Four Lectures at the 2014 Boulder School:
"Modern Aspects of Superconductivity"

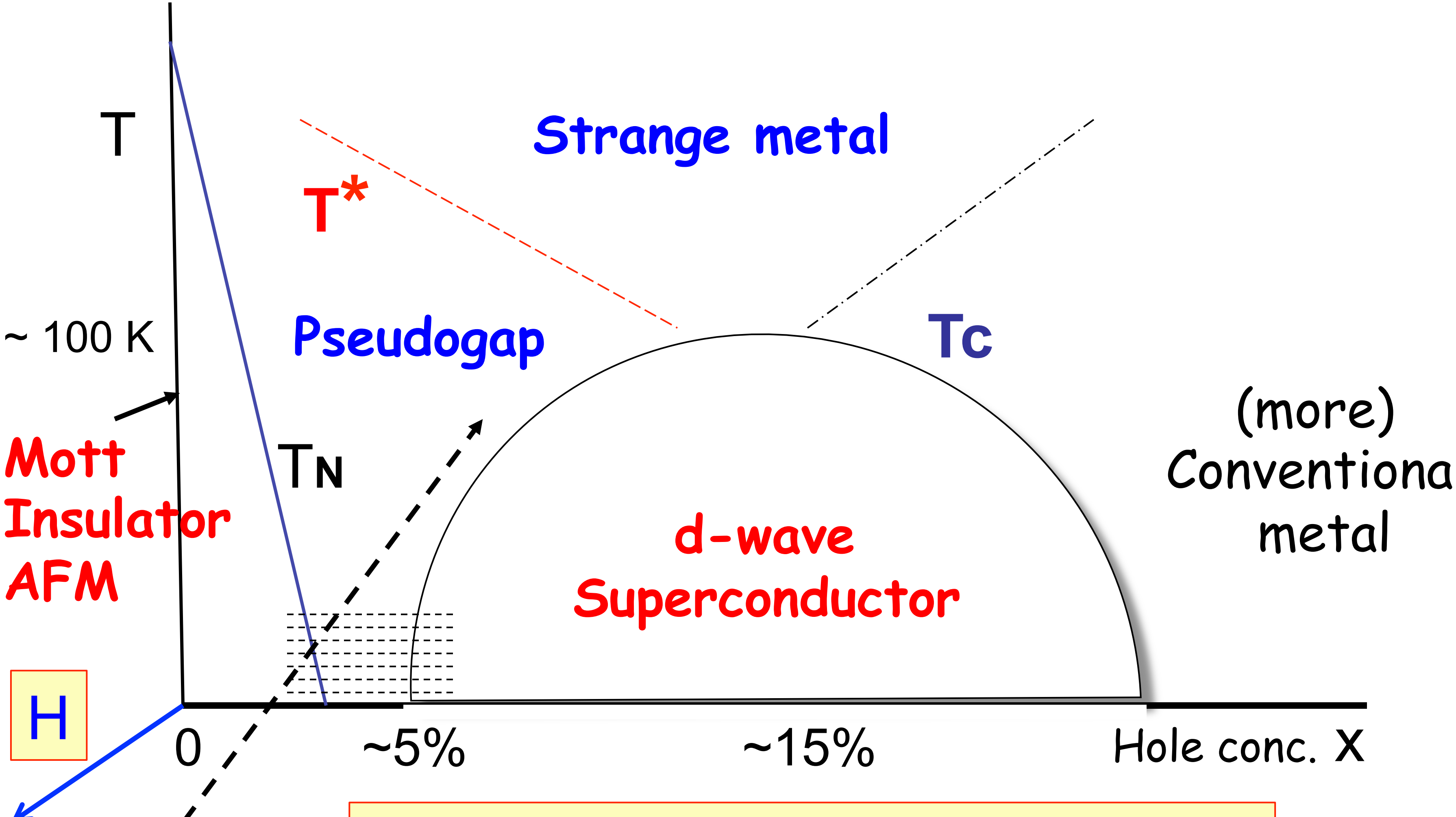
Outline of Lectures:

- Phenomenology of High Tc Cuprates I
- Phenomenology of High Tc Cuprates II
- Superconductivity in Doped Mott Insulators

- BCS-BEC crossover & unitary Fermi gas

Mohit Randeria
Ohio State University

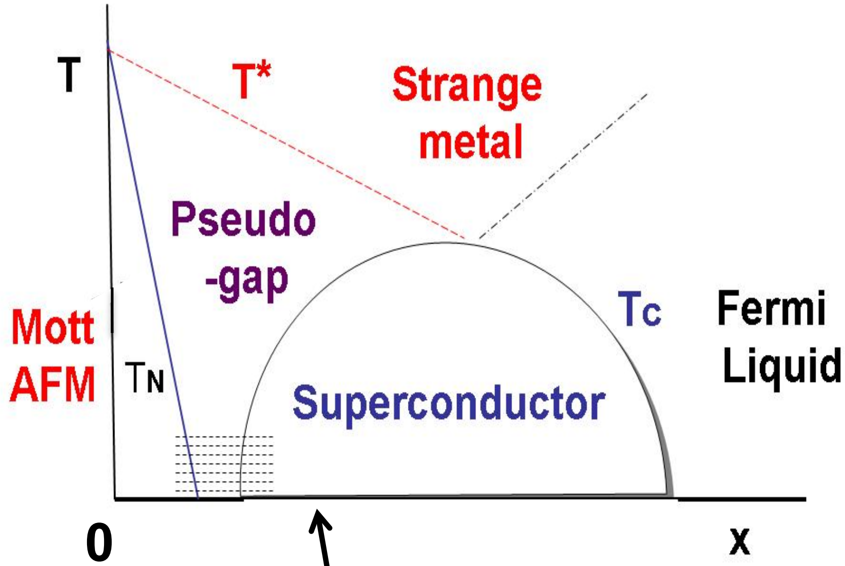
Schematic Phase Diagram of High Tc Cuprates



Goal of Lectures # 1 & 2: to help you understand this phase diagram

Failure of central paradigms of 20th Century Solid State Physics

Band theory fails for parent insulator



Landau Fermi liquid theory fails for strange metal and pseudogap regimes

BCS MF theory fails for underdoping

Competing orders:
Antiferromagnetism
CDW; nematicity; T-reversal...

Hidden Quantum Critical Point under the dome?

Phenomenology of High Tc Cuprates I

- Standard theory of metals, insulators & superconductors
- High Tc cuprate materials
- Parent insulators: Mott AFM
- Problem of doped Mott insulator
- ARPES & quantum oscillations
  - -- Fermi liquid state at overdoping
  - -- Strange metal at optimal doping
  - -- d-wave superconductor

Phenomenology of High Tc Cuprates II

- underdoped materials
  - -- pseudogap
  - -- SC fluctuations
  - -- competing order parameters
  - -- high field experiments

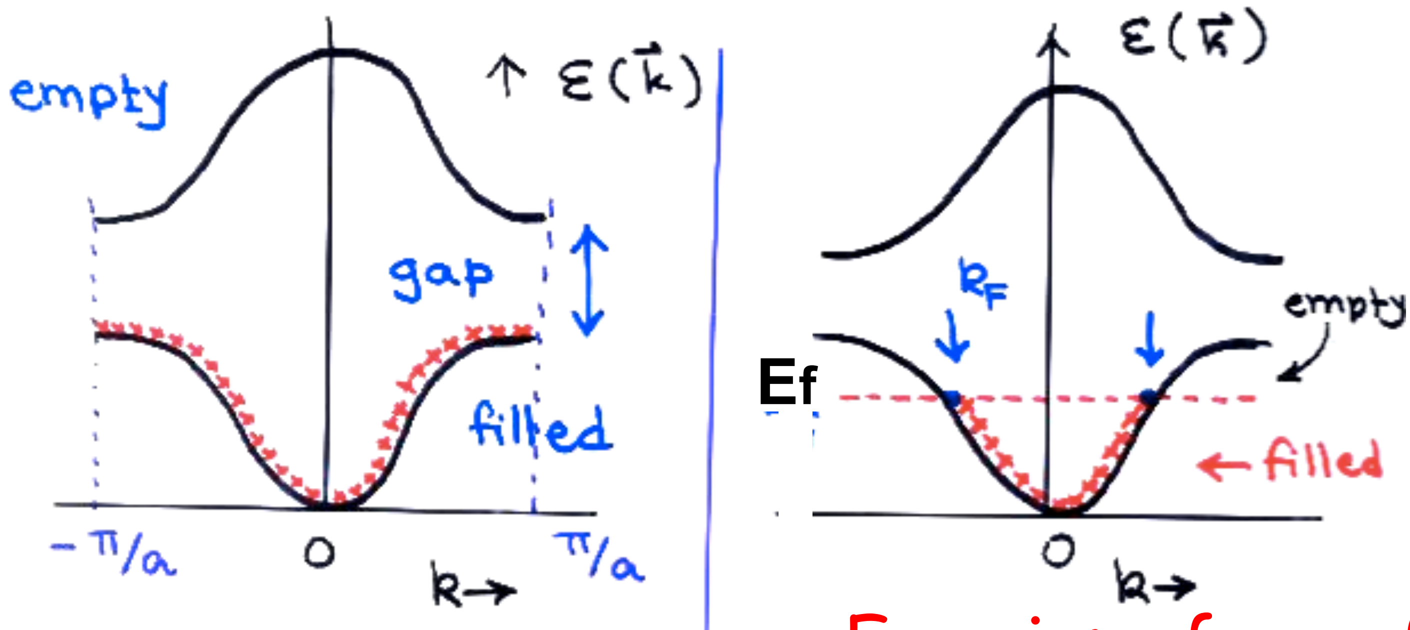
Lightening quick (superficial) review of the central paradigms:

- I) band theory of solids [1]
- II) Landau's Fermi liquid theory [2]
- III) BCS theory of superconductivity [3]

[1] Ashcroft & Mermin; Kittel
[2] Pines & Nozieres; Lifshitz & Pitaevski (L&L Stat. Phys. II)
[3] Tinkham

I) Band Theory: Insulators *vs.* Metals

- solve Schrodinger equation for a <u>single</u> electron in a periodic potential
- obtain "bands" of energy levels and "gaps"
- fill up states consistent with Pauli exclusion



Excitation <u>gap</u>
→ Insulator

Fermi surface of
<u>Gapless</u> excitations
→ Metal

Band Theory:

Spectacular success in understanding

- conventional metals
- band insulators/semiconductors
- topological insulators

Why can one (more or less) ignore Coulomb repulsion between electrons in a metal?

Landau's Theory of Fermi Liquids

II) Landau's Theory of Fermi Liquids

Interactions between electrons lead to
only quantitative changes (not qualitative ones)
in low energy, long wavelength properties

- specific heat $C \sim T$
- spin susceptibility $\chi \sim$ const. etc.
- Boltzmann eqn. for transport

Low energy excitations:
Quasiparticles … "look like" electrons
* live on the Fermi surface (Luttinger theorem)
* Q = 1, S = ½
* sharp $\Gamma << \omega$ * weakly interacting

Why does It work?

* Screening * Pauli exclusion
* all orders in perturbation theory $(d \geq 2)$
  [for RG approach: see Shankar RMP (1993)]

Spectral Function for Electrons:

$$A(\mathbf{k},\omega) = -\frac{1}{\pi}\mathrm{Im}G(\mathbf{k},\omega + i0^{+})$$

= Probability density of making a single-particle excitation with a momentum **k** within a small energy interval around ω

[Relation to ARPES discussed later]

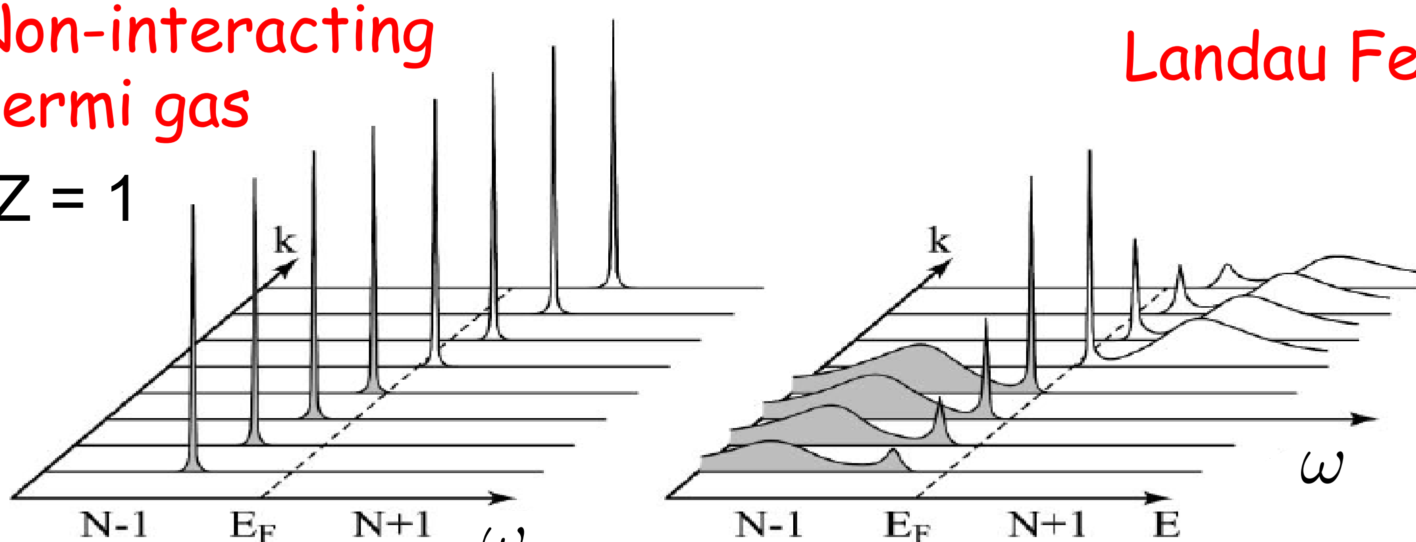
Quasiparticle = pole in G → δ-function in A
Quasiparticle weight Z

Non-interacting Fermi gas

Z = 1

Landau Fermi liquid

0 < Z < 1



figures from Damascelli, Hussain & Shen, RMP (1993)

Spectral Function for Electrons:

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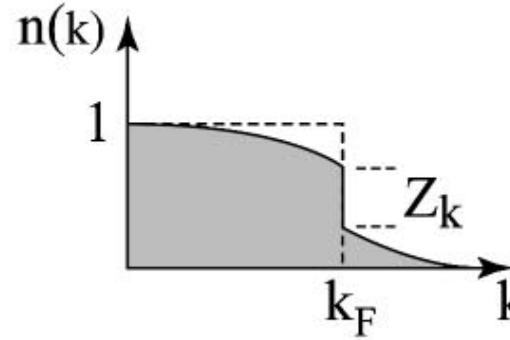
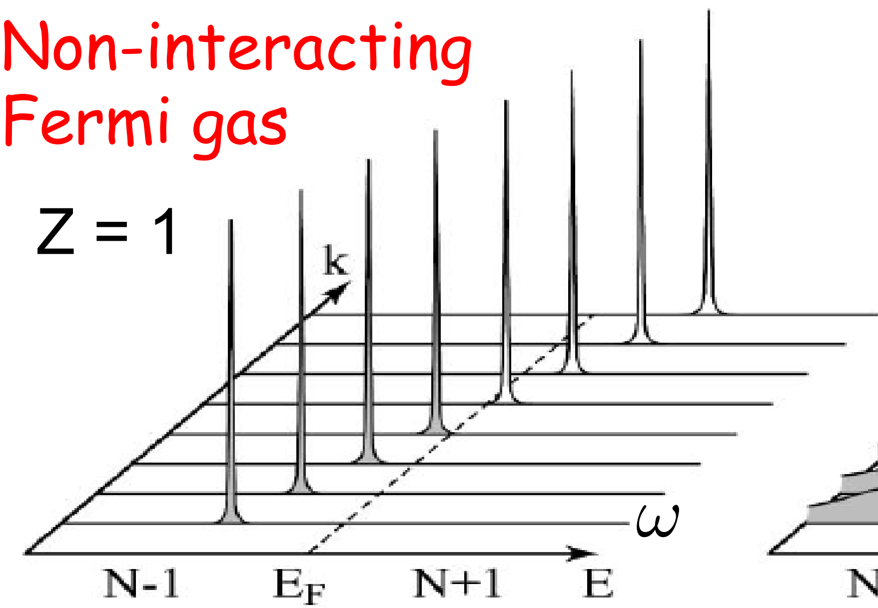


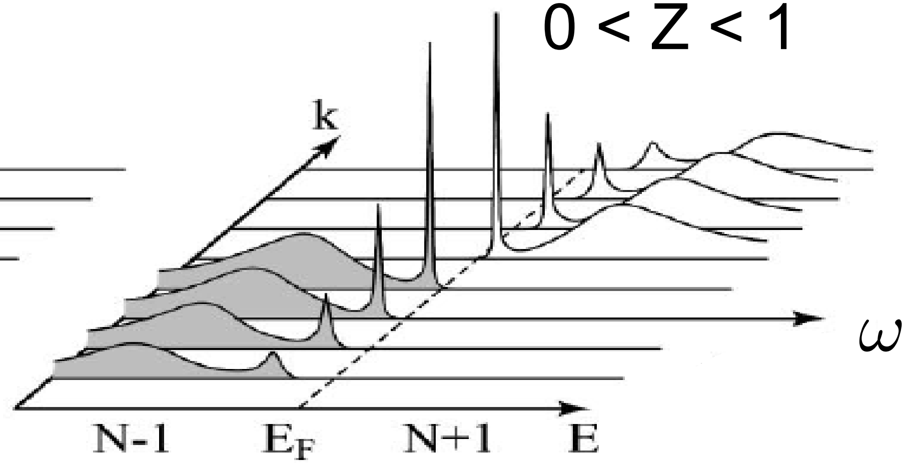
Non-interacting Fermi gas

Z = 1



Landau Fermi-liquid

0 < Z < 1



$$A(k,\omega) = \delta(\omega - \epsilon_k^0)$$

$$\epsilon_k^0 \simeq \frac{k_F}{m}(k - k_F)$$

$$A(k,\omega) = Z\delta(\omega - \epsilon_k) + \text{incoherent weight}$$

$$\epsilon_k \simeq \frac{k_F}{m^*}(k - k_F)$$

III) BCS Theory of Superconductivity

Pairing <u>and</u> Condensation

* Pairing:

Weak attraction "g" between electrons

(electron-phonon int. in conventional SCs)

→ instability of the Fermi liquid:

S = 0, 'L = 0' Pairs

Binding energy of pairs

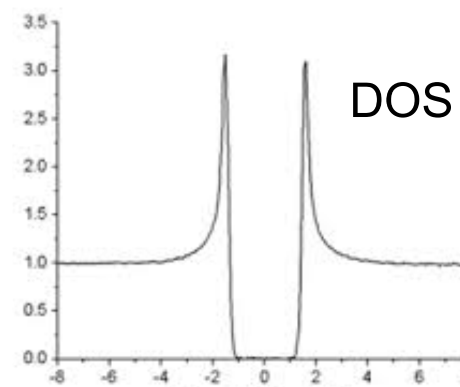
= Energy gap

$$\boxed{\Delta = \omega_0 \exp(-1/g)}$$

Experimental observation of gap Δ:

Thermodynamics: C(T); χ(T)

Spectroscopy: tunneling, optics



BCS Theory of Superconductivity: Pairing and Condensation

Condensation:

2^{nd} order phase transition at $T_c \sim \Delta$
Macroscopic number ($\sim 10^{20}$) of pairs in a single quantum state (cf. BEC)

Order parameter
broken U(1)

$\Delta = |\Delta| \exp(i\theta)$

gap phase

Experimental manifestation of the phase θ

- superconductivity
- Meissner effect
- Josephson effects

Condensation:
Off Diagonal Long Range Order
ODLRO (or algebraic order)

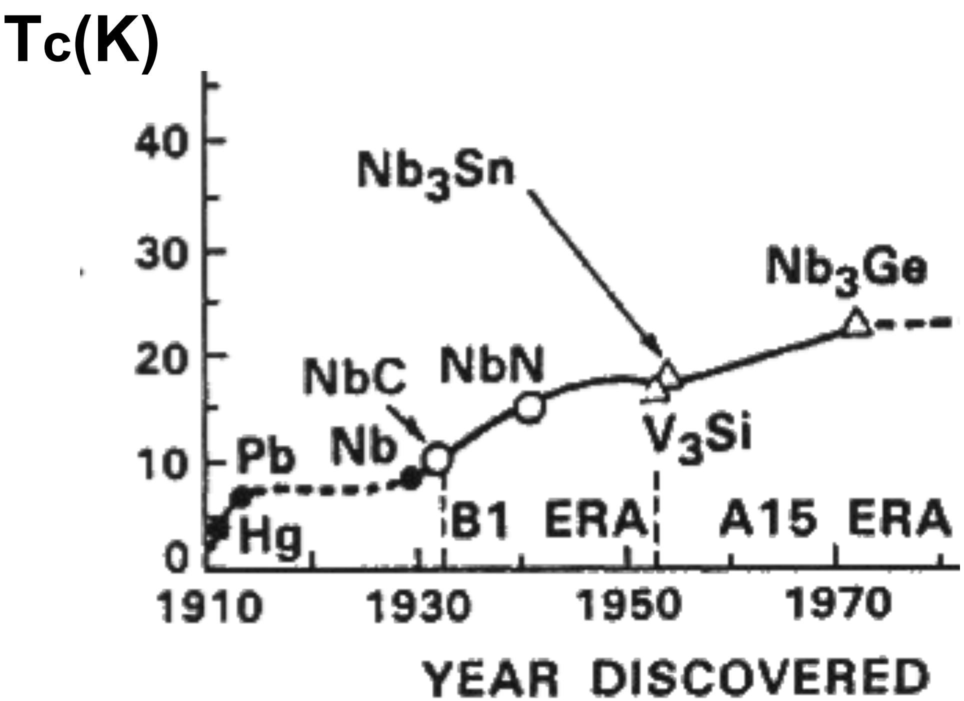
$$\langle c^\dagger_{\mathbf{k},\alpha} c^\dagger_{-\mathbf{k},\beta} \rangle$$

Phase Coherence & rigidity
Superfluid stiffness

$$\rho_s > 0$$

By the late 1970's ...
BCS and Ginzburg-Landau Theories solved all existing physics problems in superconductors

... and even superfluid Helium-3 which is a triplet, p-wave paired superfluid!



Plateau in the search for higher Tc materials

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  -- pseudogap

  -- SC fluctuations

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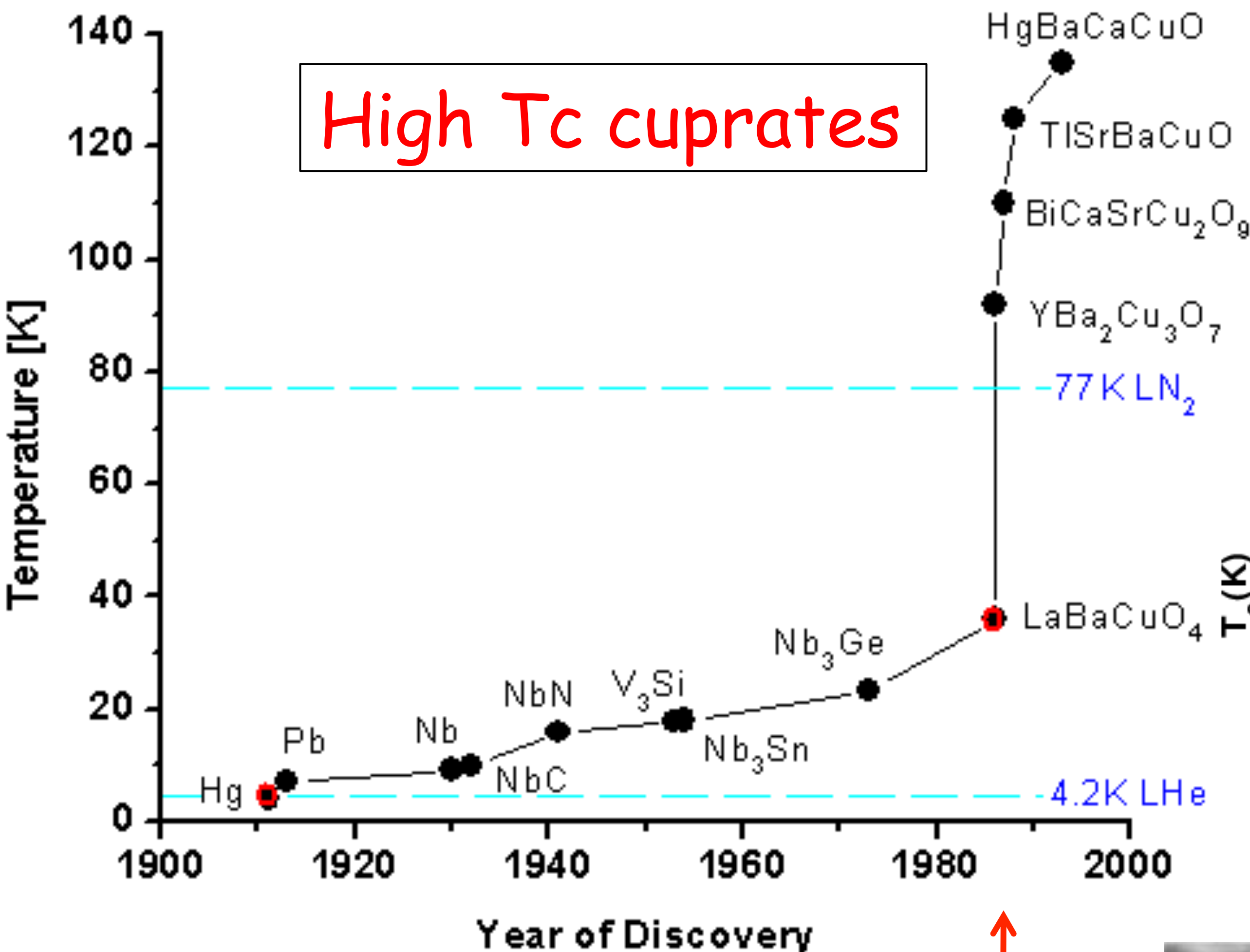
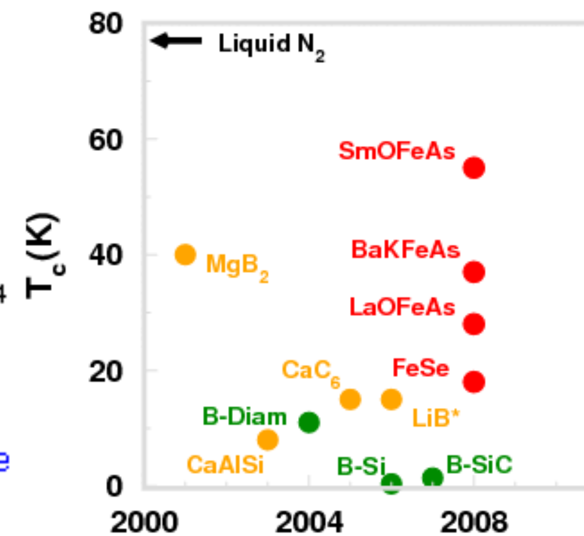


- MgB$_2$
- Fullernines
- Pnictides



"Possible high Tc superconductivity in the
Ba–La–Cu–O system", J. G. Bednorz & K. A. Müller
Z. Phys. B 64, 189 (1986)

High Tc Cuprates

$La_{(2-x)}Sr_xCuO_4$ (LSCO) max Tc = 40 K

$YBa_2Cu_3O_{(6+x)}$ (YBCO) Tc = 90 K

$Bi_2Sr_2CaCu_2O_{(8+x)}$ (Bi2212) Tc = 90 K

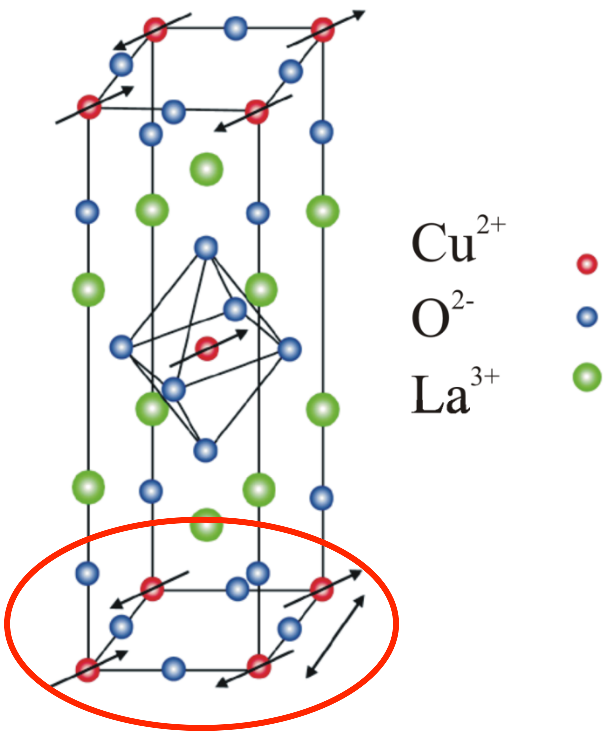
$Tl_2Ba_2Ca_2Cu_3O_{(10+x)}$ (Tl2223) Tc = 125 K

Highest Tc ~ 160K under pressure

- 4-5 elements
- Off-stoichiometric

* Yet very similar properties

$La_{(2-x)}Sr_xCuO_4$



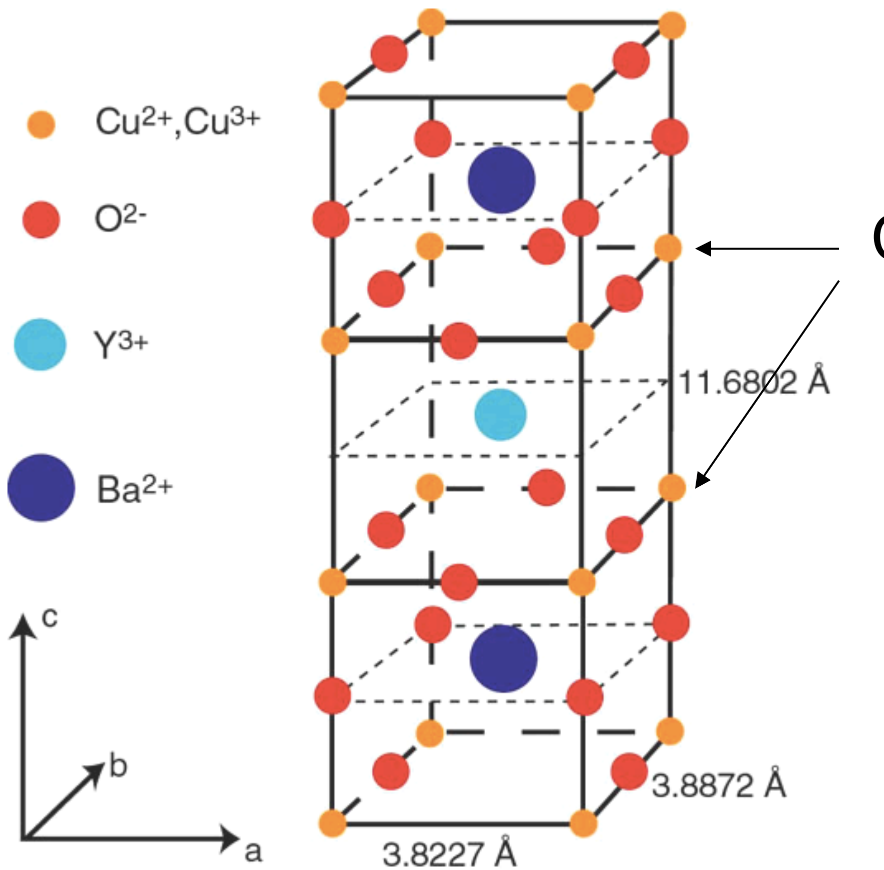
* Common feature:

CuO_2 plane

1, 2 or 3 planes/unit cell

High Tc Cuprates:

Layered structure
→ Quasi-2D
electronic structure



YBa2Cu3O(6+x)

All the action –
superconductivity,
magnetism –
is on the
2D CuO_2 planes

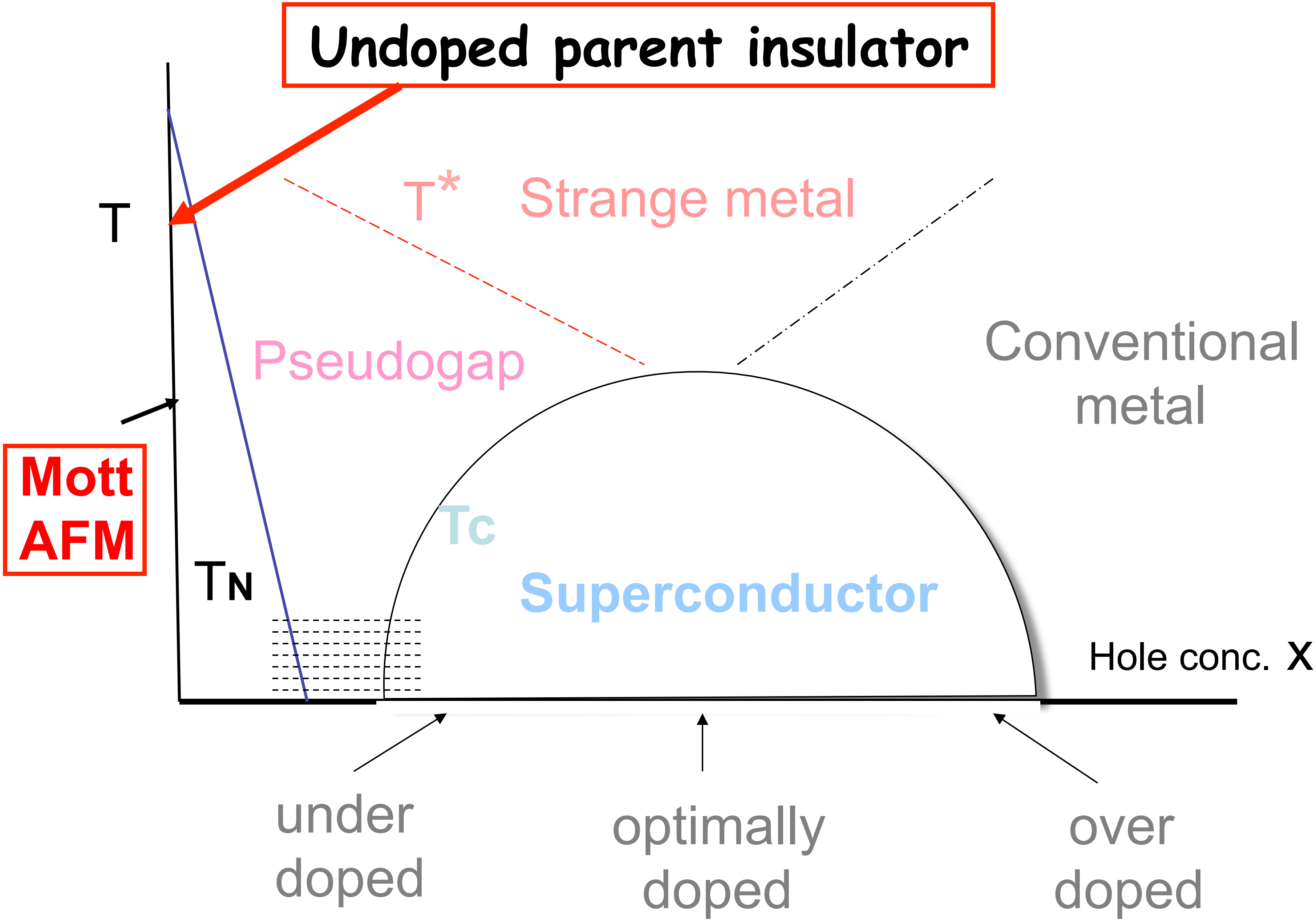
Stoichiometry of "spacer layers" (between planes)
→ controls the carrier concentration of CuO_2 layers

"Matthias' Rules" for finding new superconductors (1960's)

1. Transition metals are better than simple metals
2. Peaks of density of states at the Fermi level are good
3. High crystallographic symmetry is good: Cubic is best
4. Stay away from oxygen
5. Stay away from magnetism
6. Stay away from insulating phases
7. Stay away from theorists

Strongly Violated by Bednorz & Muller

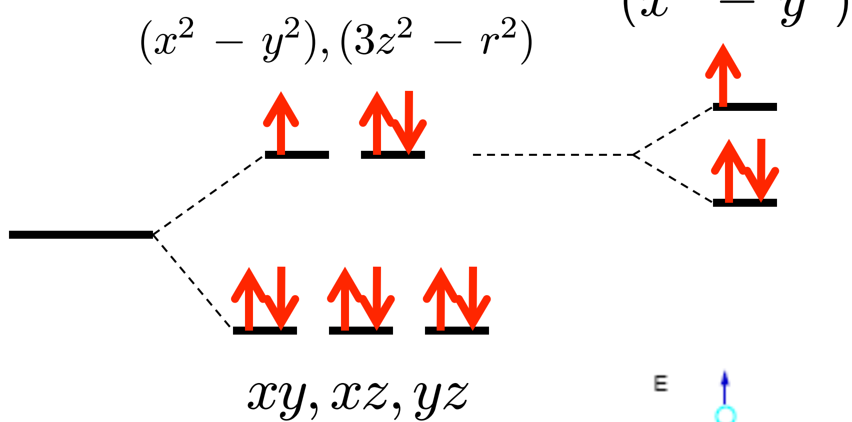
T. H. Geballe & J.K. Hulm,
"Bernd Theodor Matthias"
(National Academies Press, 1996).


