Doped Mott insulators and high Tc superconductivity
Lecture 2

T. Senthil and M. Randeria

Plan

0. Unfinished business from Lecture 1
- Quasi-2d organic materials

1. Cuprate phenomenology

How many ways does Nature have to deal with doping a Mott insulator?

Electron doped.

AF with localized carriers.

$La_{2-x}Sr_xNiO_{4+\delta}$

Micro phase separation: stripes

$Sr_{1-x}La_xTiO_3$

3 Dimension. Brinkman-Rice Fermi liquid.

Organic ET salts.

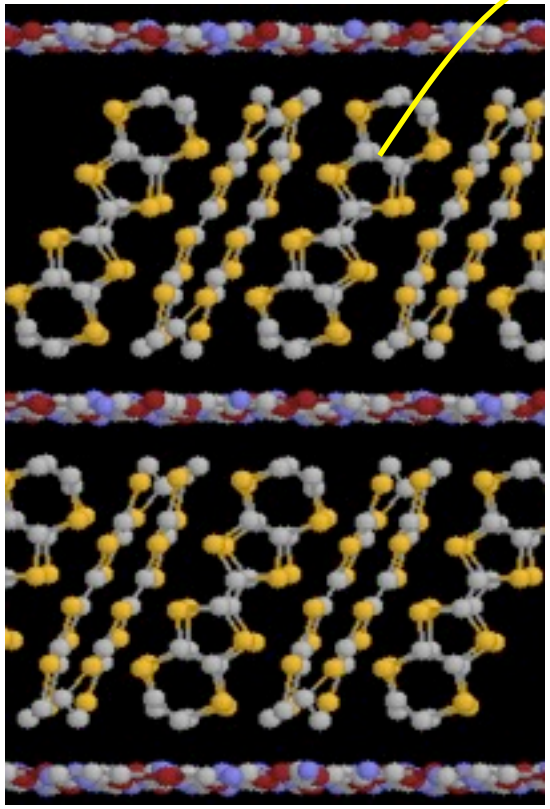
Metal-insulator transition by tuning U/t.

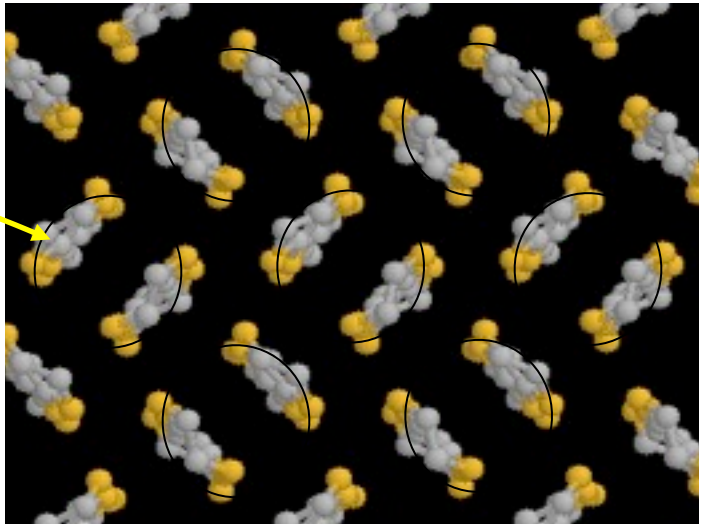
Possibility of a “spin liquid”.

Doping yields a superconductor.

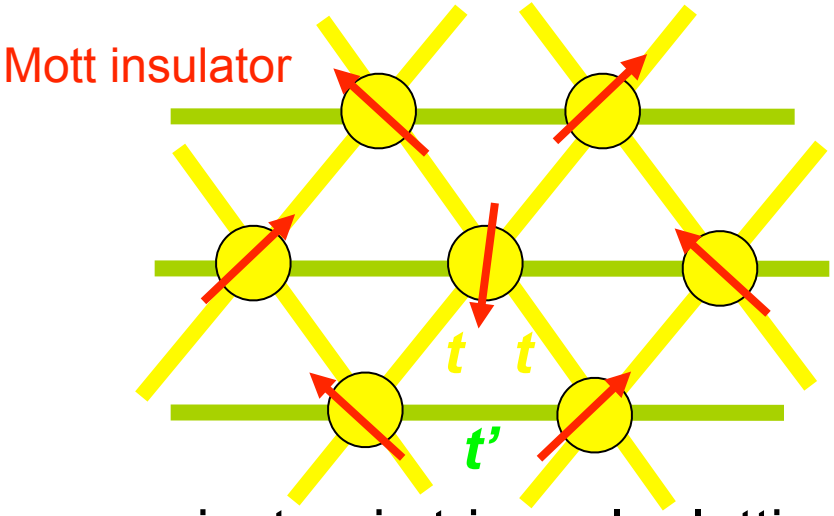
A second family of HiTc superconductors!

