Sawubona

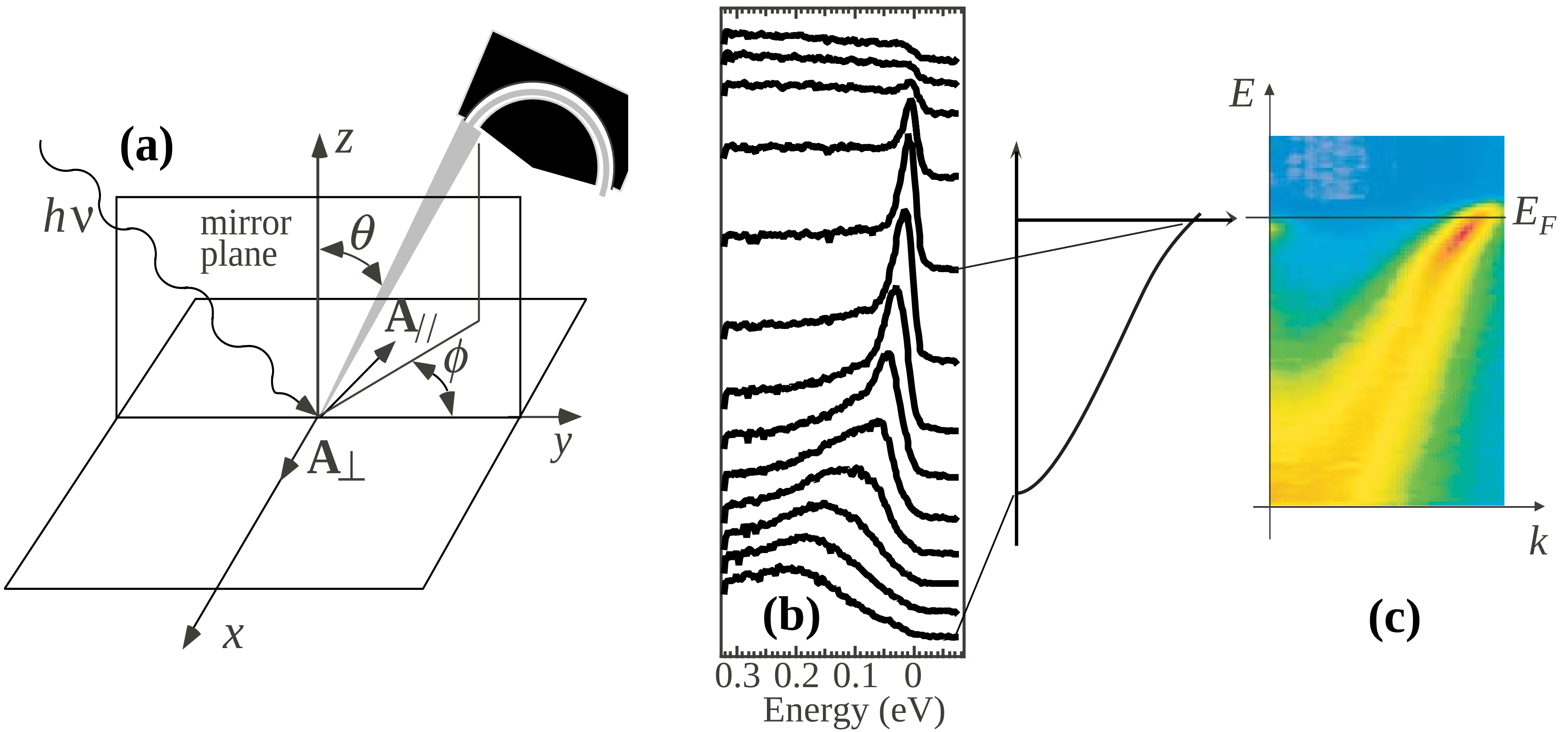
Khuyadakh

(this word caused quite some discussion:
I meant to use the Afrikaans word for ‘Good day’ and I had written it down in Hindi when I learnt it from the students. Now Hindi is a phonetic language. But when I tried to write it in English again phonetically this is how I did it!

It turned out to have no resemblance to the way it is written in Afrikaans which is ‘Goieidag’. However I was told that my pronunciation was correct!!

There is much to be said for using languages like Hindi which is a phonetic language and can therefore do a much more accurate rendition of the sounds.

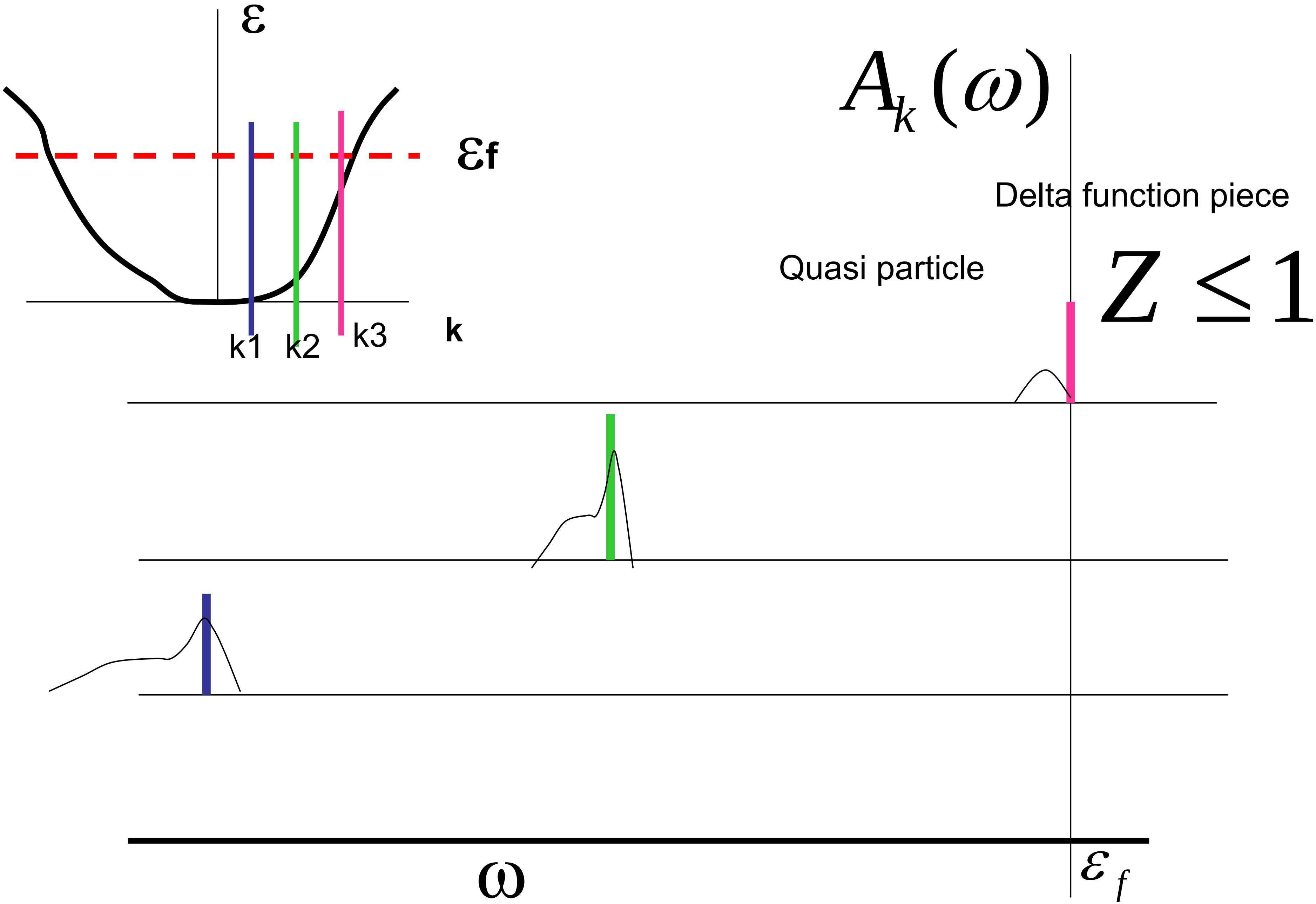
Angle resolved photoemission spectroscopy (ARPES)