Undoped parent insulator
T
T*
Strange metal
Pseudogap
Conventional metal
Mott AFM
Tc
TN
Superconductor
Hole conc. X
under doped
optimally doped
over doped

La_2CuO_4

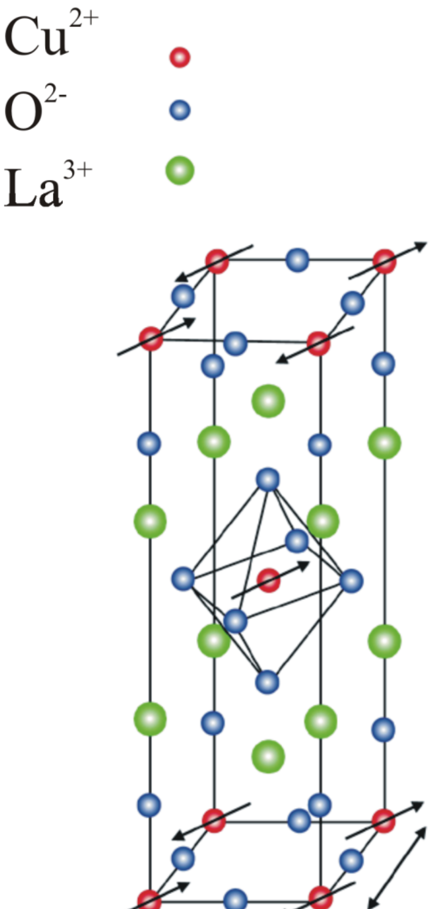
$2(+3) + Cu + 4(-2) = 0$

→ $Cu\ 2+ \Rightarrow 3d^9$



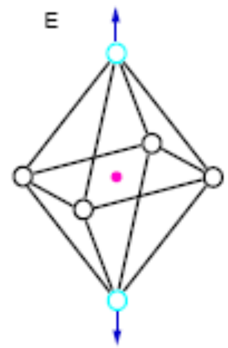
1 elect. (or 1 hole) per u.c. = Spin 1/2

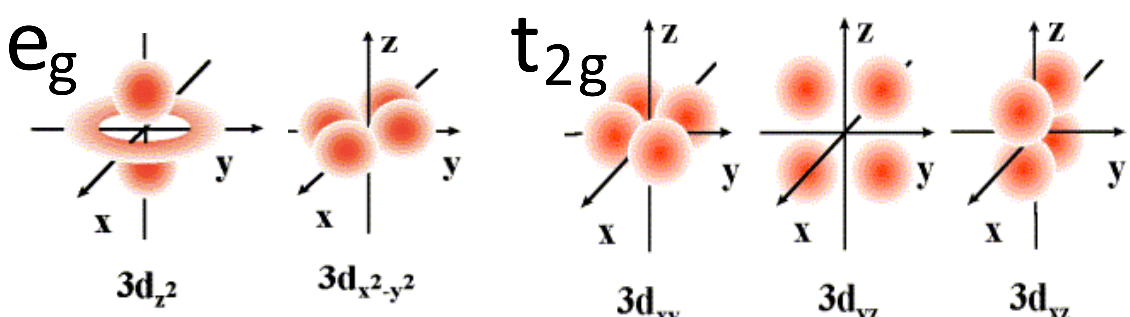
→ Hybridize with O pσ orbitals



corner sharing octahedra

Octahedral/ Cubic crystal field



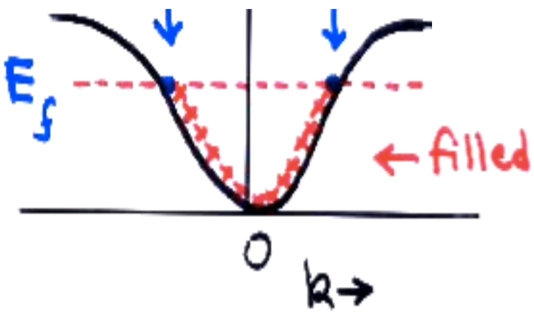


<u>Band theory</u>

La_2CuO_4

1 el/unit cell

→ Half-filled band (**k**-space)



Treating Interactions perturbatively

→ ~~metal~~

Experiments → La_2CuO_4 Insulator!

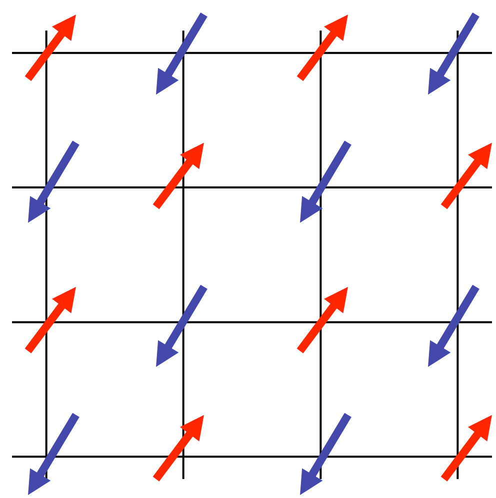
Mott Insulator*

driven by strong Coulomb correlations in a half-filled band

On-site Coulomb = Hubbard U

$$U n_{i\uparrow} n_{i\downarrow} \qquad U \gg t$$

Half-filled in **r**-space: one el./site



<u>Charge</u> → Mott Insulator

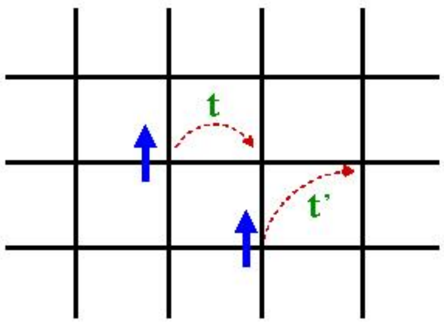
<u>Spin</u> → Antiferromagnet

(*will <u>not</u> discuss charge-transfer Insulator)

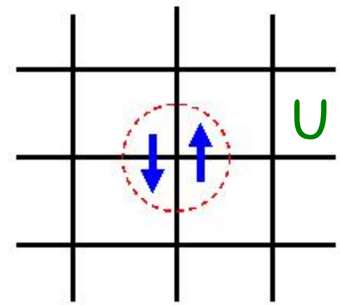
Hubbard model: minimal model for CuO2 planes

$$\mathcal{H} = \sum_{\mathbf{k},\sigma} \epsilon(\mathbf{k}) c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + U \sum_{\mathbf{r}} n_{\mathbf{r}\uparrow} n_{\mathbf{r}\downarrow}$$

$\epsilon(\mathbf{k})$

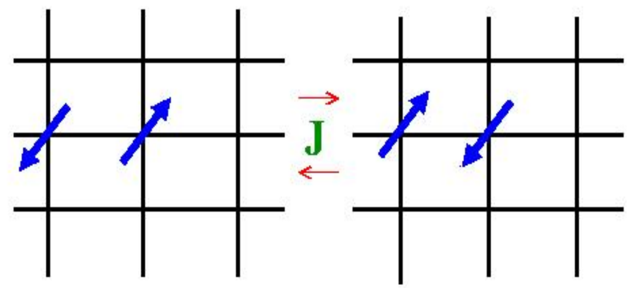


$U \gg t, |t'|$



AF superexchange

$J \sum \mathbf{S}_i \cdot \mathbf{S}_j \qquad J = 4t^2/U$



- neutron
- Raman

~ 100-150 mev ← $J \leq |t'| \leq t \ll U$ → 3.6 eV

↓

300 meV

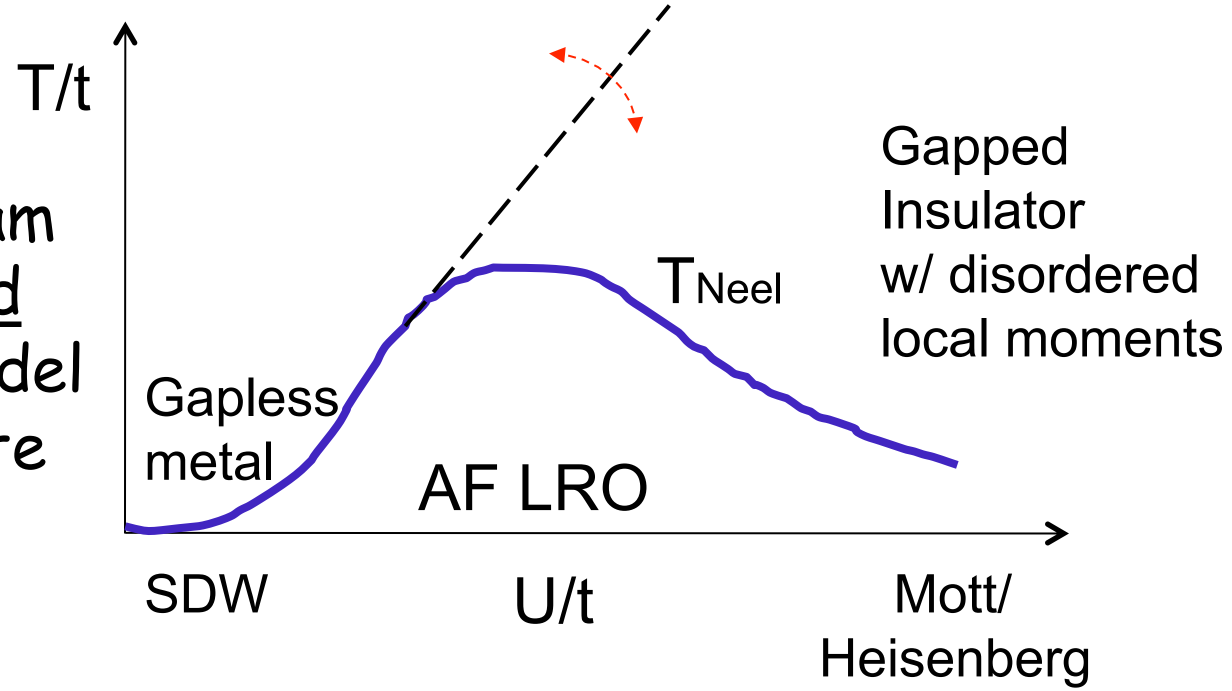
t' ~ t/4

- photoemission
- electronic structure calc.

Insulator →
2D S=1/2 Heisenberg AFM

Spin Density Wave (SDW) vs. Heisenberg AF

Phase diagram of <u>half-filled</u> Hubbard model d=3; bipartite



Do Mott insulators always show AFM order at T=0 ?

- Yes, for bipartite lattices, no frustration & d > 1
  → parent insulator in cuprates has a Neel Long Range Order

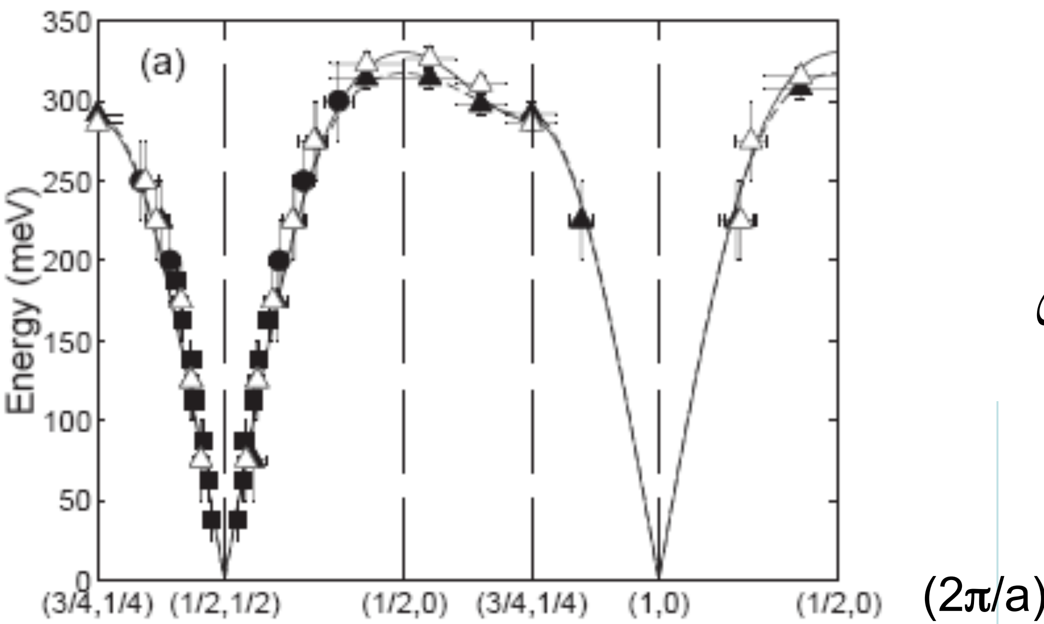
- No, for non-bipartite & frustrated systems
  → quantum spin liquids (triangular lattice organics, kagome lattice materials,…)

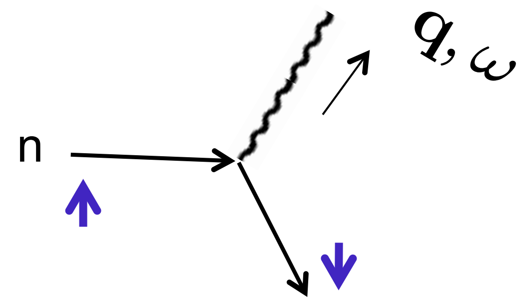
See Senthil's lectures

Undoped cuprates → Probe spins using neutrons

- elastic scattering → magnetic order Q = (π,π) or (1/2,1/2)
- ordered moment reduced by quantum fluctuations
- inelastic → spin wave excitations