Q2D organics κ-$(ET)_2X$





dimer model

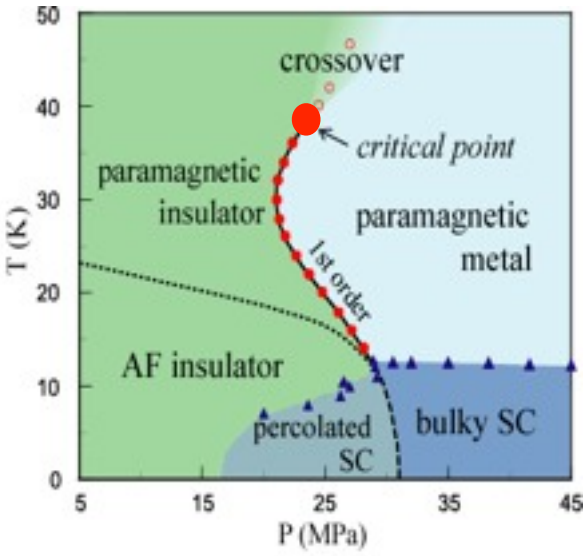


X = $Cu(NCS)_2$, $Cu[N(CN)_2]Br$, $Cu_2(CN)_3$…..

anisotropic triangular lattice

$t' / t = 0.5 \sim 1.1$

Pressure tuned superconductivity in the organics