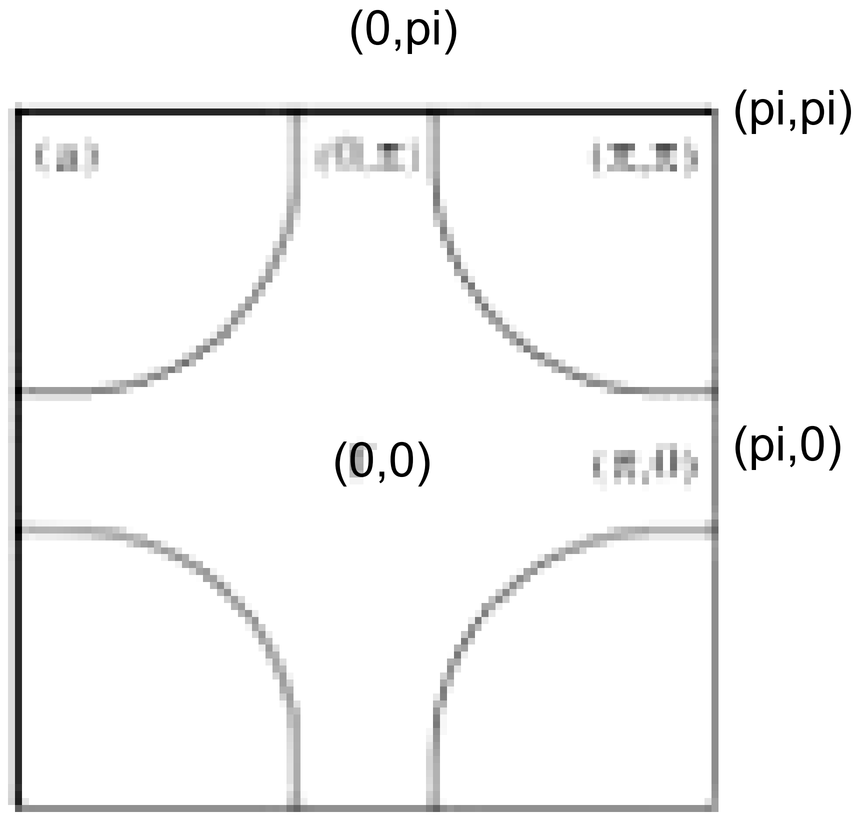
$$I(k;\omega) = I_o(k)f(\omega)A(k;\omega)$$

A(k,ω)= probability of finding an electronic excitation (k,ω)

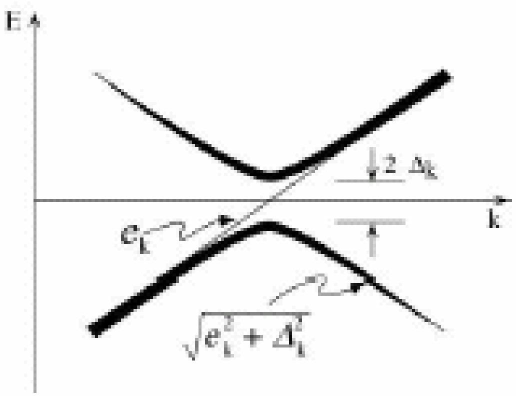
review:J. C. Campuzano, M. R. Norman and M. Randeria; **cond-mat/0209476**
Handbook of Physics: "Physics of Conventional and Unconventional Superconductors",
Vol.II, eds. K. H. Bennemann and J. B. Ketterson, (Springer Verlag, 2004)

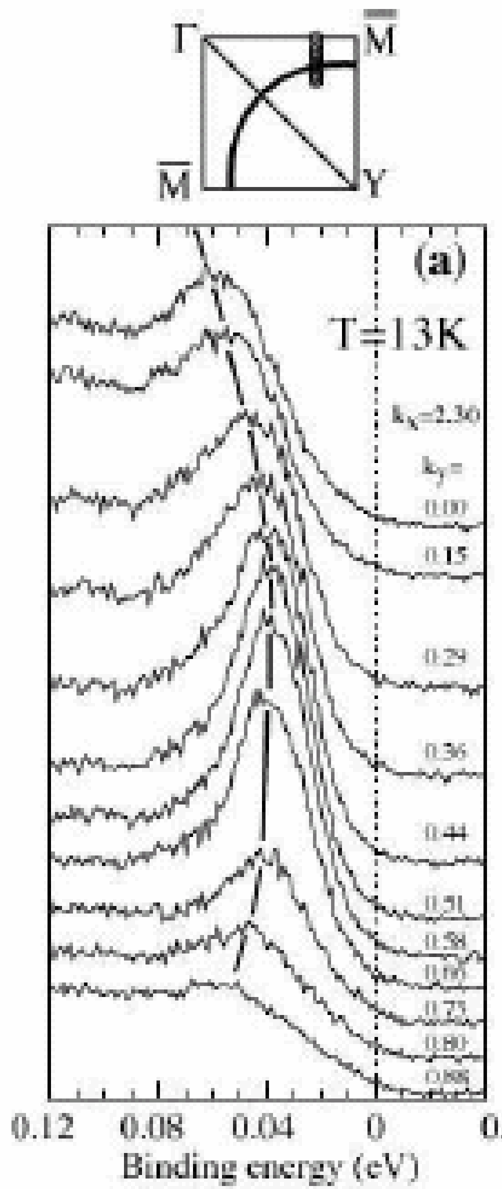


ε
εf
k1
k2
k3
k
$A_k(\omega)$
Delta function piece
Quasi particle
$Z \leq 1$
ω
ε_f

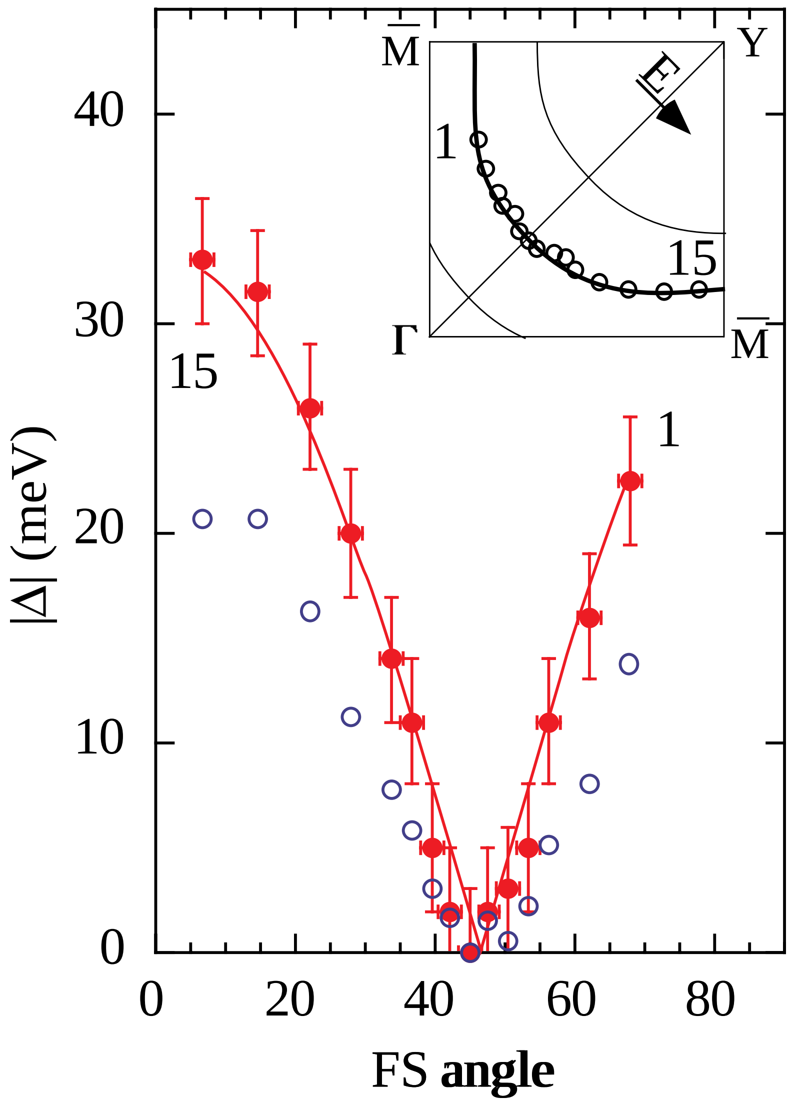


Fermi Surface

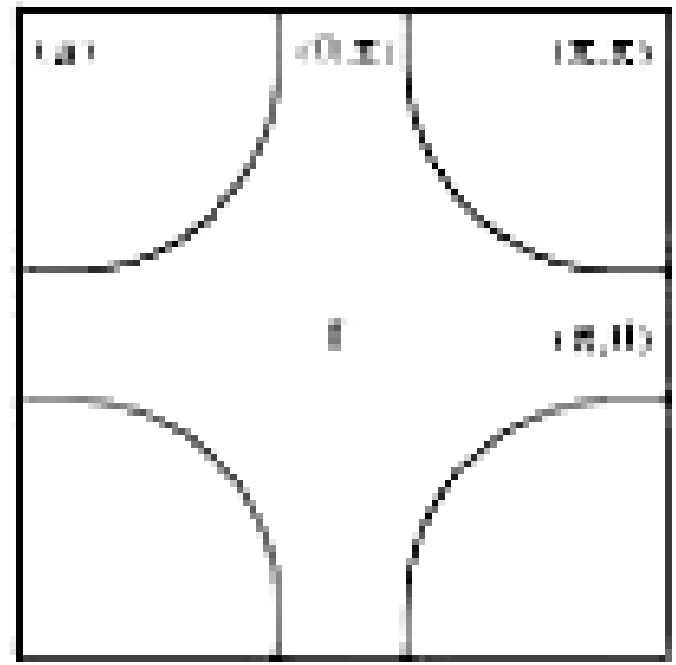

E
k
2 Δk
ek
$\sqrt{e_k^2 + \Delta_k^2}$


Γ
M̄
M̄
Y
(a)
T=13K
kx=2.30
ky=
0.10
0.15
0.29
0.36
0.44
0.51
0.58
0.73
0.80
0.88
0.12
0.08
0.04
0
0.
Binding energy (eV)

