \cdot \tau) \right) \Psi_0 \qquad (2)$$

the [electronic] phase diagram



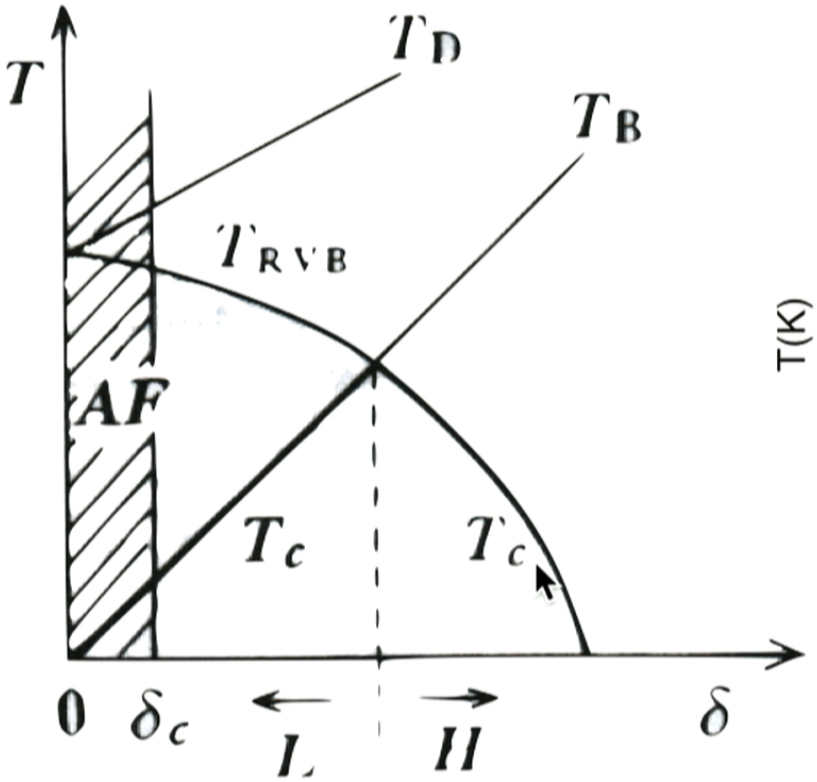


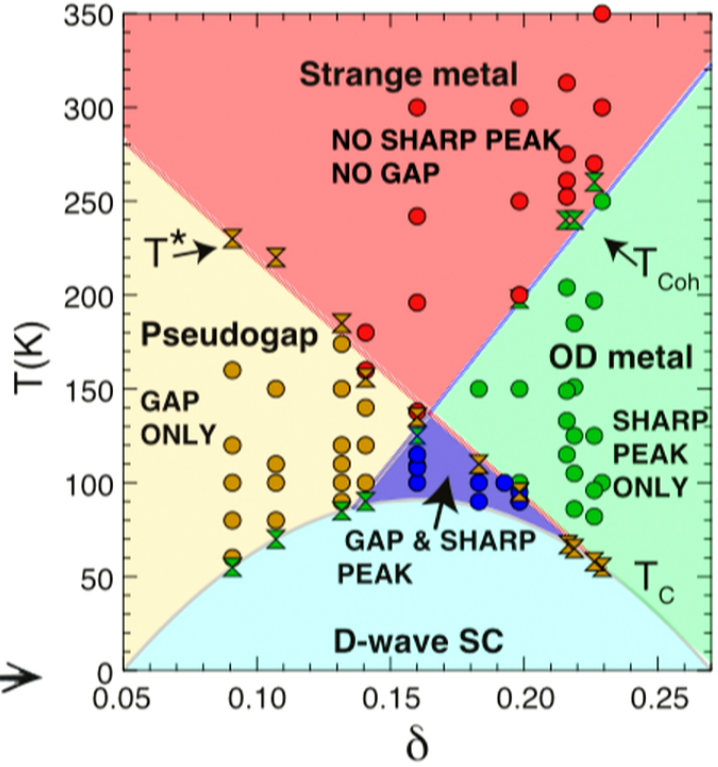
PNAS **108,** (2011) 9346

Kotliar G Phys Rev B **37,** 3664 (1988)

Suzumura Y, et al. J Phys Soc Jpn. 57, 2768 (1988).

the [electronic] phase diagram





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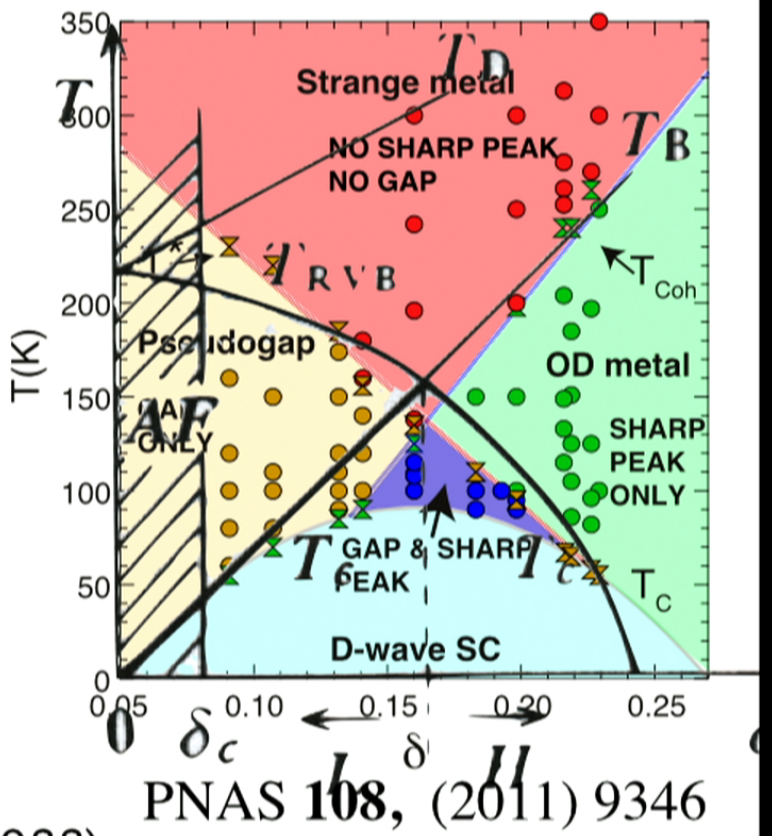
the [electronic] phase diagram



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Gerald Zeldin (2000)