R. Coldea et al, PRL (2001)





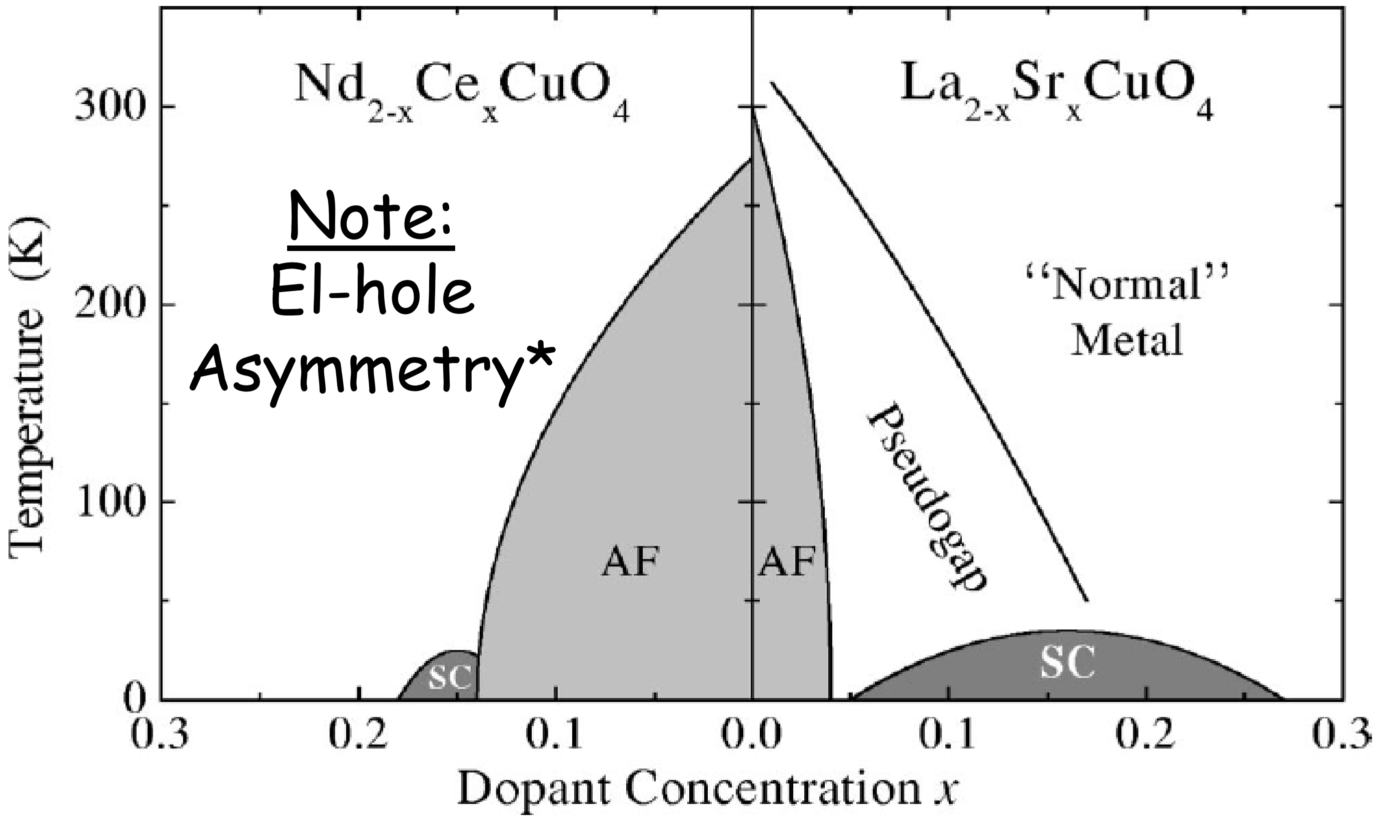
$$\omega(\mathbf{q}) \simeq cq \quad (q \to 0)$$

highest J among
2 & 3 dim.
TM oxides

La_2CuO_4 → S=1/2 Heisenberg AF with n.n. J = 150 meV

+ small ring exchange consistent with t^4/U^3

What happens when you put mobile carriers in a Mott insulator?



focus only on hole doping here

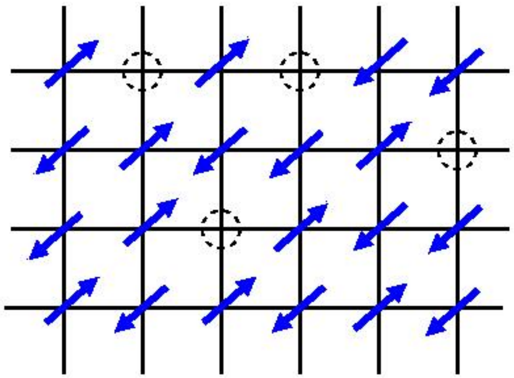
← Electron doping | Hole doping →

Mott

*see A. Paramekanti's lectures

$La^{3+} \rightarrow Sr^{2+}$: $La_{2-x}Sr_xCuO_4$

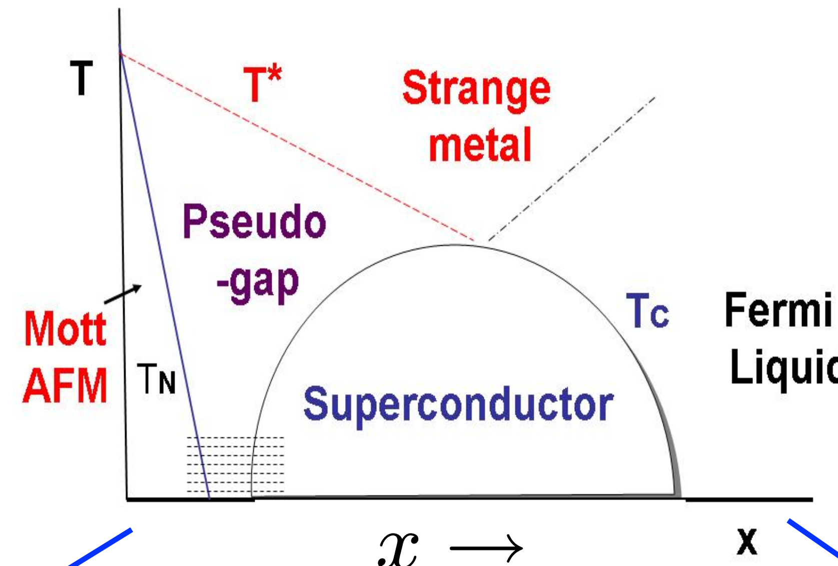
Central problem: **Electronic structure of a doped 2D S=1/2 Mott insulator?**



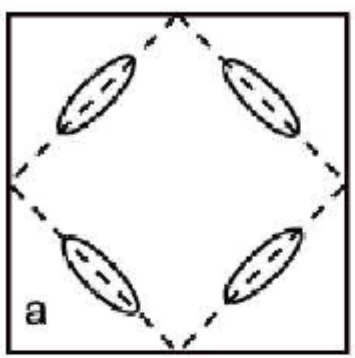
hole conc. x

?

$\Rightarrow$

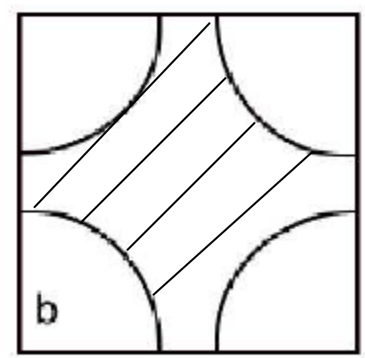


FS Pockets
with x holes
(violates Luttinger
without AFM order
Or exotic order)



?

Large FS with
Luttinger count
(1-x) electrons
= (1+x) holes



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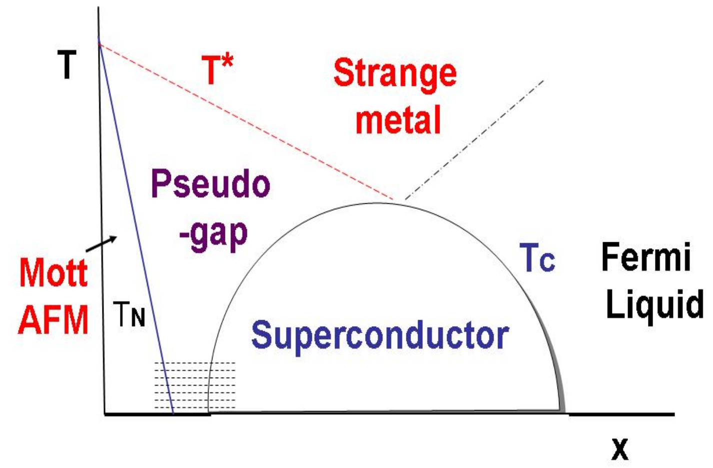
One of the most important probes of the electronic structure of all phases of the High Tc cuprates



Angle-Resolved PhotoEmission Spectroscopy (ARPES)

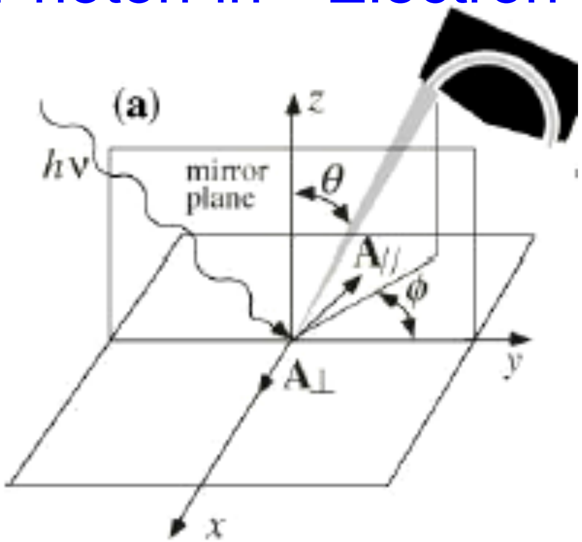
Review articles:

- 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*", eds. K. H. Bennemann and J. B. Ketterson, (Springer 2004); cond-mat/0209476.

See also: D. Dessau's lectures at this School

ARPES $\boxed{I(\mathbf{k},\omega) = I_0(\mathbf{k}) f(\omega) A(\mathbf{k},\omega)}$

Photon-in Electron-out



k = momentum in 2D zone

ω = - binding energy

(w.r.t. chemical potential)

Matrix elements: $I_0(\mathbf{k})$

- polarization selection rules
- incident photon energy hν
- No T or ω dependence

Fermi fn $f(\omega) = \frac{1}{\exp(\omega/T)+1}$

Spectral Function $A(\mathbf{k},\omega)$

$f(\omega)A(\mathbf{k},\omega) =$ <u>occupied</u> part of Spectral Function

Spectral function:

$$A(\mathbf{k},\omega) = -\frac{1}{\pi}\mathrm{Im}G(\mathbf{k},\omega + i0^+)$$

= Probability density of making a single-particle excitation with momentum **k** at an energy ω

Green's function:

$$G(\mathbf{k},\omega) = \frac{1}{\omega - \epsilon_{\mathbf{k}} - \Sigma(\mathbf{k},\omega)}$$

Self Energy

$$\Sigma(\mathbf{k},\omega) = \Sigma'(\mathbf{k},\omega) + i\Sigma''(\mathbf{k},\omega)$$

→ Effects of Interactions

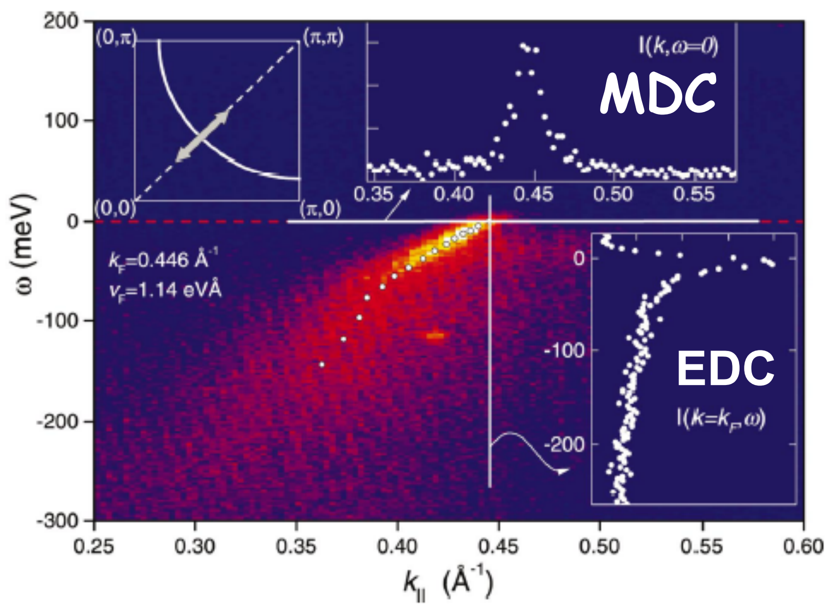
renormalized dispersion

scattering rate ~ 1/(lifetime)

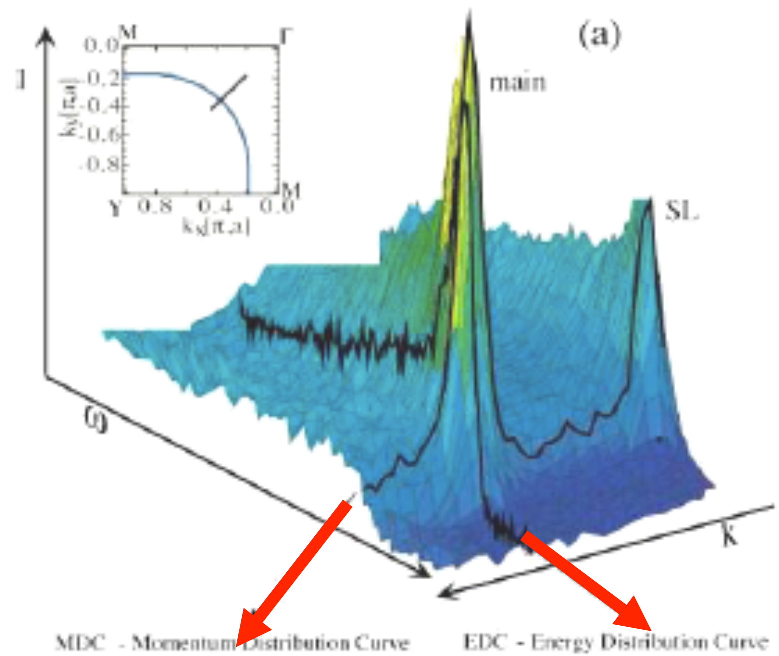
$$A(\mathbf{k},\omega) = \frac{1}{\pi}\,\frac{|\Sigma''(\mathbf{k},\omega)|}{[\omega-\epsilon_k-\Sigma'(\mathbf{k},\omega)]^2+[\Sigma''(\mathbf{k},\omega)]^2}$$

$\Sigma'(\omega)$ → Renormalized dispersion

$\Sigma''(\omega)$ → Line width



Valla et al, Science (2000)



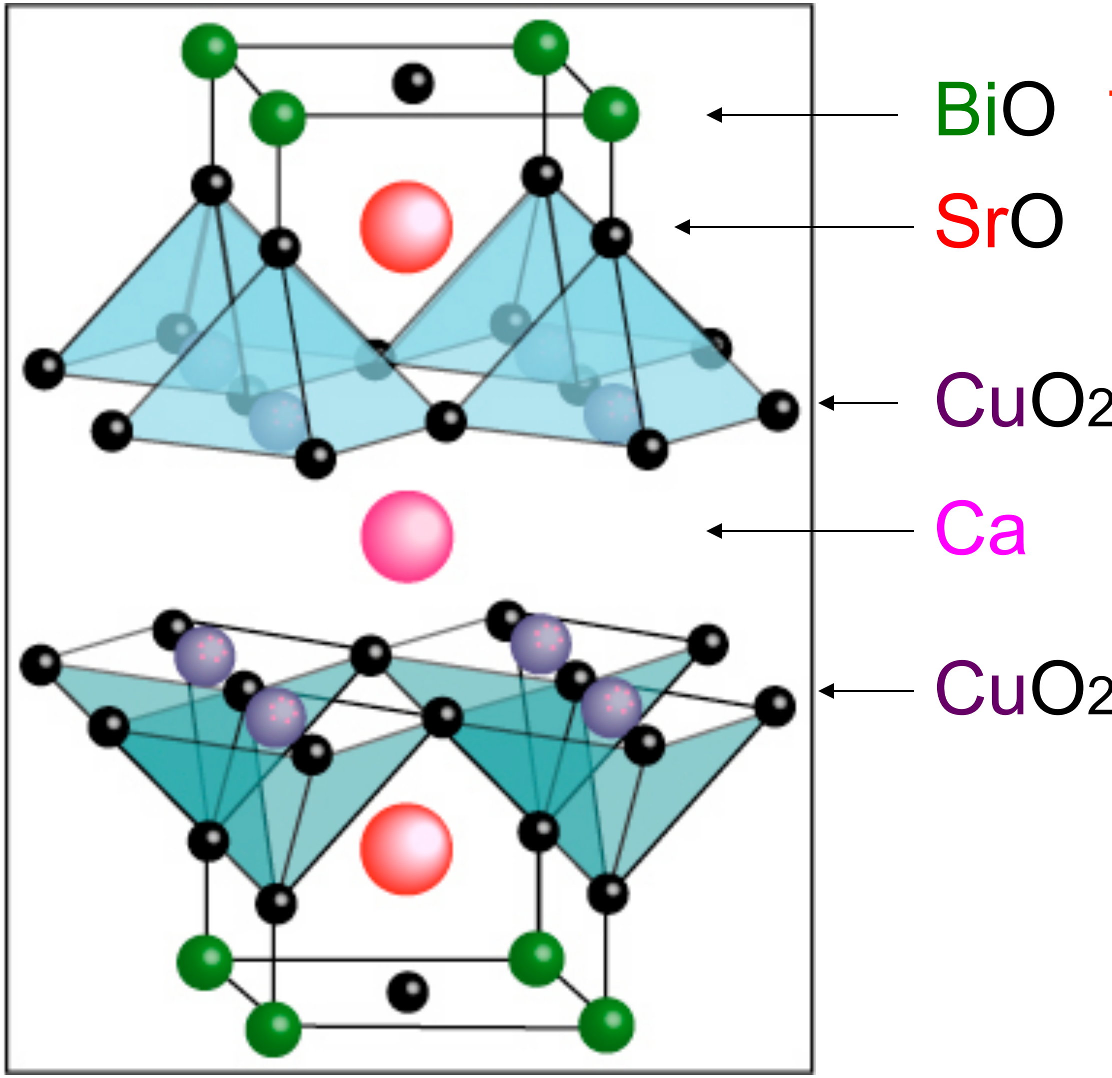
MDC EDC

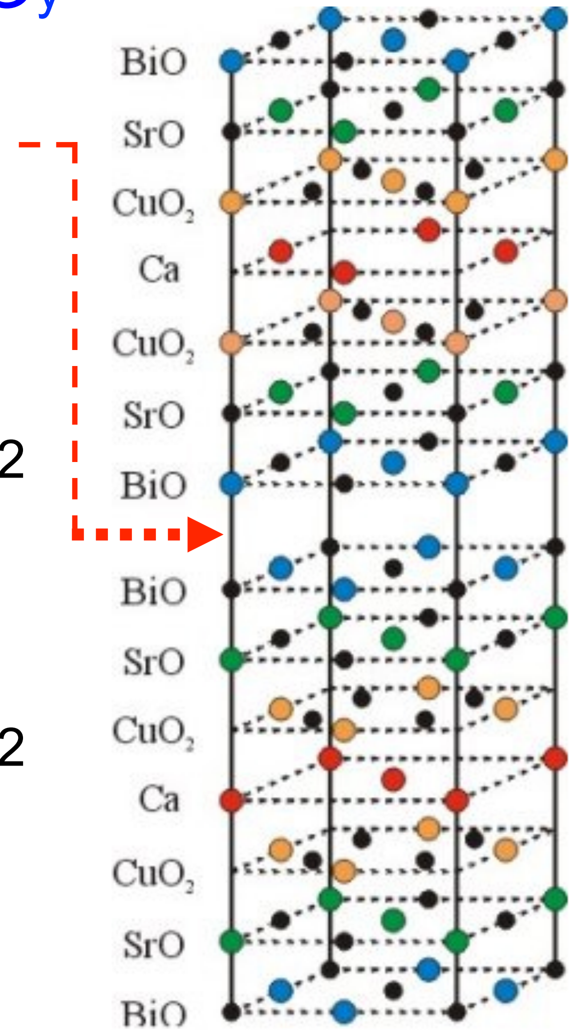
A. Kaminski et al, PRL (2001)