SUPERCONDUCTING GAP

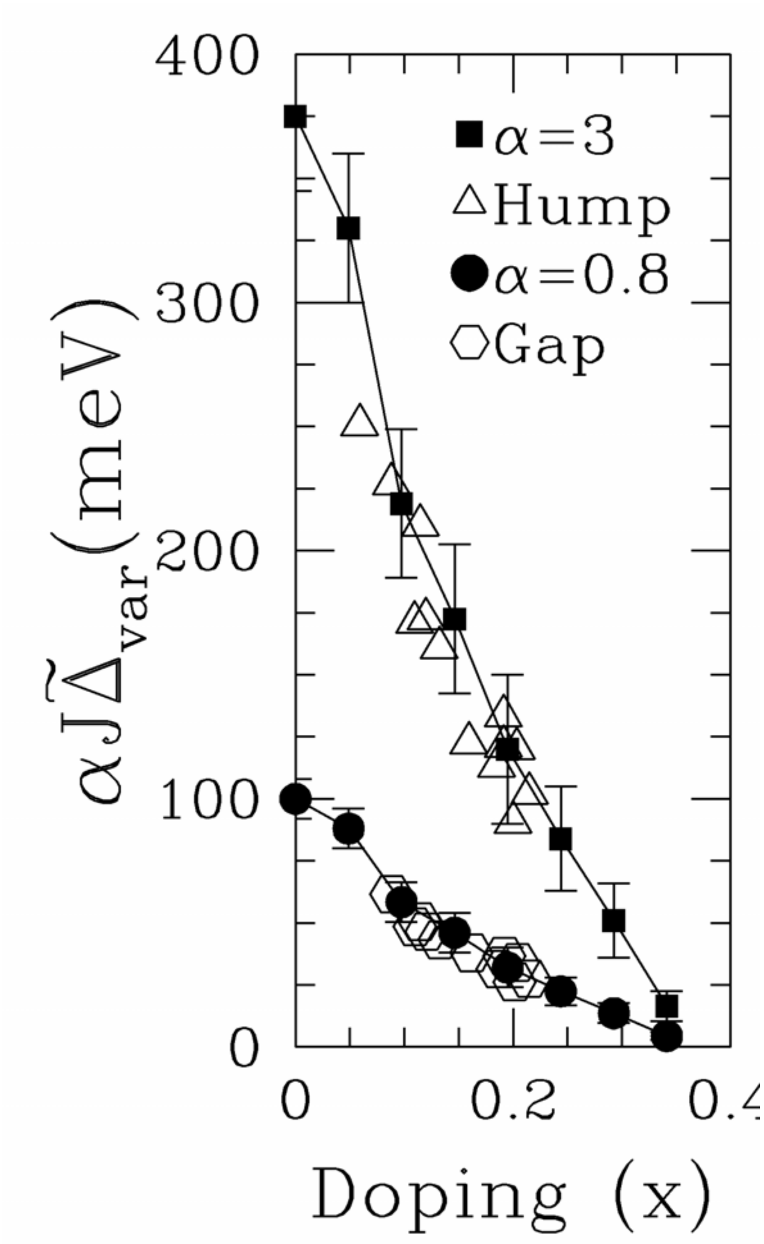


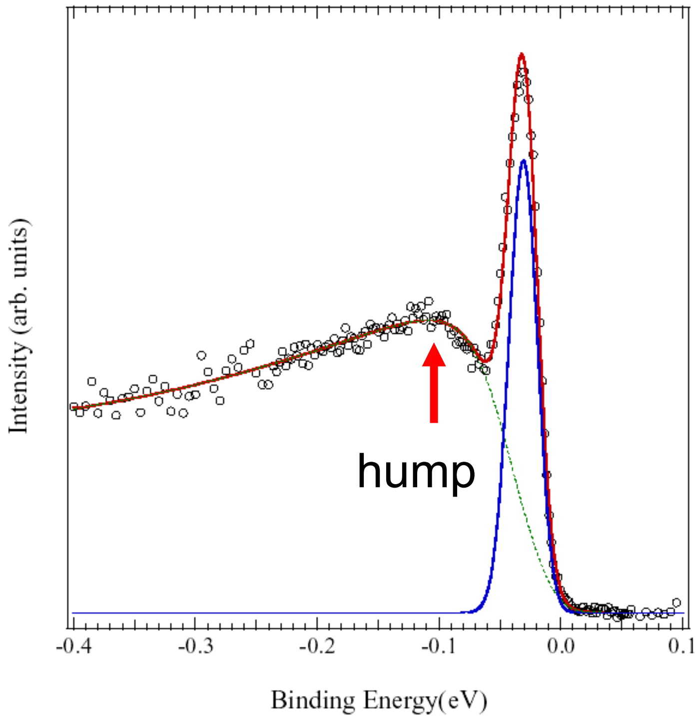
H. Ding, et.al. Phys. Rev. Lett. 74, 2784 (1995); Phys. Rev. B 54, R9678 (1996).



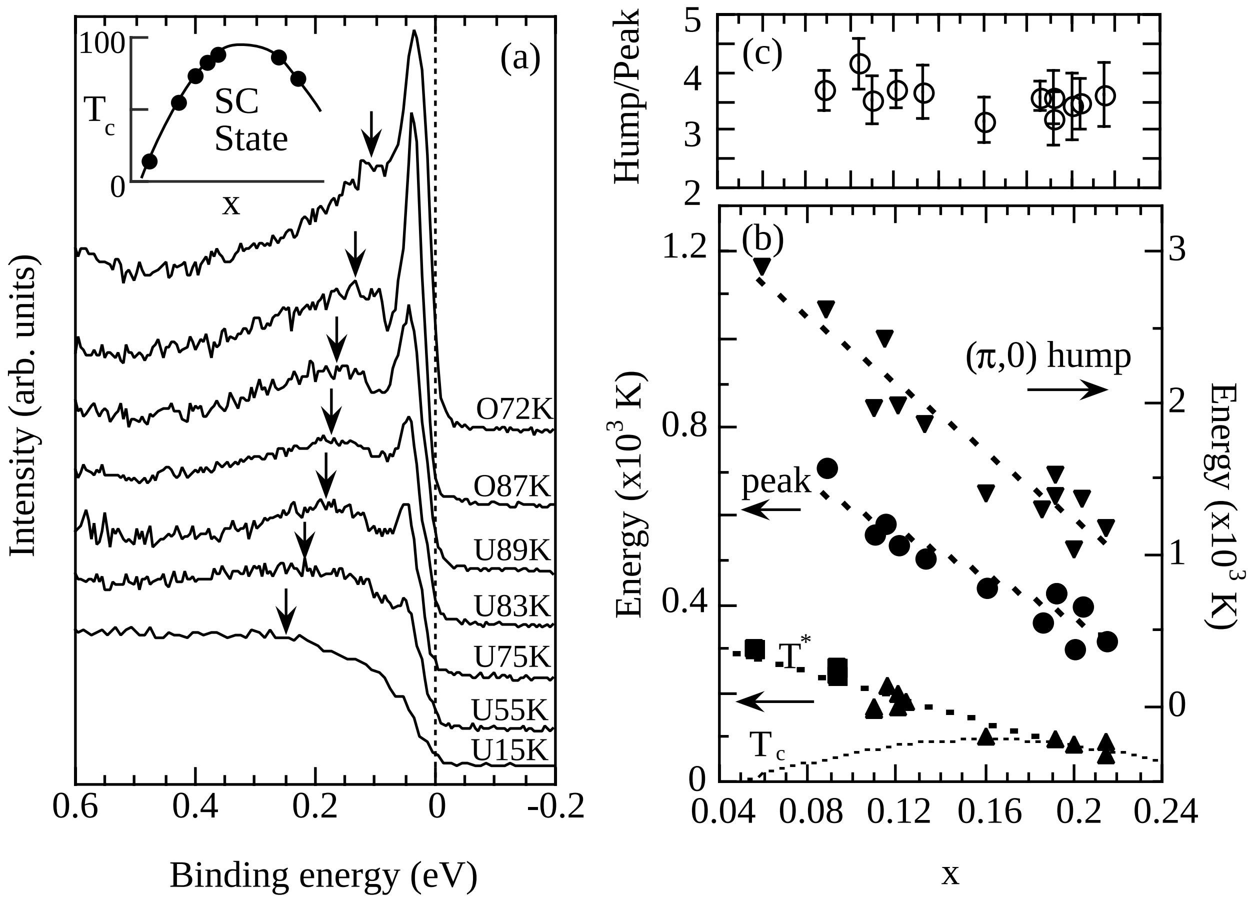
$$\Delta(\mathbf{k}) = \Delta_0\,(\cos k_x - \cos k_y)$$

Phase sensitive expts. → D. J. Van Harlingen, Rev. Mod. Phys 67, 515 (1995); C. C. Tsuei and J. R.Kirtley, ibid 72, 969 (2000).





Campuzano et al. PRL 1999
Ding et al. PRL 2001

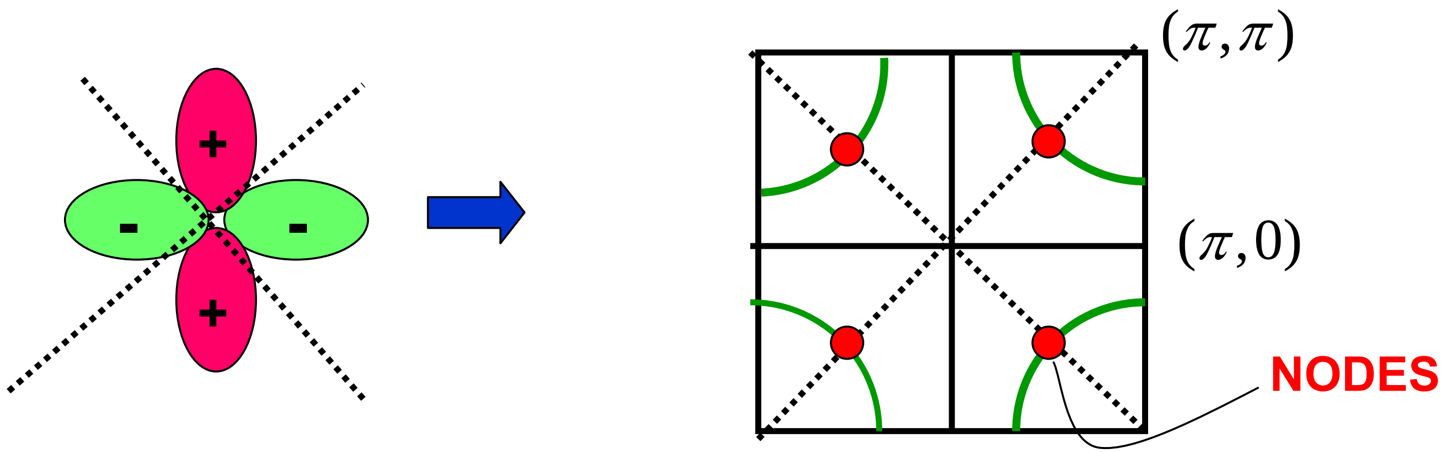


$2\Delta/T_c$: non-BCS

Low lying excitations in a dwave SC

Nodal quasiparticles

Node: Point on FS where SC gap vanishes



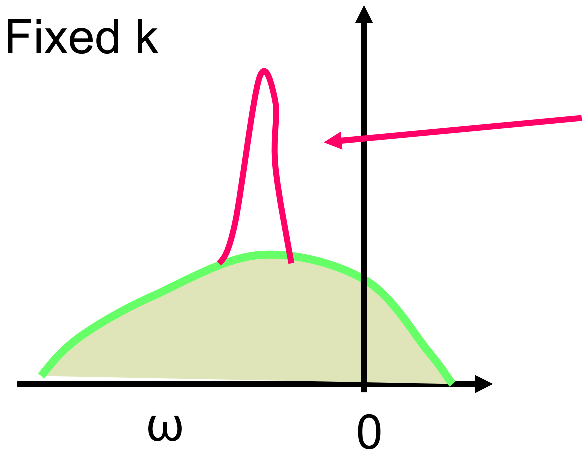
quasiparticle → sharp $(\Gamma \ll \omega)$ excitation

expt. → only seen for T< Tc

- Dominate thermal and spin transport for T<<Tc
- Determines the low T behavior of superfluid density
- Seen directly in ARPES Kaminsky et al. PRL 2000, 2001

SPECTRAL FUNCTION

=probability of finding an electronic excitation with (k,ω)



For k=kF:

$$A(k,\omega) = Z\delta(\omega - \xi_k) + A_{inc}$$

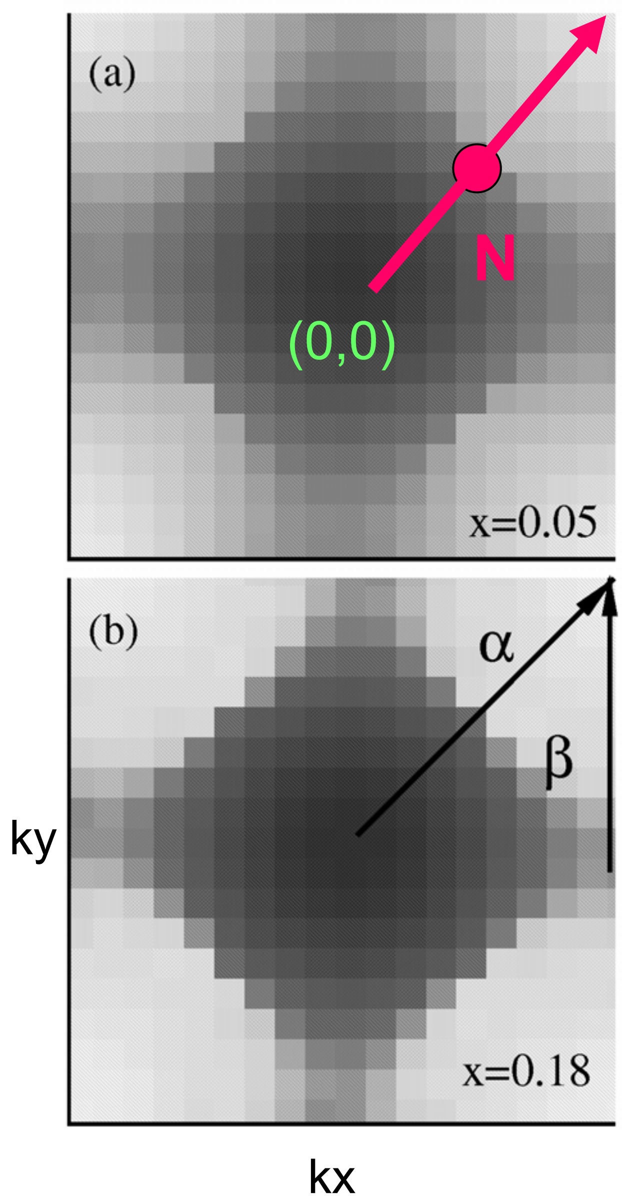
$$\xi_k \sim v_F(k - k_F)$$

QP dispersion

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

$$\sum_k A(k,\omega) = N(\omega)$$

Momentum Distribution Function n(k)