EDC: energy distribution curve: $A(\mathbf{k},\omega)$ fixed **k**, as a function of ω

MDC: momentum distribution curve: $A(\mathbf{k},\omega)$ fixed ω as a function of **k**

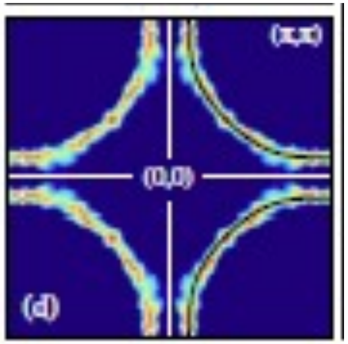
Bi2212: $Bi_2Sr_2CaCu_2O_y$

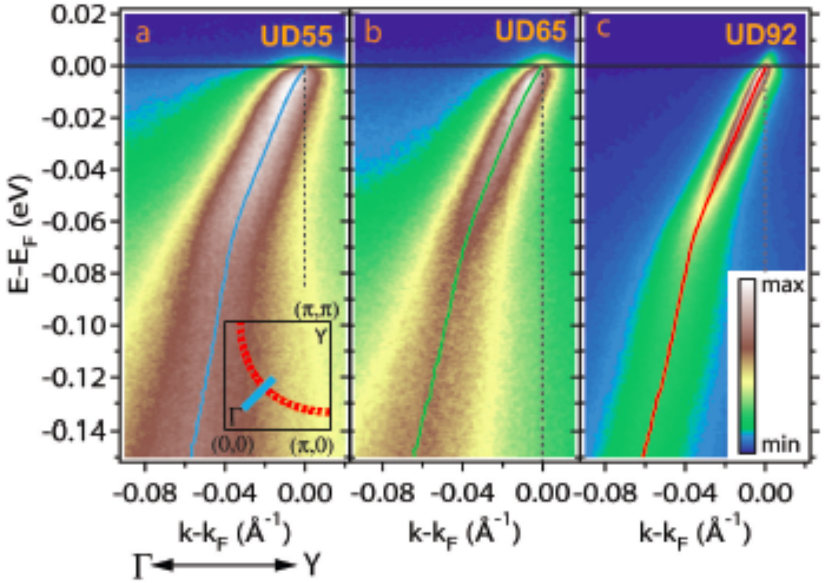




Both ARPES & STM are surface sensitive probes
→ exploit cleavage plane in Bi2212 & Bi2201

What can we learn from ARPES?





Vishik, PRL (2012)

- Fermi surface k_f
- Fermi velocity v_f
- Dispersion & Σ'
- Linewidths Σ'' and Z
  - → Fermi Liq or not?

- k-resolved Gaps
  - → SC gap
  - → "pseudogap"

Phenomenology of High Tc Cuprates I

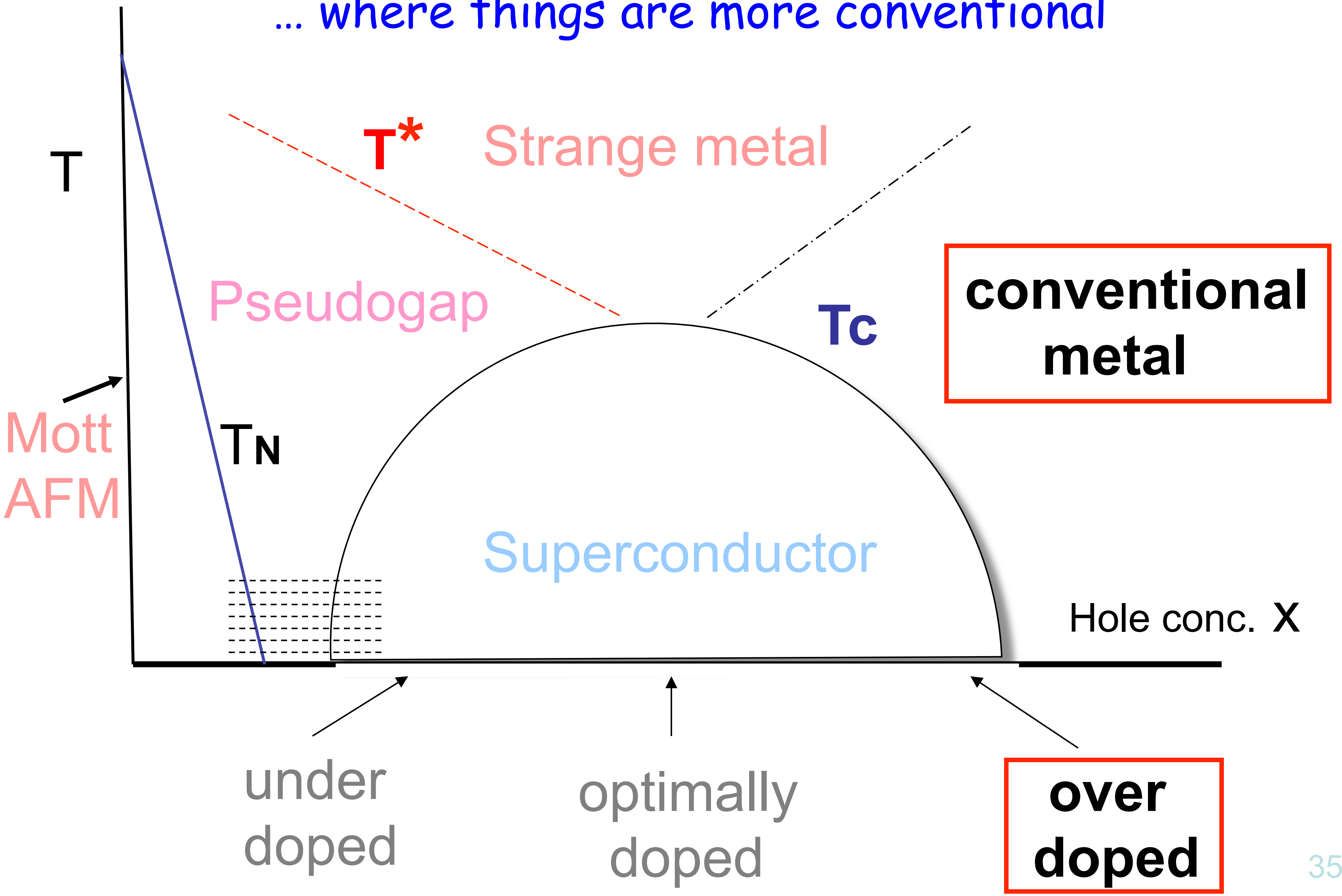
- Standard theory of metals, insulators & superconductors
- High Tc cuprate materials
- Parent insulators: Mott AFM
- Problem of doped Mott insulator
- ARPES & quantum oscillations
  - -- Fermi liquid state at overdoping
  - -- Strange metal at optimal doping
  - -- d-wave superconductor

Phenomenology of High Tc Cuprates II

- underdoped materials
  - -- pseudogap
  - -- SC fluctuations
  - -- competing order parameters
  - -- high field experiments

Conducting Phases of Doped Mott Insulators

Start far from the Mott insulator
… where things are more conventional

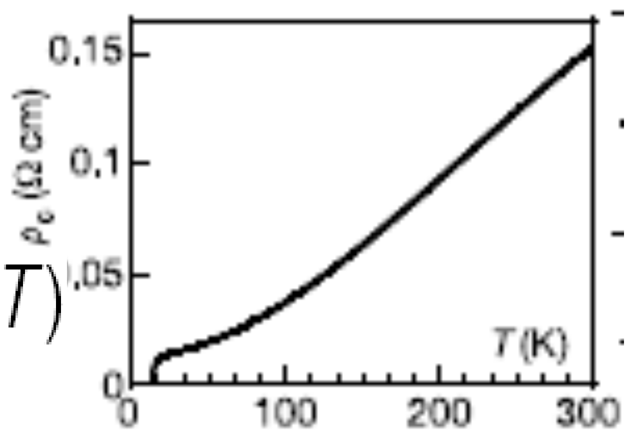


Overdoped Cuprates look like Fermi liquids

OD Tl 2201 (Tc = 20 K)
Resistivity "looks like"
Fermi liquid ρ ~ T^2

$$\rho \sim T^{\alpha} \qquad \alpha > 1$$

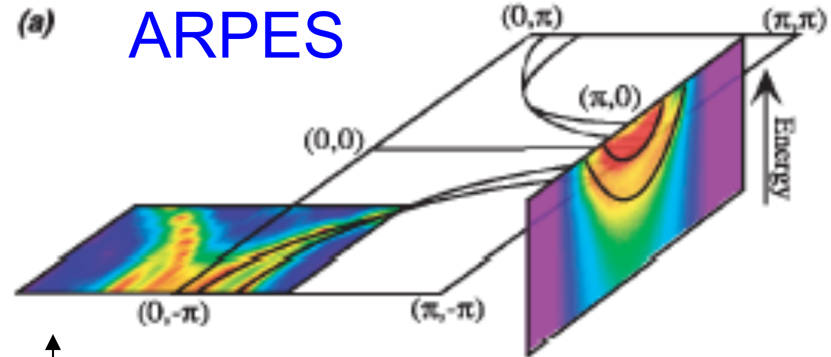
$\rho_{\perp}(T)$



$$\rho_{\perp}/\rho_{ab} \approx 1{,}000$$

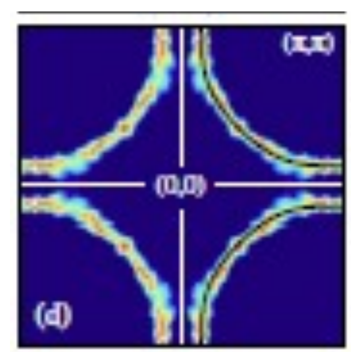
N. Hussey et al, Nature (2003)

ARPES



OD Bi2212:
A. Kaminski et al, PRL (2003)

$$A(\mathbf{k}_F, \omega = 0)$$



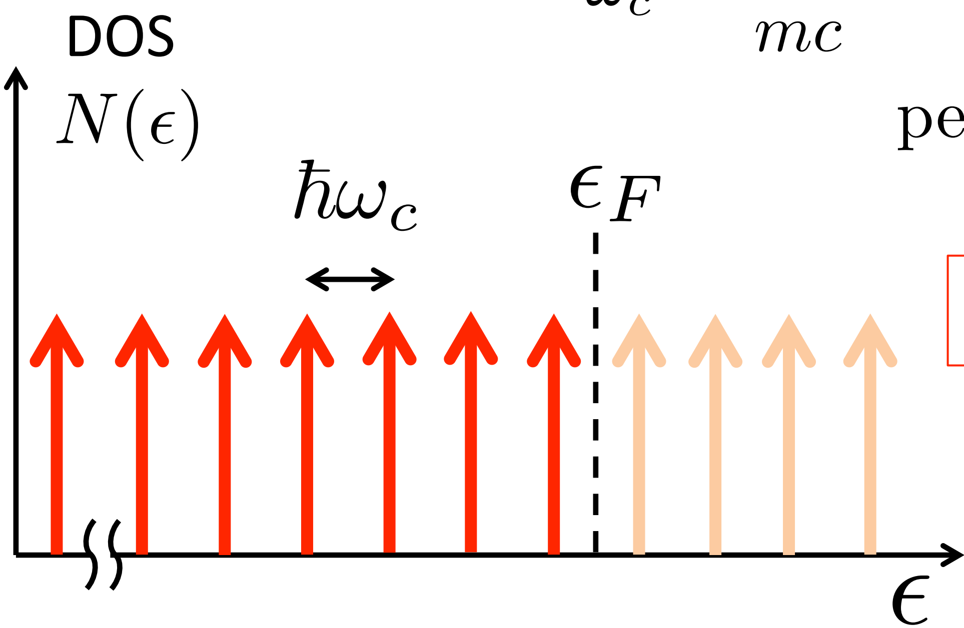
OD Tl2201:
Damascelli group, PRL (2005)

Quantum Oscillations → Large FS with (1+x) holes in Tl2201

Quantum Oscillations: the simplest example

Exactly solved problem
of free electrons in 2-dim
→ Landau levels

$$\omega_c = \frac{eH}{mc}$$



Oscillations in the DOS
→ Oscillations in "all observables"

peak in $N(\epsilon_F)$ when

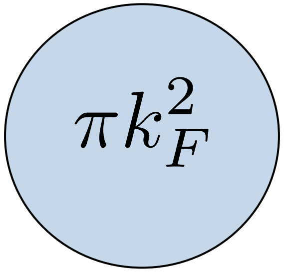
$$\epsilon_F = (n + 1/2)\,\hbar\omega_c$$

$$\frac{1}{H_n} = \left(n + \frac{1}{2}\right)\frac{\hbar e}{mc}\frac{1}{\epsilon_F}$$

$$\text{period in } \frac{1}{H} = 2\pi\left(\frac{e}{\hbar c}\right)\frac{1}{\pi k_F^2}$$

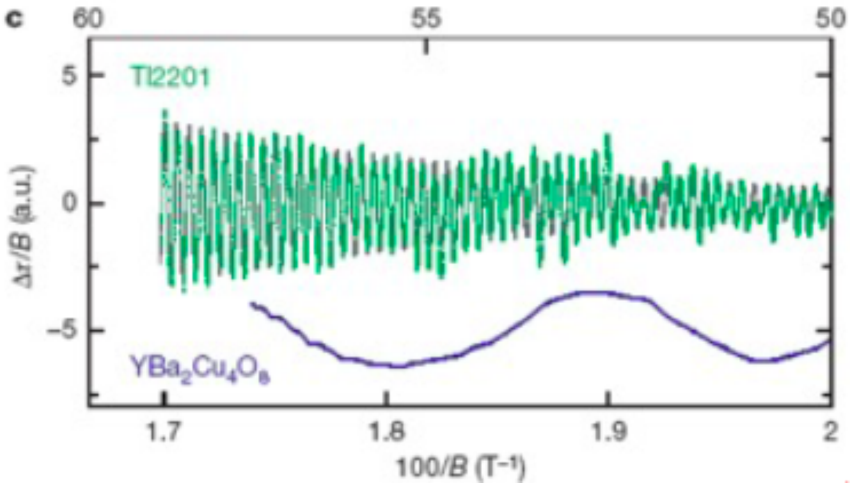
Frequency ←→ FS area

$$\boxed{f = \frac{\hbar c}{2\pi e} A_{\mathbf{k}}}$$

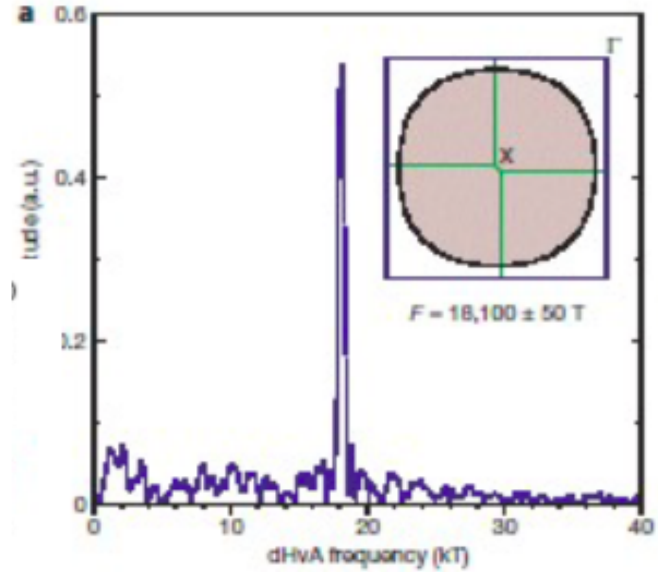


General Fermi-liquid result
for 3D, arbitrary dispersion
[Onsager, Lifshitz-Kosevich]

Quantum Oscillations in Overdoped (OD) Tl2201



Vignolle,..., Hussey, Nature (2008)