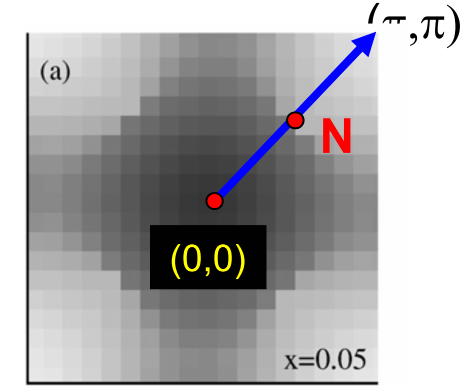


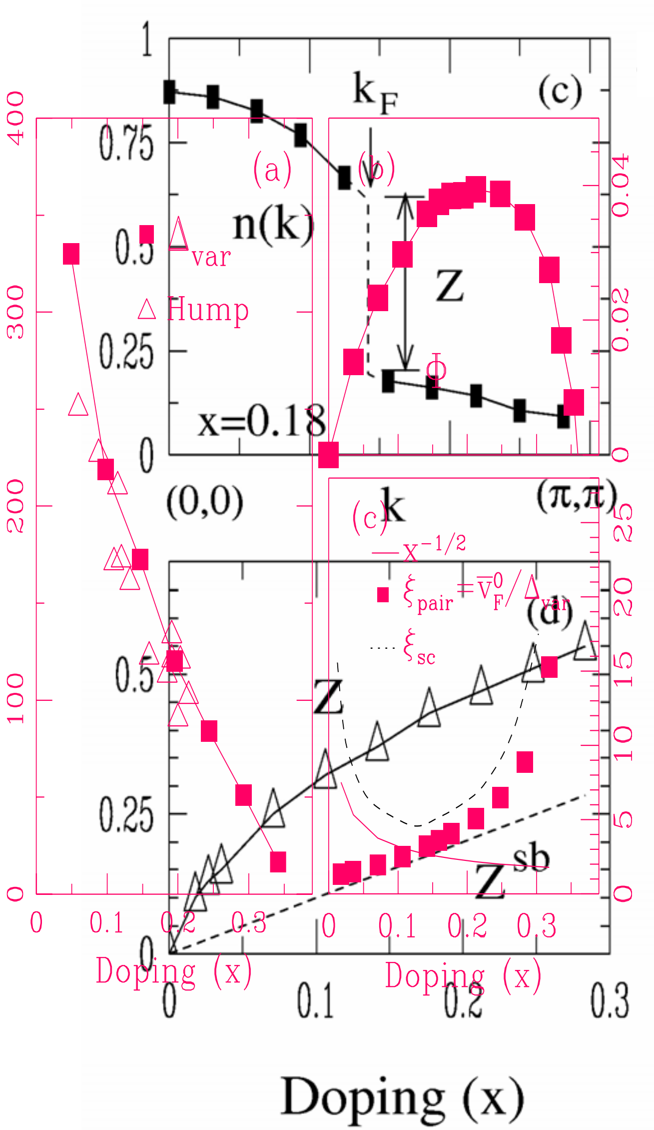
Fermi Surface:
Contours of n(k)=1/2 or max |∇n(k)|

LARGE FERMI SURFACE

(no hole pockets)
counts (1-x) electrons

NODAL QUASIPARTICLES





Discontinuity in n(k)

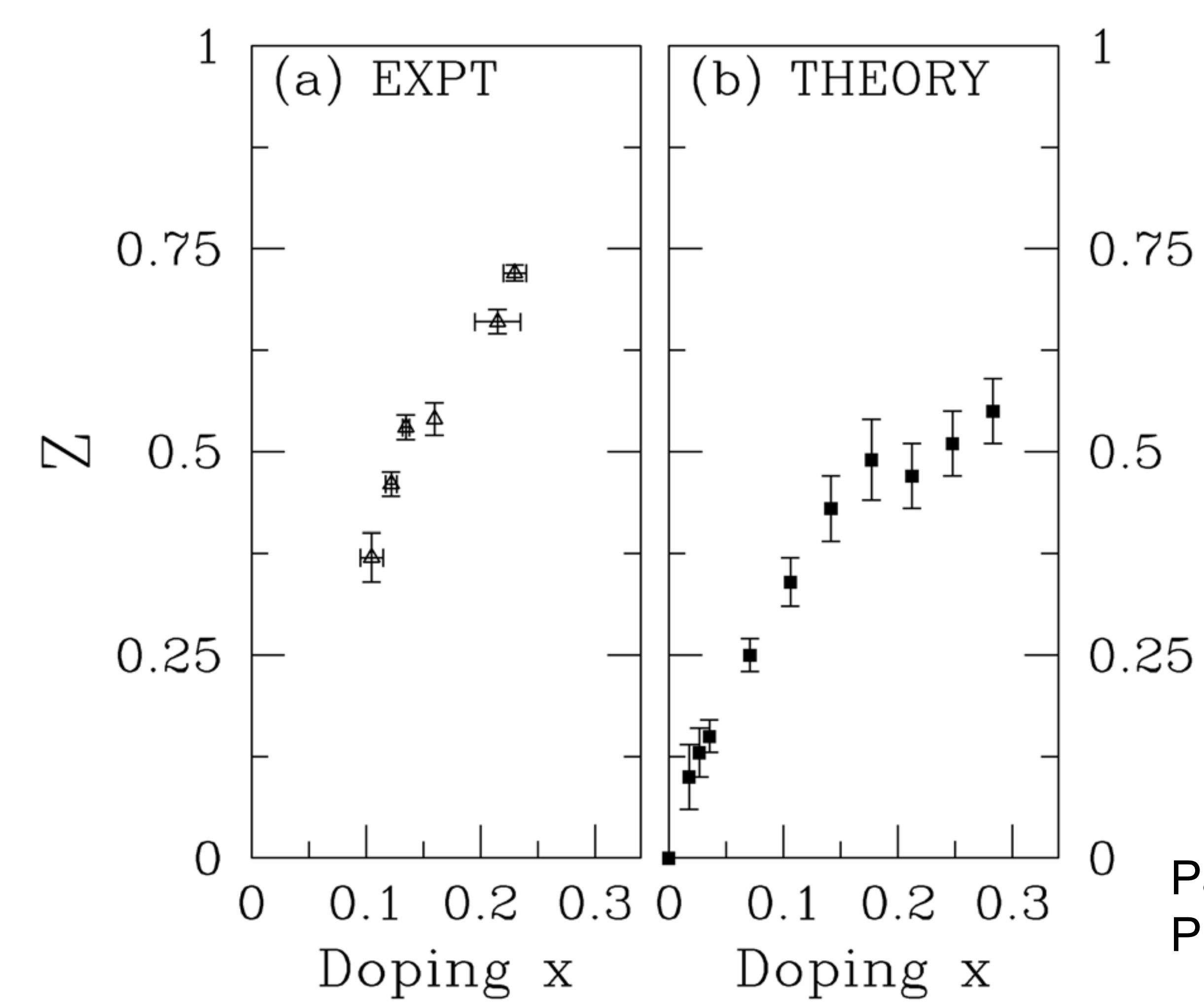
- Existence of **gapless** **QUASIPARTICLES at nodal point N**

- **Coherent weight (QP residue)**
  Z~x as x → 0
  Projection leads to incoherence

- **Route to Mott Insulator**
  Large FS
  Vanishing Quasiparticle wt. Z

SBMFT: Z~x

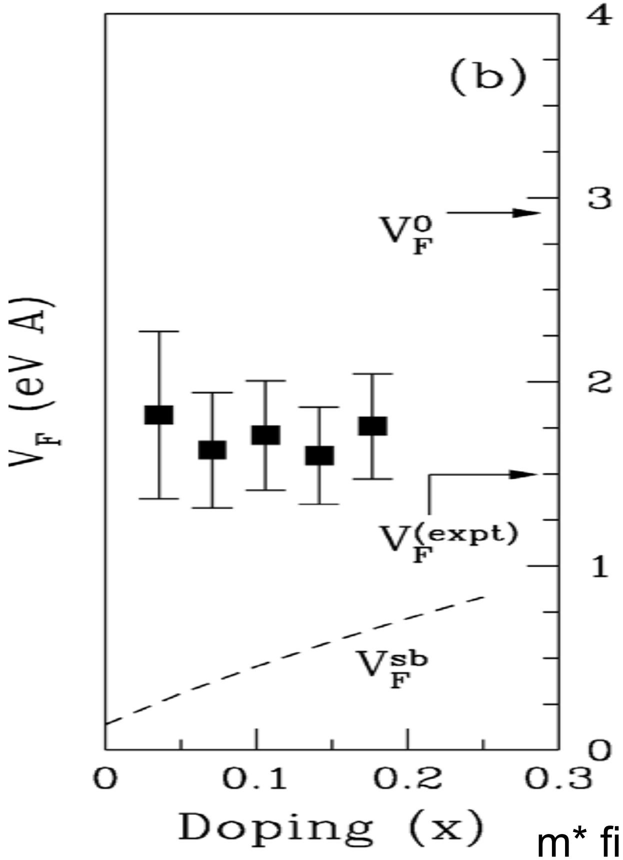
Nodal QP Z(x)



Paramekanti, Randeria, NT
PRL **87**, 217002 (2001)

Z derived from data of
P. Johnson et. al PRL **87**, 177007 (2001)

QUASIPARTICLE DISPERSION



PREDICTION

v_F~ const as x→0

What are the implications?

Mott insulating state does NOT arise because of a diverging effective mass

(c.f. heavy fermions m*~1/Z

$$Z \sim x \Rightarrow \left(1 - \frac{\partial \Sigma'}{\partial \omega}\right)_{(k_F,0)} \sim \frac{1}{x}$$

m* finite or $v_F \sim const \Rightarrow \left(1 + \frac{\partial \Sigma'}{\partial \varepsilon_k}\right)_{(k_F,0)} \sim \frac{1}{x}$

PREDICTION: Singular k-dependence of Σ along zone diagonal

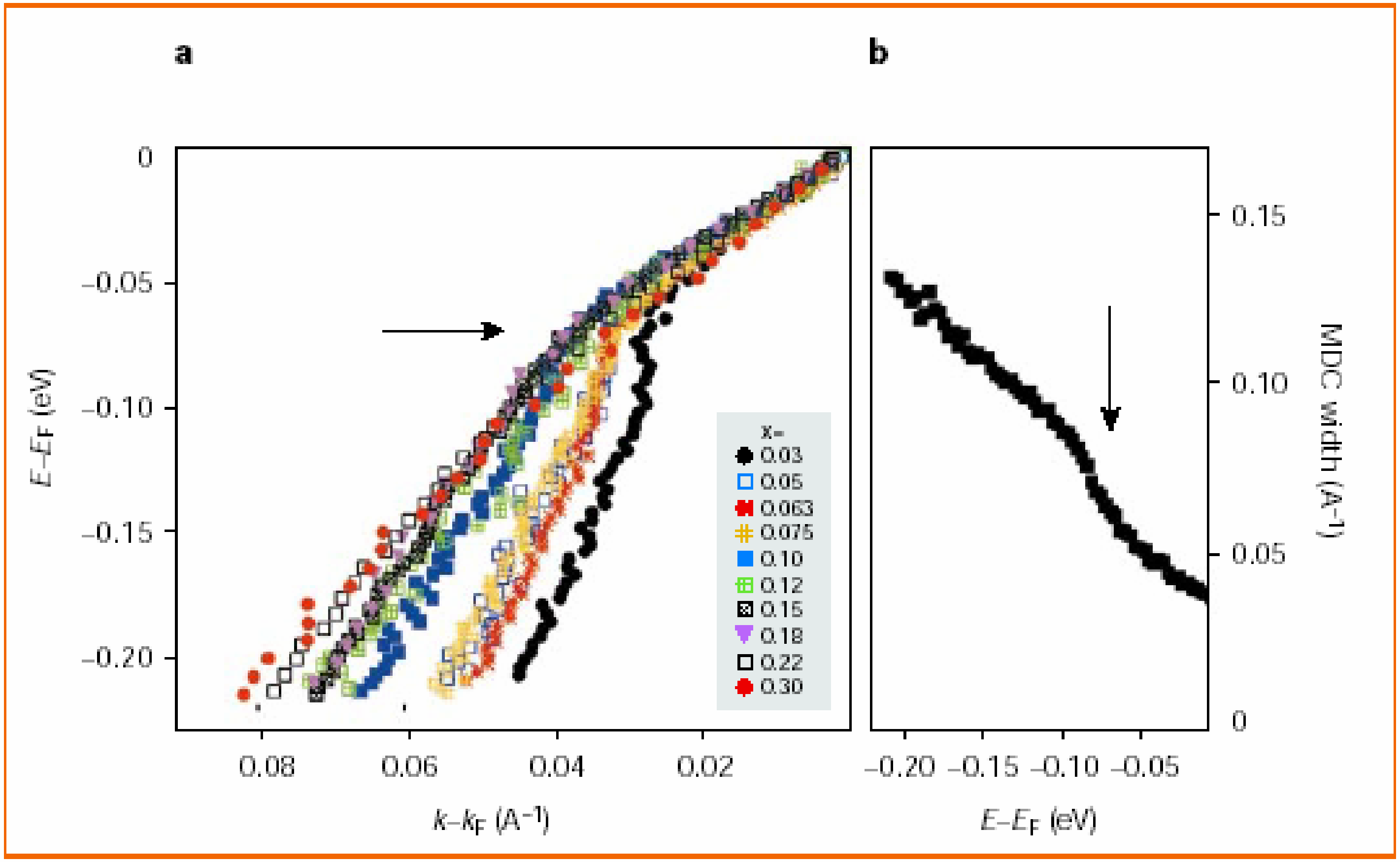
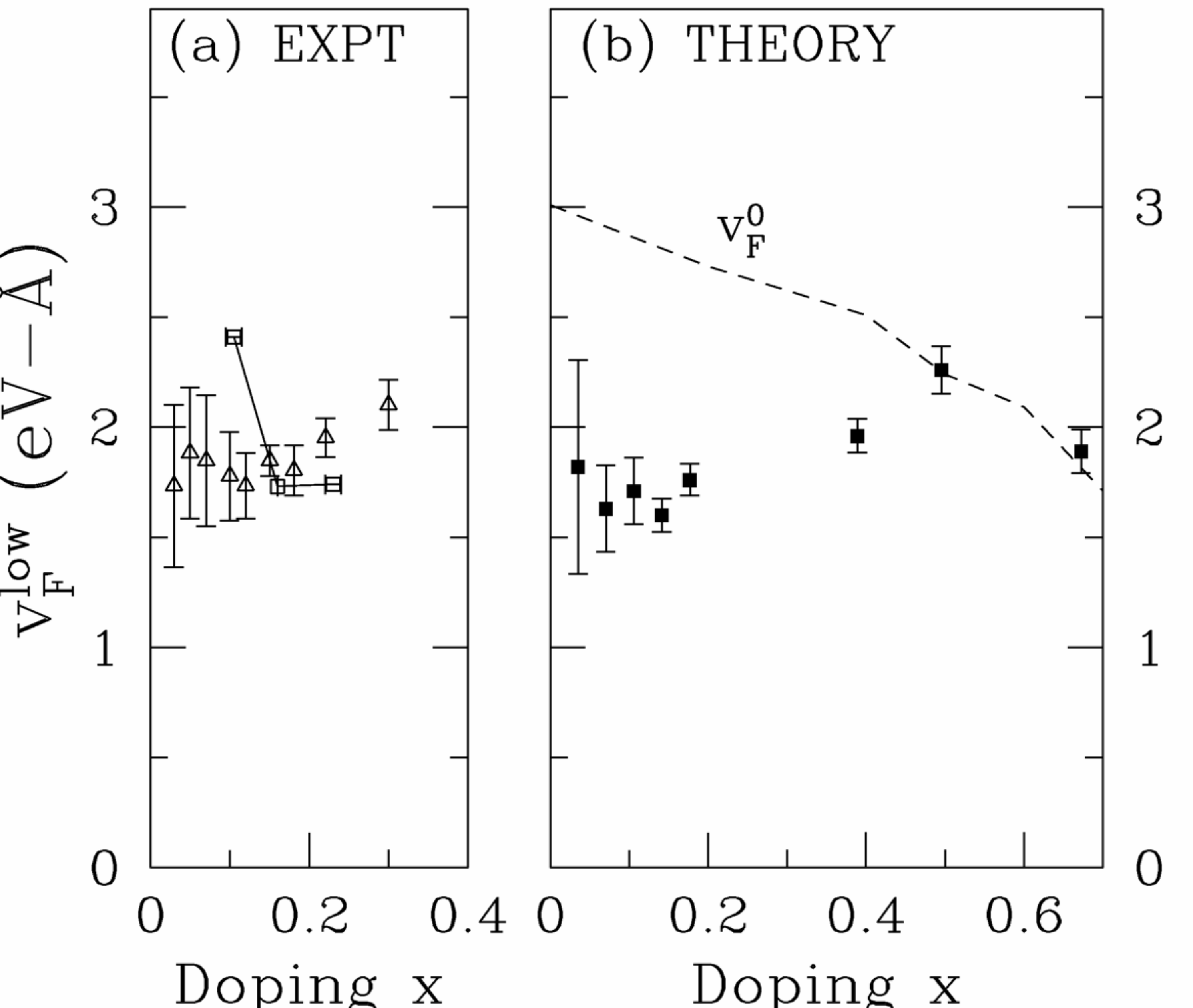


Figure 1 Electron dynamics in the $(La_{2-x}Sr_x)CuO_4$ (LSCO) system. **a**, Dispersion energy, E, as a function of momentum, k, of LSCO with various dopings (where x is between 0.03 (black circles, right curve) and about 0.30 (red circles, left) measured at a temperature of 20 K along the (0,0)–(π,π) nodal direction. The dispersion is obtained by fitting momentum-distribution curves (MDCs), which represent the photoelectron intensity as a function of momentum, for a given energy. The arrow indicates the position of the kink that separates the dispersion into high-energy and low-energy parts with different slopes. E_F and k_F, Fermi energy and Fermi momentum, respectively. **b**, Scattering rate as measured by MDC width (full width at half-maximum) of the LSCO ($x = 0.063$) sample measured at 20 K. The MDC width is proportionally related to the scattering rate of electrons. The arrow indicates a decrease at an energy of about 70 meV.