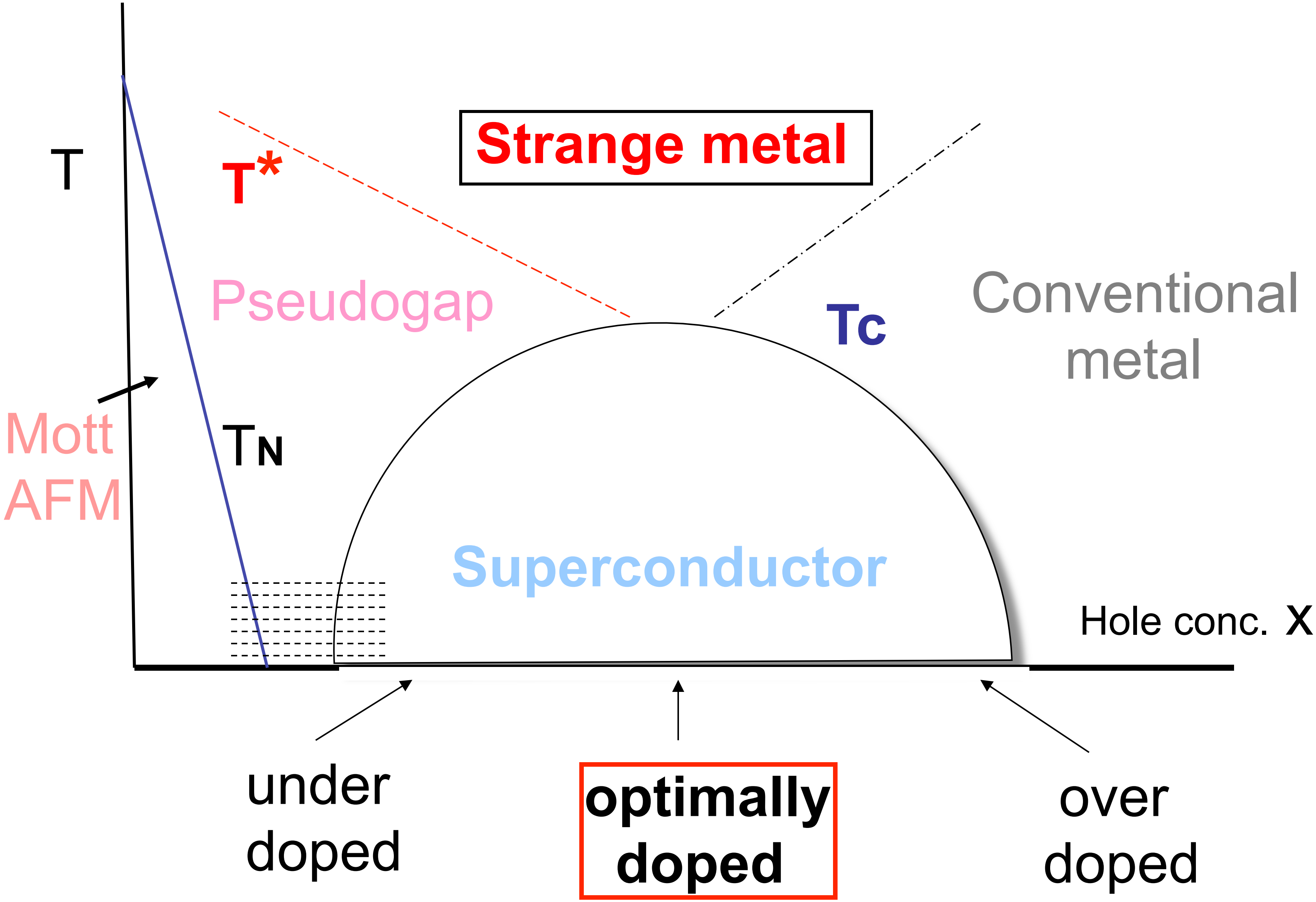


* Tc = 10K, B < 60T; dHvA in M; SdH in c-axis ρ

* T and B-dependences fit Lifshitz-Kosevich theory
Freq. = 18,100 T → large (Luttinger) FS with (1+x) holes
Sharp quasiparticles with m*/m ~ 4 (consistent with other probes)

For OD cuprates, no conflict between
(T > Tc, H=0) expts, like ARPES &
(low T, high H) expts, like quantum oscillations

... Unlike underdoped cuprates!



Corresponding to max Tc

Summary of experiments in Strange metal regime

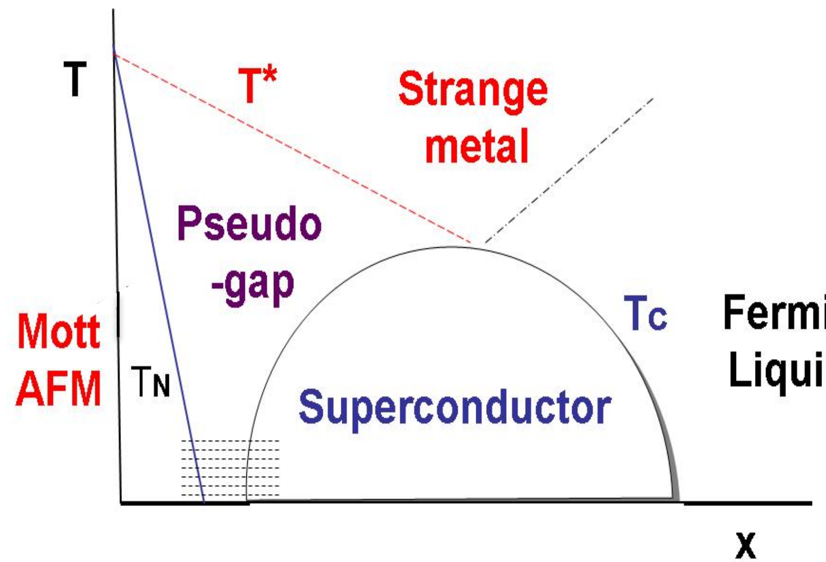
- electronic excitations show dispersion similar to band theory with m*/m ~ 3

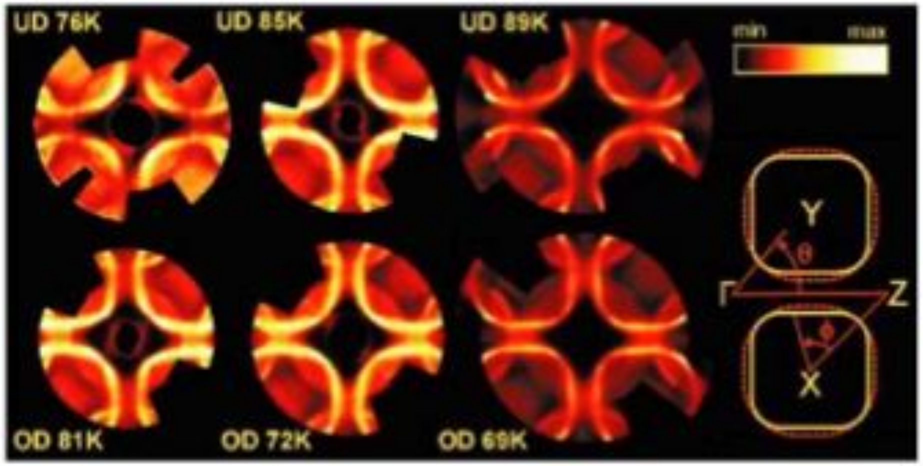
- large "Fermi surface" with (1+x) holes = Luttinger count

but

- anomalous spectral linewidths: quasiparticles ill-defined

- anomalous transport





$A(\mathbf{k}_F, \omega=0)$ A. Kordyuk et al PRB (2002)

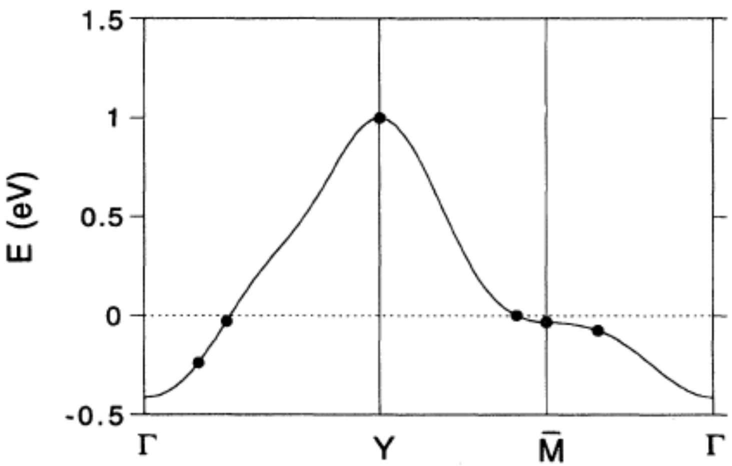
ARPES

* large "Fermi surface" consistent with (1+x) holes

* Dispersing "band"

$$\epsilon(\vec{k}) = \sum c_i \eta_i(\vec{k})$$

Norman, Randeria, Ding & Campuzano, PRB (1995)

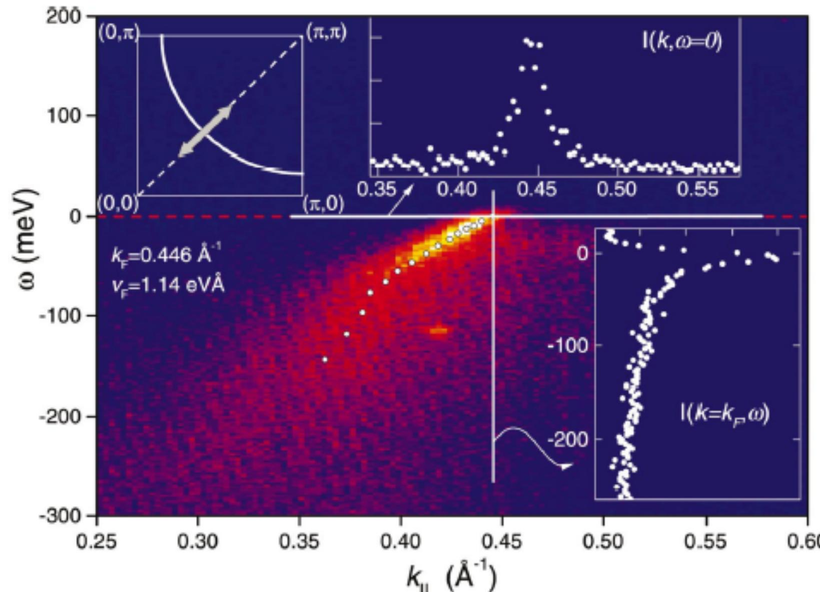


c_i	$\eta_i(\vec{k})$
0.1305	1
-0.5951	$\frac{1}{2}(\cos k_x + \cos k_y)$
0.1636	$\cos k_x \cos k_y$
-0.0519	$\frac{1}{2}(\cos 2k_x + \cos 2k_y)$
-0.1117	$\frac{1}{2}(\cos 2k_x \cos k_y + \cos k_x \cos 2k_y)$
0.0510	$\cos 2k_x \cos 2k_y$

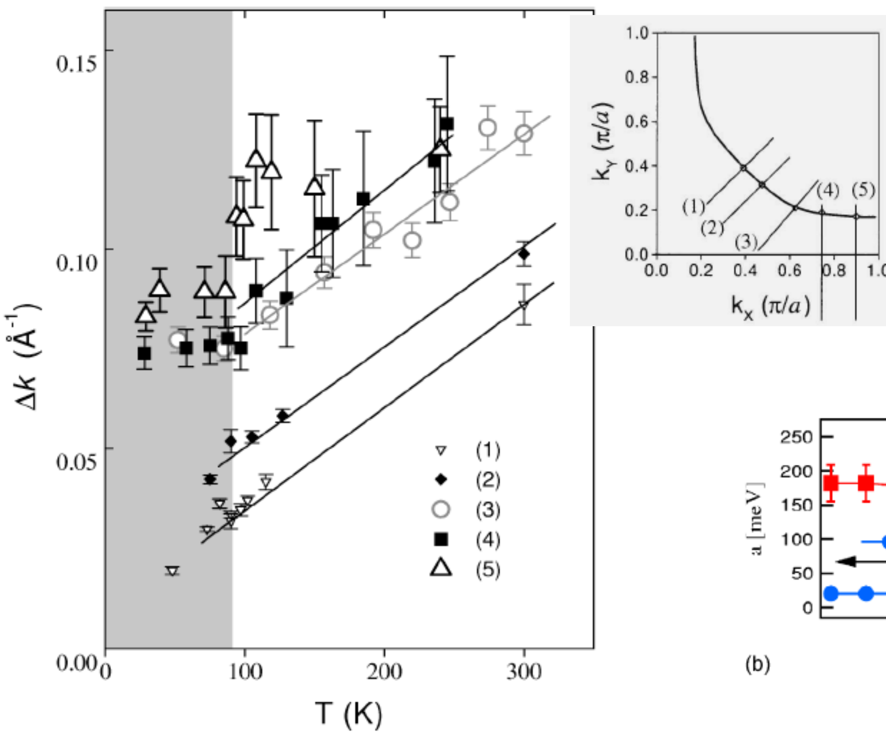
Absence of Quasiparticles in Strange Metal (T > Tc)

Arpes lineshape

$$\boxed{\begin{array}{lll} \mathrm{Im}\Sigma \sim a + b\omega & \text{fixed}\,T \\ \qquad\;\; a' + b'T & \omega = 0 \end{array}}$$

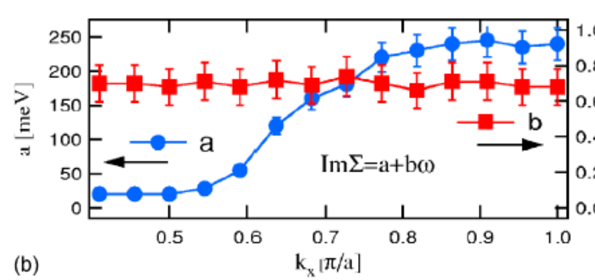


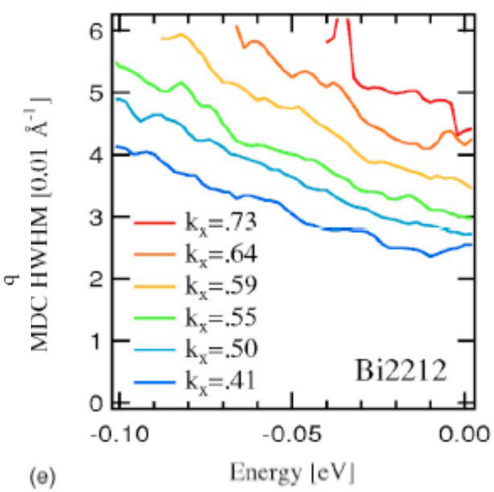
Valla et al, Science (2000)



Valla et al, (2000)

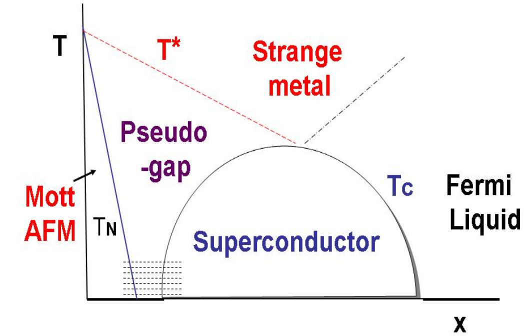
MDC linewidths





Kaminski et al, (2005)

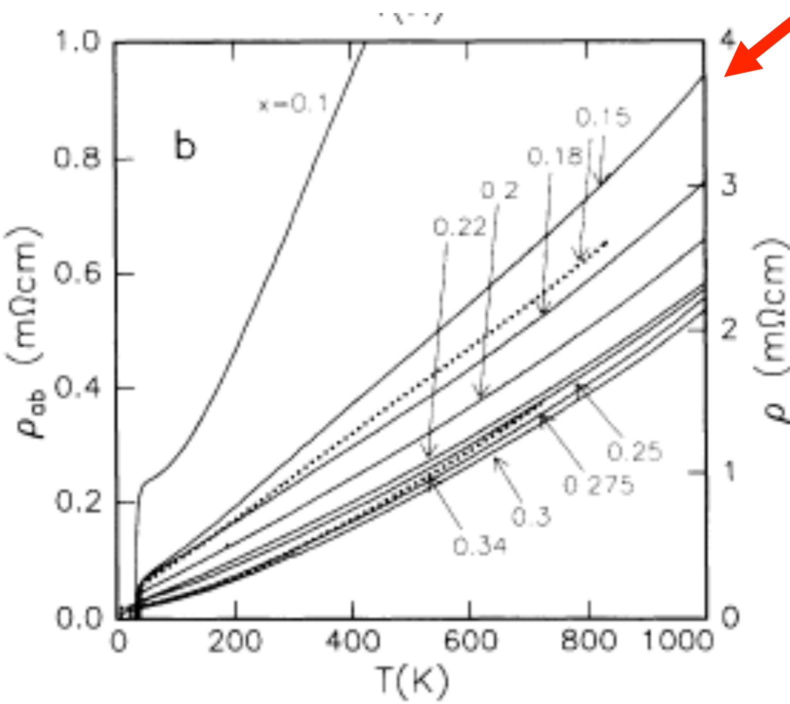
The "strange metal" regime

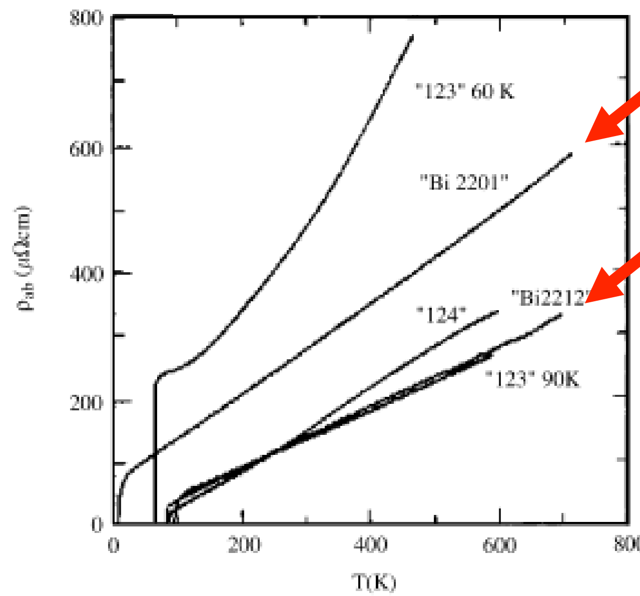


Linear-T resistivity
in ab-plane

$$\boxed{\rho \sim T}$$

Why?