Expt: Zhou et. al Nature **423**, 398 (2003)

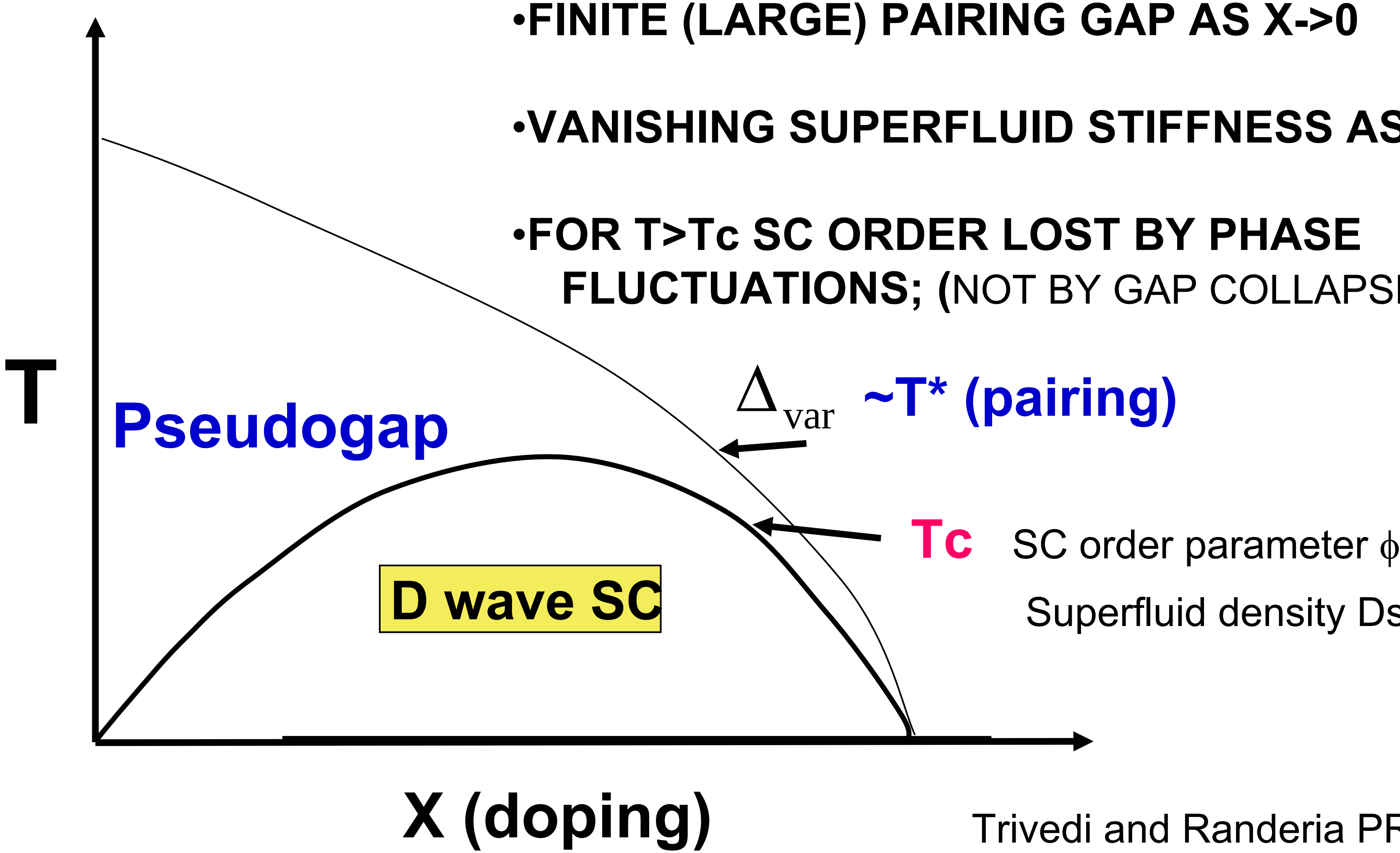


Expt: Zhou et. al
Nature **423**, 398 (2003)

Theory: Paramekanti, Randeria, NT;
PRL **87,** 217002 (2001)

IMPLICATIONS FOR FINITE TEMPERATURE PHASE DIAGRAM

- **FINITE (LARGE) PAIRING GAP AS X->0**
- **VANISHING SUPERFLUID STIFFNESS AS X->0**
- **FOR T>Tc SC ORDER LOST BY PHASE FLUCTUATIONS; (**NOT BY GAP COLLAPSE)



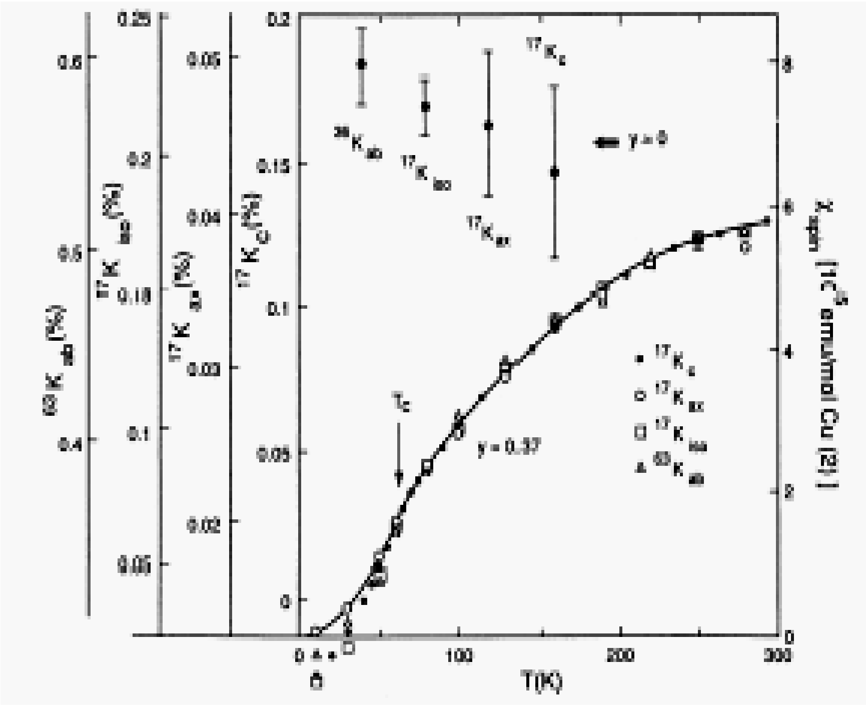
Trivedi and Randeria PRL 1995;
Randeria et al PRL 1992

Open questions

Unusual normal state
“strange” metal
pseudogap metal

NMR spin gap: pairing of spins above Tc

chi



Takigawa et al (1991) T

Alloul et al (1989,93)

- **dχ/dT > 0**
- **1/T$_1$T ~ χ(T)**

$1/T_1T = \lim \Sigma_{\mathbf{q}} F(\mathbf{q}) \, \mathrm{Im} \, \chi(\mathbf{q},\omega)/\omega$

Electronic Specific Heat

C = T (dS/dT)

Loss of entropy above Tc in underdoped cuprates

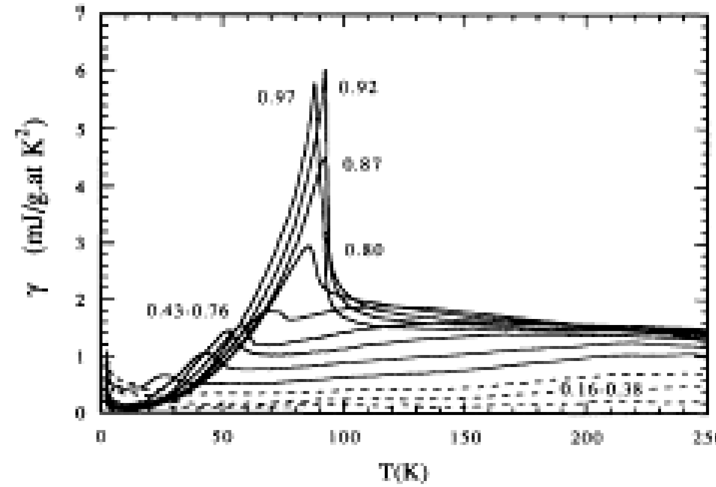


FIG. 4. Electronic specific heat coefficient $\gamma(x,T)$ vs T for $YBa_2Cu_3O_{6+x}$ relative to $YBa_2Cu_3O_6$. Values of x are 0.16, 0.29, 0.38, 0.43, 0.48, 0.57, 0.67, 0.76, 0.80, 0.87, 0.92, and 0.97.