LSCO: Takagi et al, PRL (1992)

* Not el-phonon
- linear down to 10 K
- no "saturation" (Ioffe-Regel-Mott)

Slope of resistivity/layer roughly the same (1.5 μΩ cm/K) for all materials.
Sheet resistance = ρ/d ~ (h/e^2) T/J

"Marginal Fermi Liquid" Phenomenology for Strange Metal

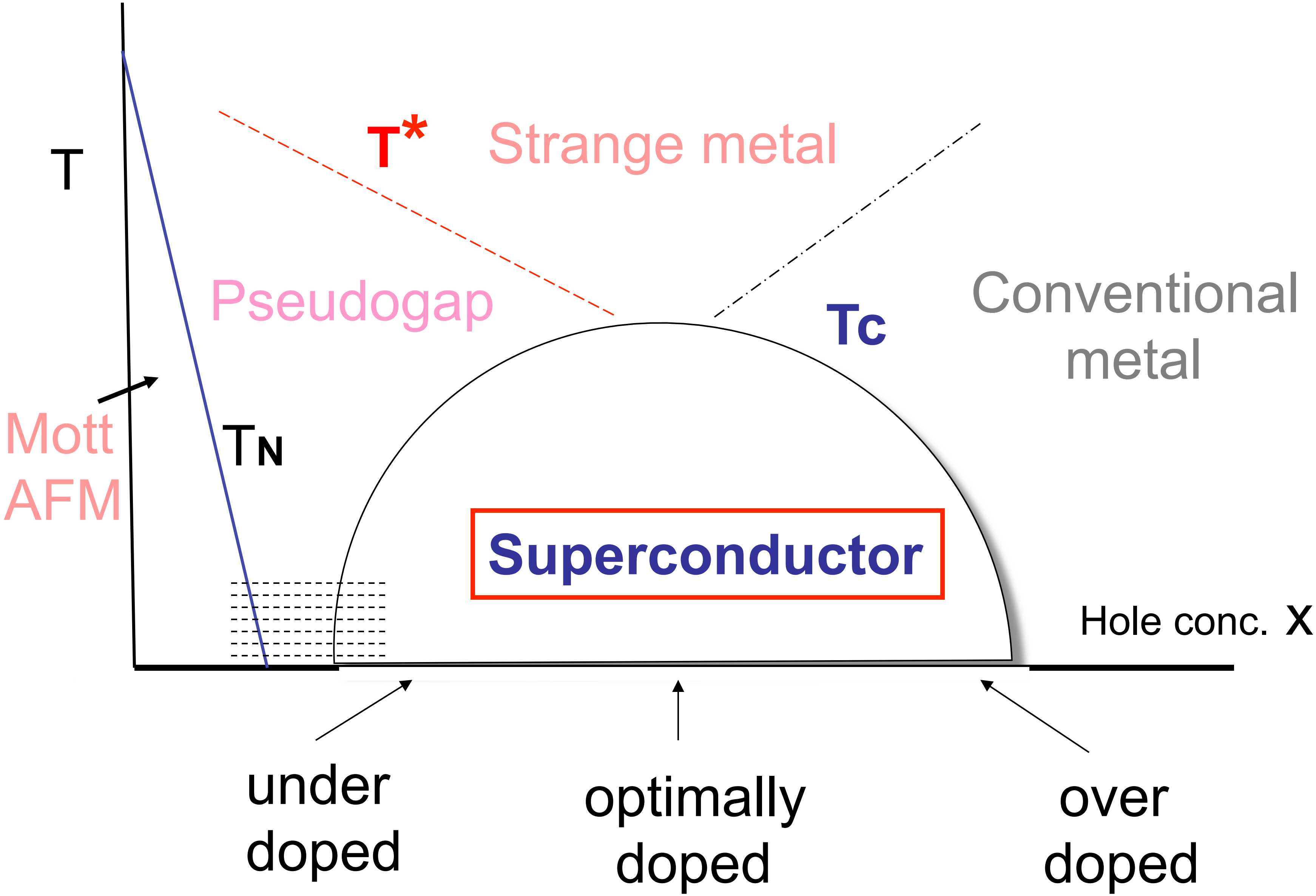
C. M. Varma et al, PRL (1989)

- No energy scale (E_f, Θ_D)
- Only energy scale is T
- Both single-particle and transport scattering rates $1/\tau \simeq \max(\omega, T)$

$$\left.\begin{array}{l}\Sigma'' \sim \omega \quad \Rightarrow \Sigma' \sim \omega \log \omega \\ \Rightarrow Z \sim 1/|\log \omega| \to 0\end{array}\right\}$$

Quasiparticles
Not well-defined

Open qs:
Microscopic origin?
Quantum Critical Point under the SC dome ?


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

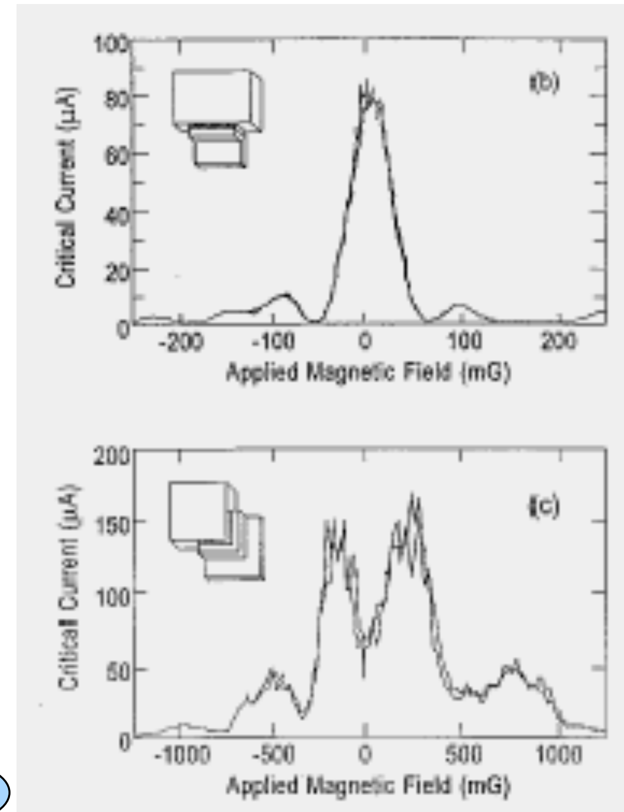
SC Order Parameter:

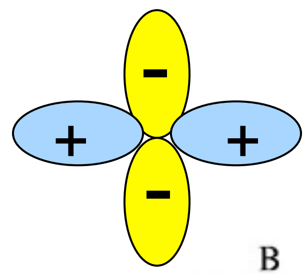
- **pairing:**
  (hc/**2**e) flux quantization
  2$eV/\hbar$ a.c. Josephson

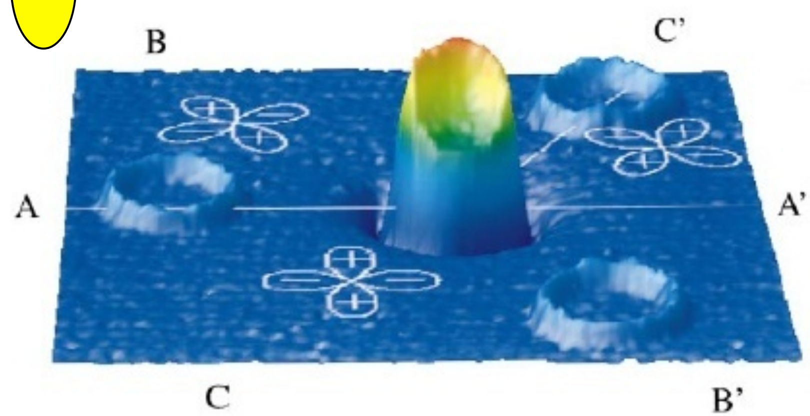
- S = 0 singlet pairing
  NMR $\chi(T \rightarrow 0) = 0$

- d-wave (B_{1g})
  changes sign under
  $\pi/2$ spatial rotation

phase sensitive experiments:
π -junctions



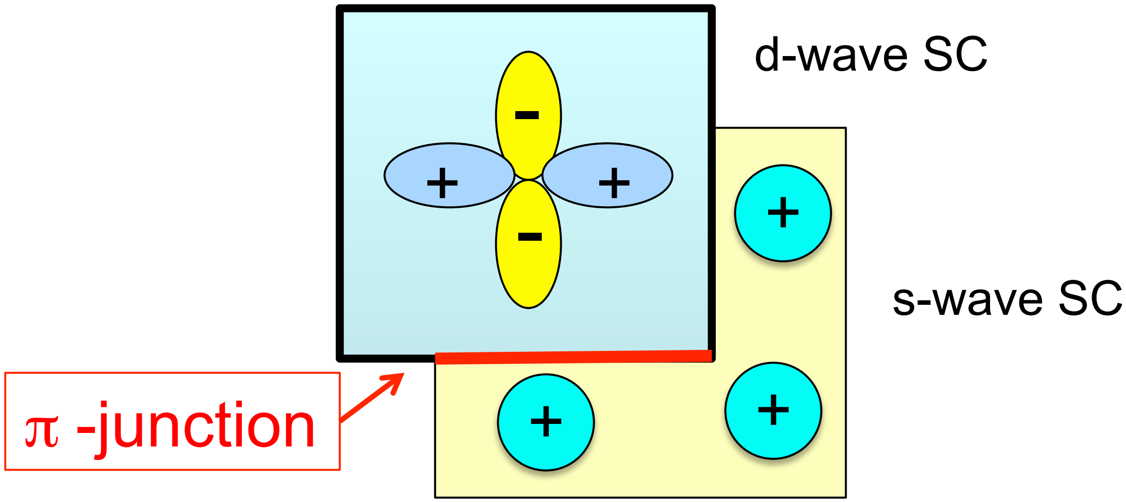


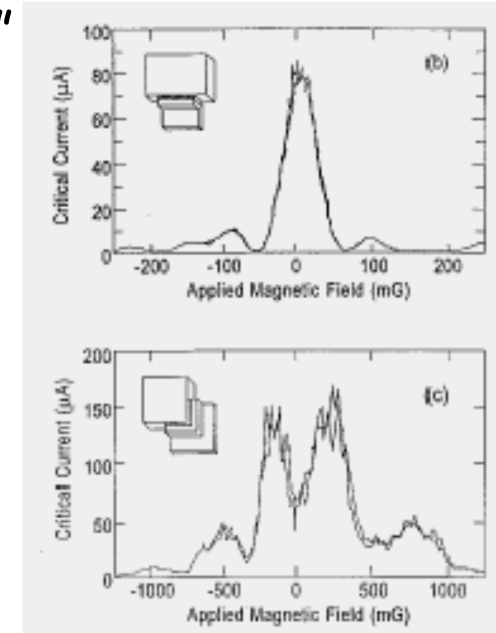


van Harlingen (1993,95); Tsuei & Kirtley (1994,95)

$d_{x^2-y^2}$ Pairing in High Tc cuprates

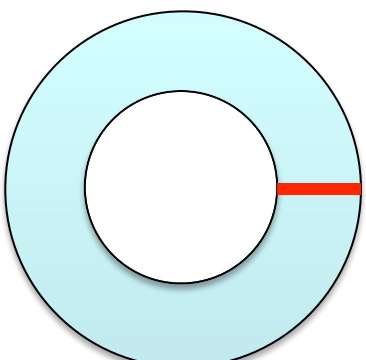
Initial skepticism – robustness against disorder – was wrong! Proof from "Josephson interference"





$$I = I_c \sin(\delta\theta + \pi)$$

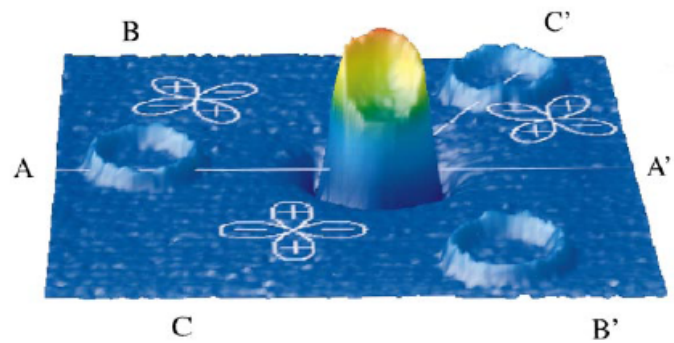
Van Harlingen, RMP **67**, 515 (1995)



d-wave SC

Frustration across π –junction
→half-flux quantum

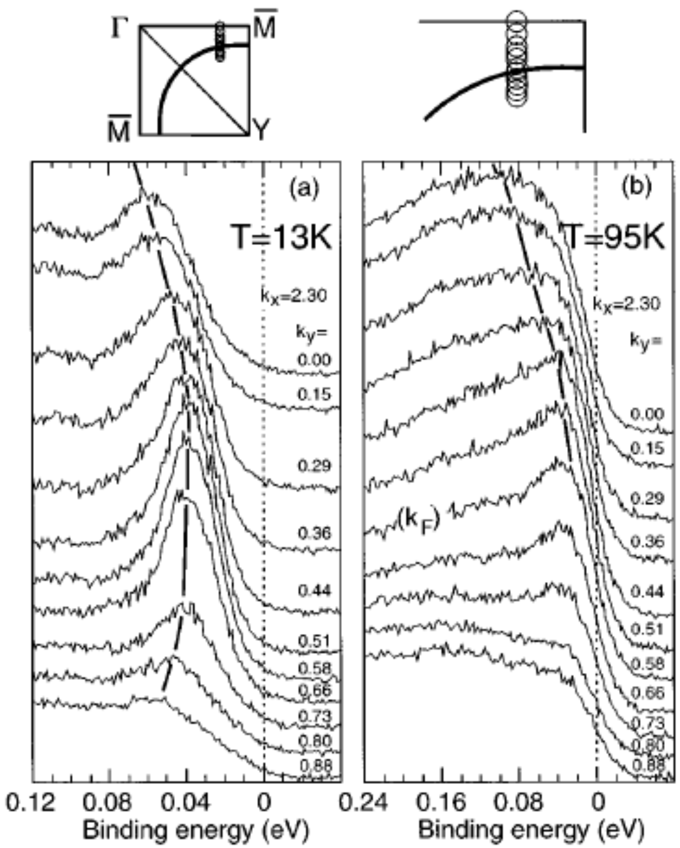
Sigrist & Rice,
RMP **67**, 503 (1995)

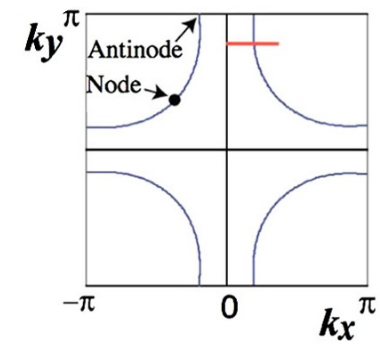


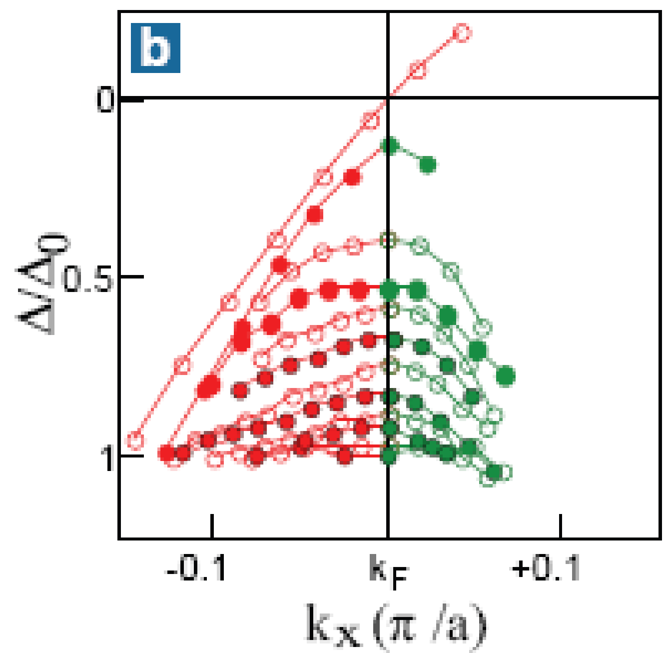
Tsuei & Kirtley, RMP 72, 969 (2000)

SC gap → Change in ARPES dispersion: "p-h mixing"

$$\epsilon_k \rightarrow \sqrt{\epsilon_k^2 + \Delta_k^2}$$







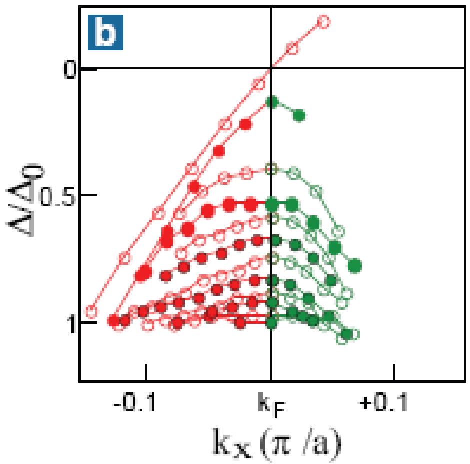
Campuzano et al, PRB (1996)