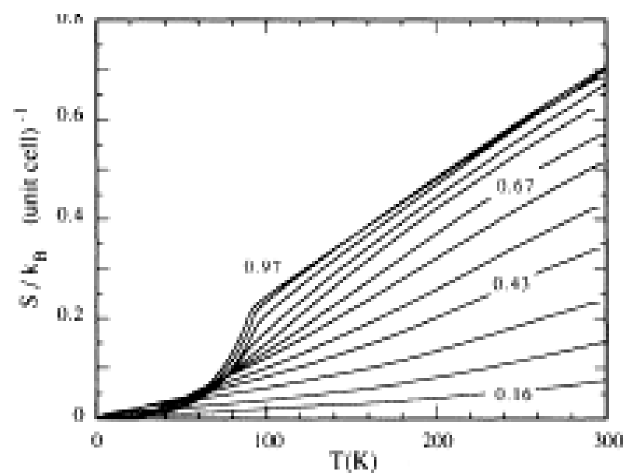


FIG. 5. Electronic entropy $S(x,T)$ for $YBa_2Cu_3O_{6+x}$. Values of x as in Fig. 4.

J. Loram et al, PRL (1993)

Pseudogap above Tc

for small x

- **NMR: spin pairing**

  T > Tc

- **C(T): loss of entropy**

  T > Tc

- **Tunneling & Photoemision:**

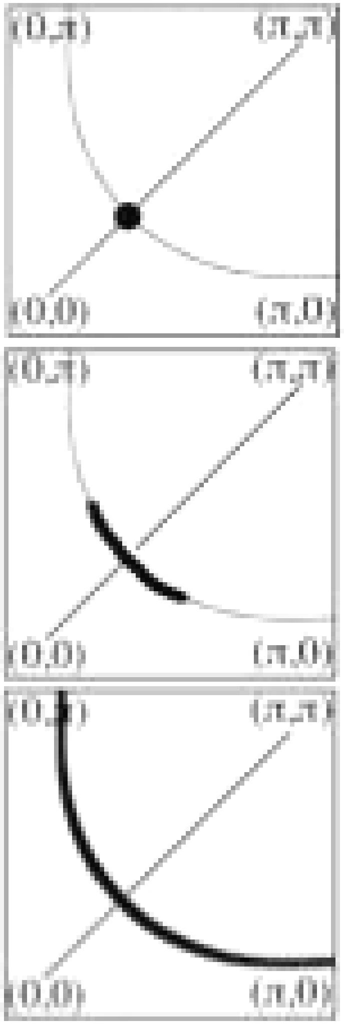
Spectral Gap visible above Tc!

- **No quasiparticles**
- **Fermi surface destroyed**

SC
T = 0

pseudogap
T* > T > Tc

T > T *



Norman et al, Nature (1998)

OPEN AREAS FOR FURTHER RESEARCH

Quantum Antiferromagnets
Frustrated magnets
Spin Liquids

Bosons
Higher spin bosons (spinor states) realized in atomic traps

BCS-BEC Crossover

Organic Superconductors

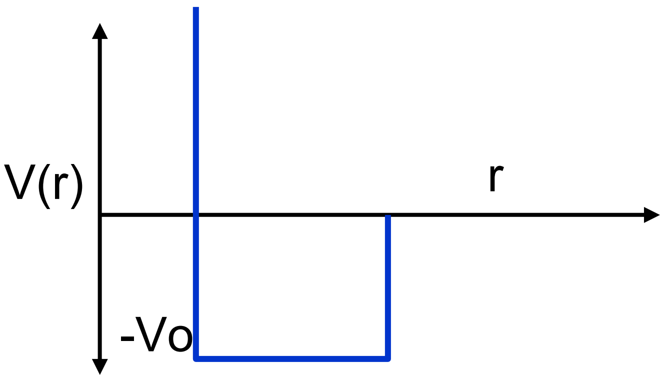
FERMIONS IN TRAPS

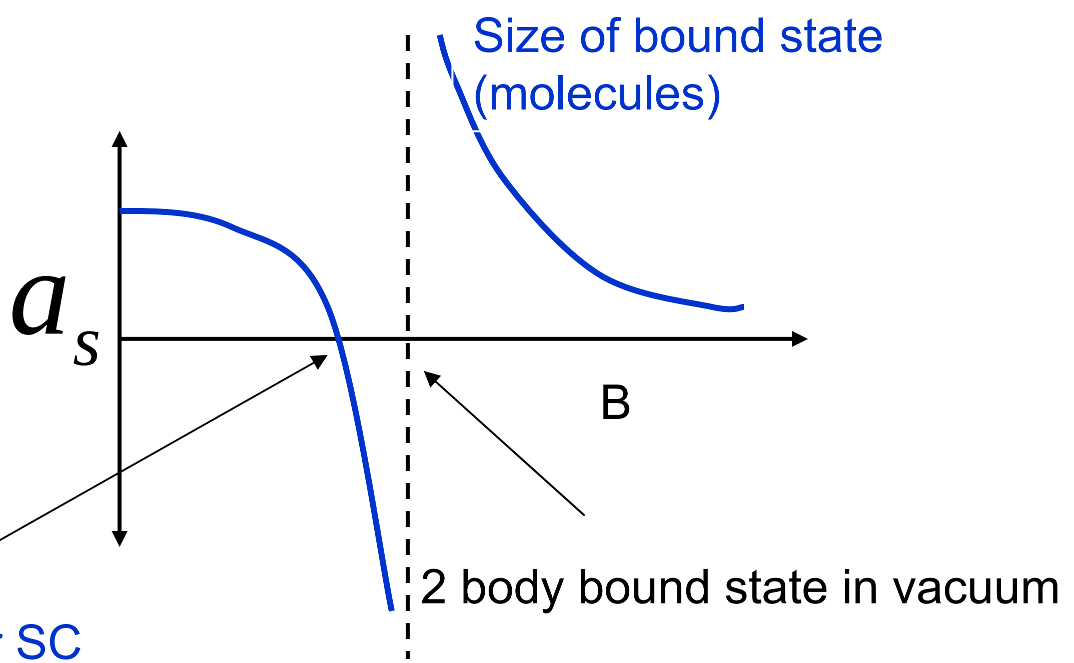
Ultracold fermionic atoms: Can they form Cooper pairs?

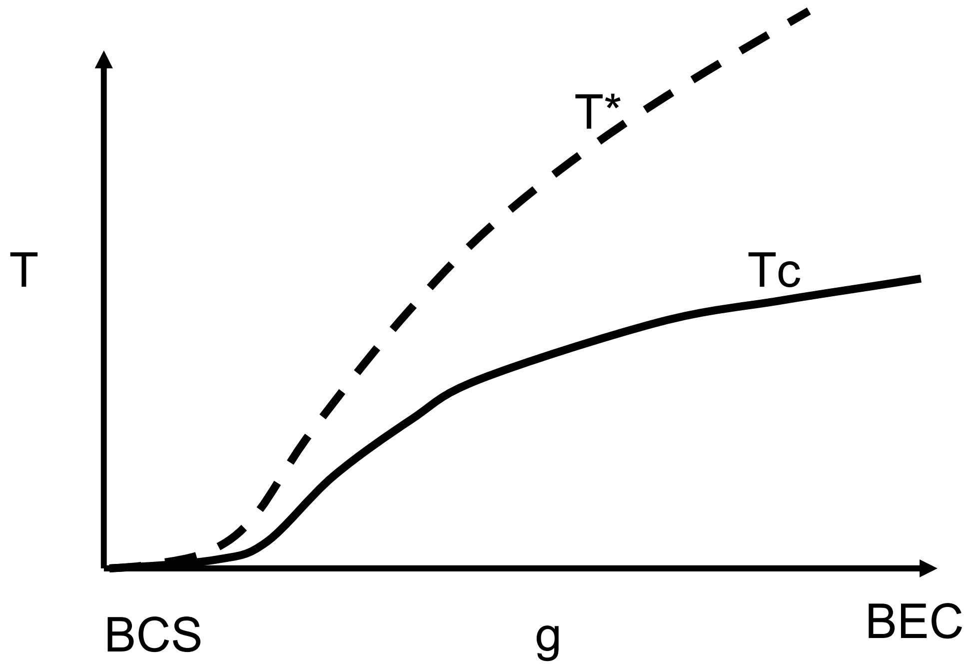
• Degenerate Fermions

• Tune the interaction between atoms with magnetic field
—Feshbach resonance

•Pairing and Coherence







Questions:
Pairing vs Coherence

Any special signature where
the two body bound state is formed

What are the experiments actually
measuring by projecting to the
molecular side

Main lesson:

Use Variational wave functions to calculate many other correlation functions of interest (besides the energy).
That may generate complicated operators but these can be programmed without much difficulty.

Keep in close touch with experiments.