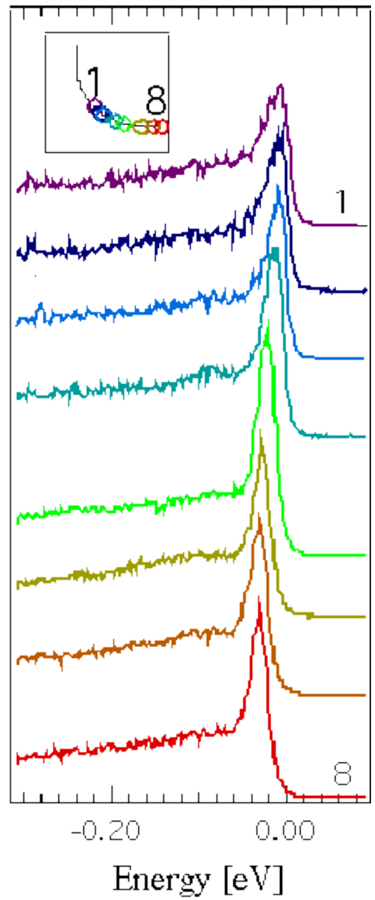
Kanigel et al, PRL (2008)

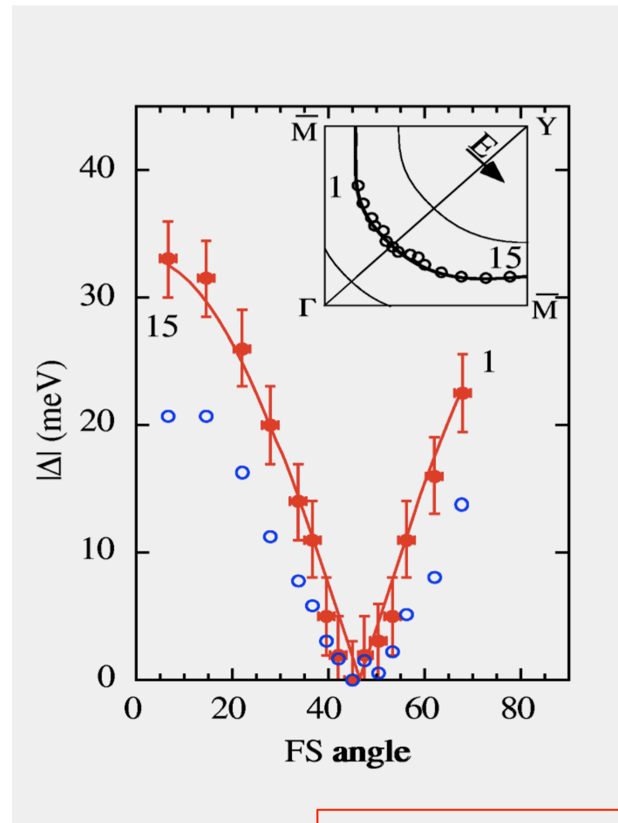
SC state gap anisotropy from ARPES

Node/antinode: Shen & Dessau (1993)

Ding et al., PRB (1996)



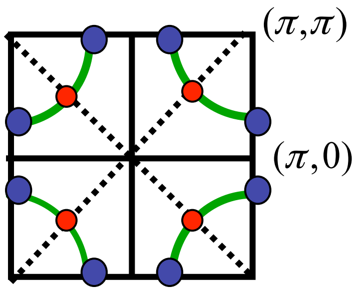




Optimal/Overdoped Samples:

$$\boxed{\Delta(\mathbf{k}) = \Delta_0 |(\cos k_x - \cos k_y)|/2}$$

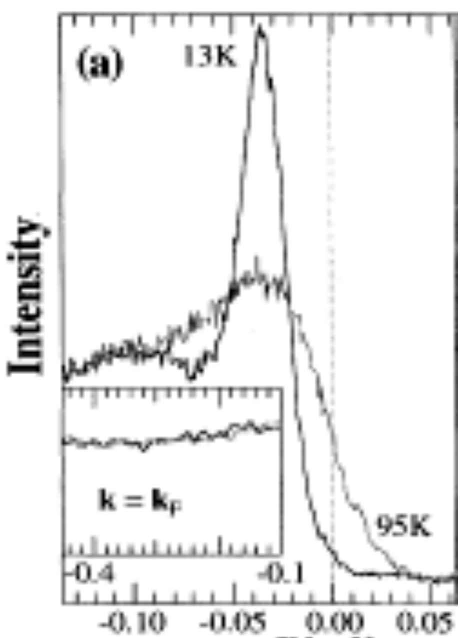
Warning! Can have strong deviations with underdoping!
→ see lecture#2



Sharp Quasiparticles:

- Absent above Tc
- Present for T << Tc

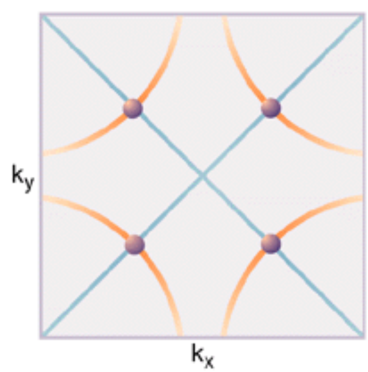
ARPES

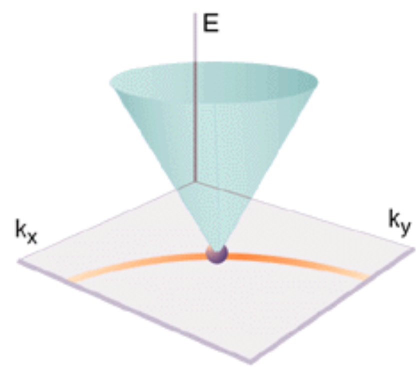


Randeria et al
PRL (1995)

Dirac cone for d-wave SC Bogoliubov QP excitations

$$E_{\mathbf{k}} \approx \sqrt{(v_F \delta k_\perp)^2 + (v_\Delta \delta k_\parallel)^2}$$





→low-energy DOS

$$N(\omega) \approx \frac{|\omega|}{\pi v_F v_\Delta}$$

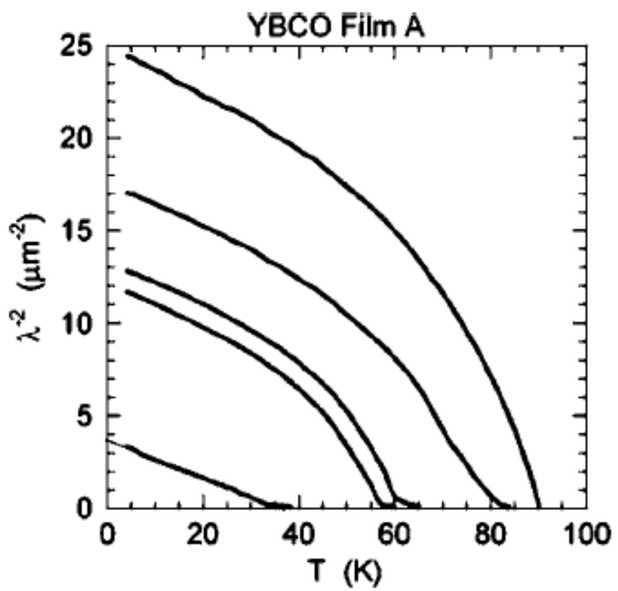
Nodal QPs & SC state properties

Linear T sf density

Bonn & Hardy (UBC)

$$\lambda_\perp^{-2} = \frac{4\pi n_s^{3d} e^2}{m^* c^2}$$

$$\boxed{\frac{n_s(T)}{m} = \frac{n_s(0)}{m} - \frac{2\ln 2}{\pi}\alpha^2\left(\frac{v_F}{v_\Delta}\right)T.}$$



Lemberger group, Physica C 341,561 (2000)

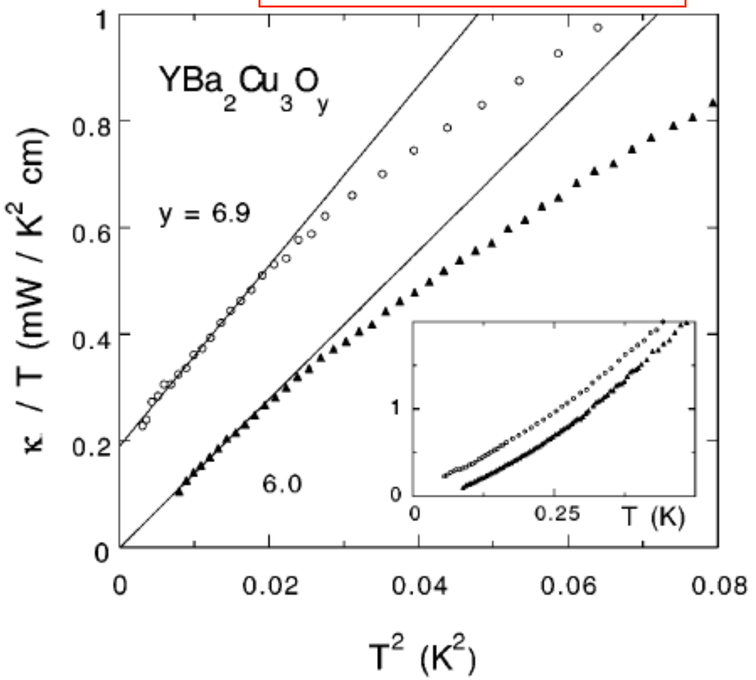
Universal transport

(independent of impurities)

thermal conductivity

Durst and Lee PRB (2000)

$$\boxed{\frac{\kappa}{T} = \frac{k_B^2}{3\hbar}\left(\frac{v_F}{v_\Delta} + \frac{v_\Delta}{v_F}\right)}$$



Taillefer group, PRL 79, 483 (97)

What is the doping dependence of Superconducting state parameters as measured by ARPES?

- Gap anisotropy $\Delta(\mathbf{k})$
- Antinodal gap $\Delta_{\max}$
- Nodal QP dispersion v_F & v_Δ

Nontrivial answers as function of underdoping,

Will discuss together with pseudogap physics in Lecture #2

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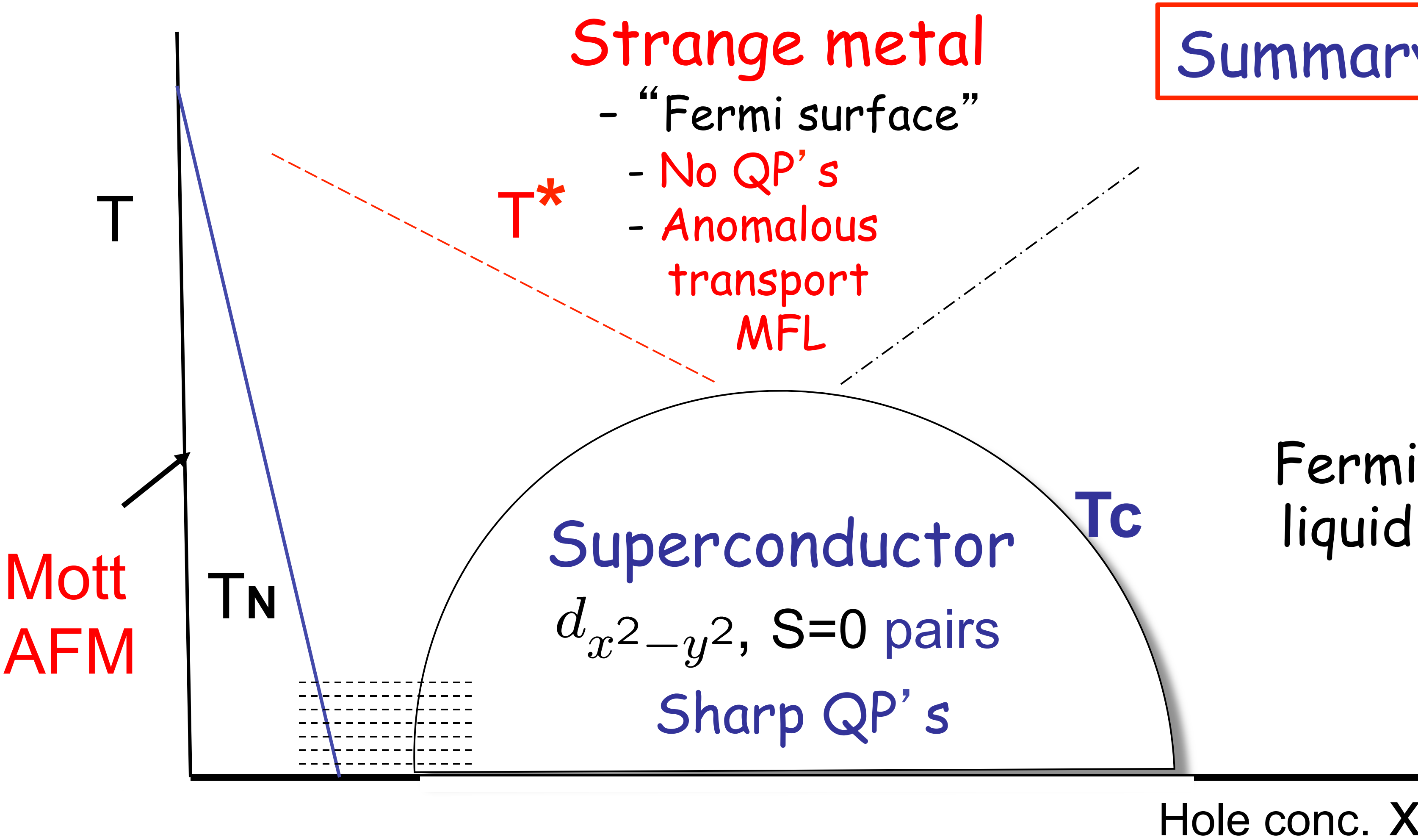
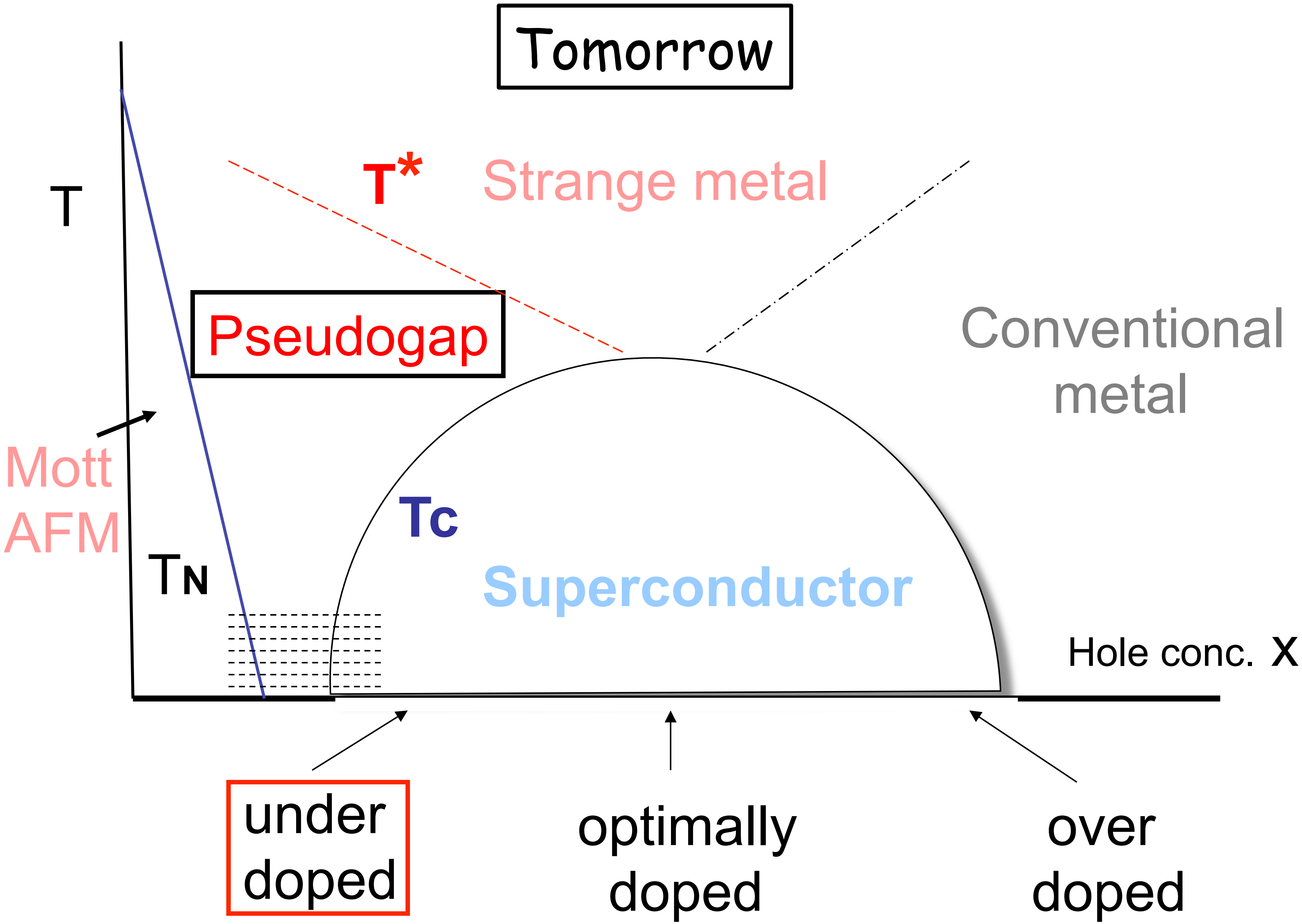
Summary


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



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

The end