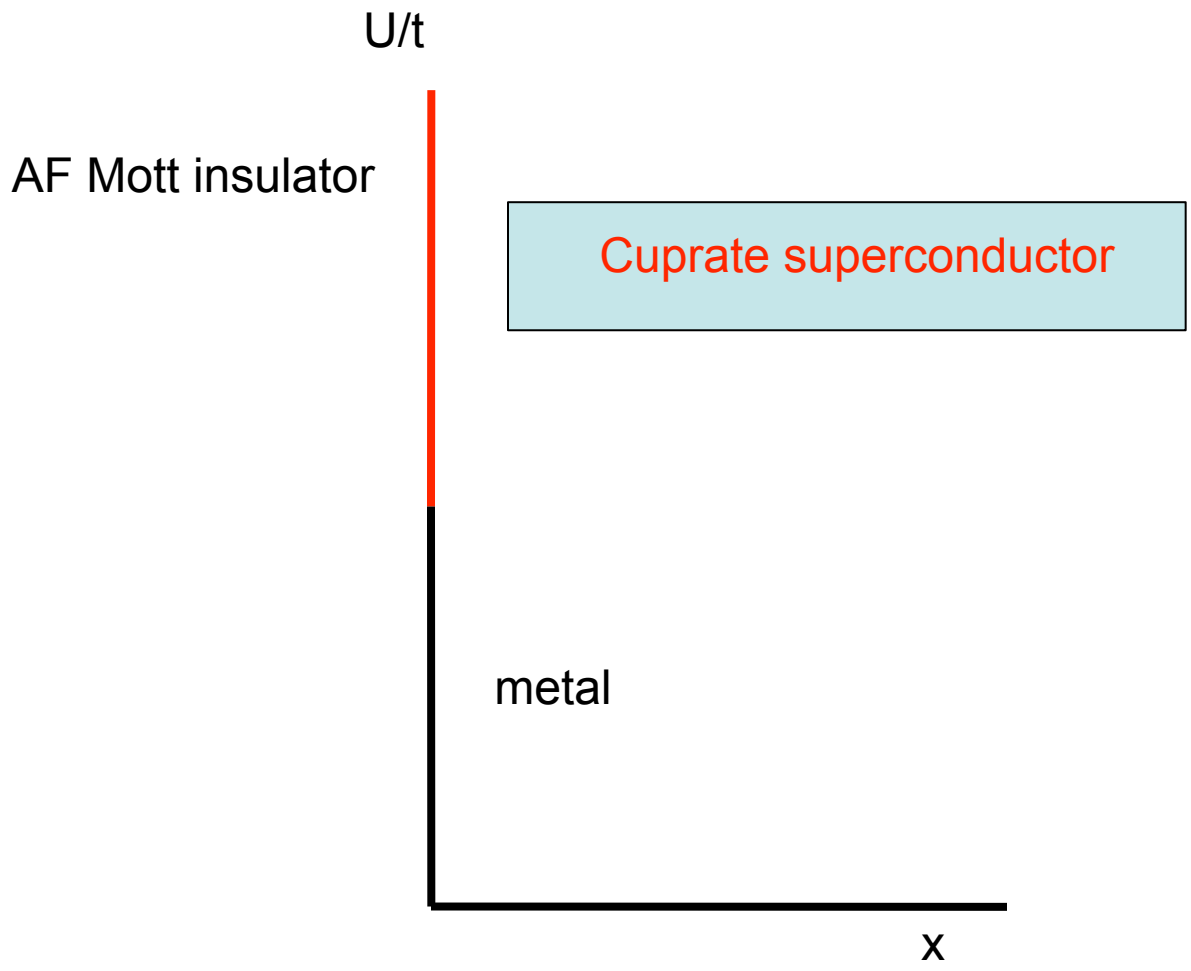


κ-Cu[N(CN)$_2$]Cl
t'/t = 0.75

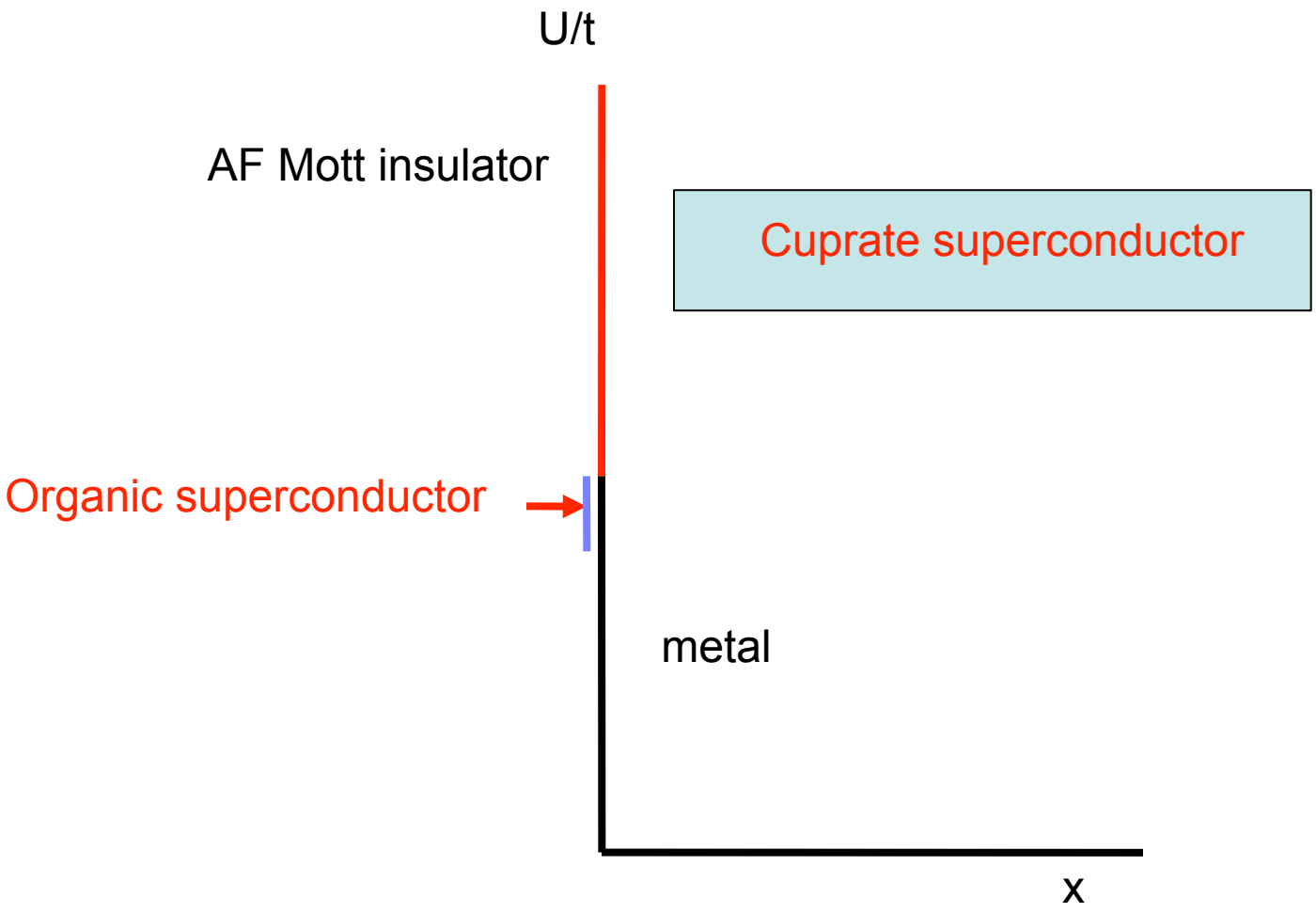
Pressure decreases U/t.

Mott transition is induced by tuning U/t at fixed density of one electron per site.

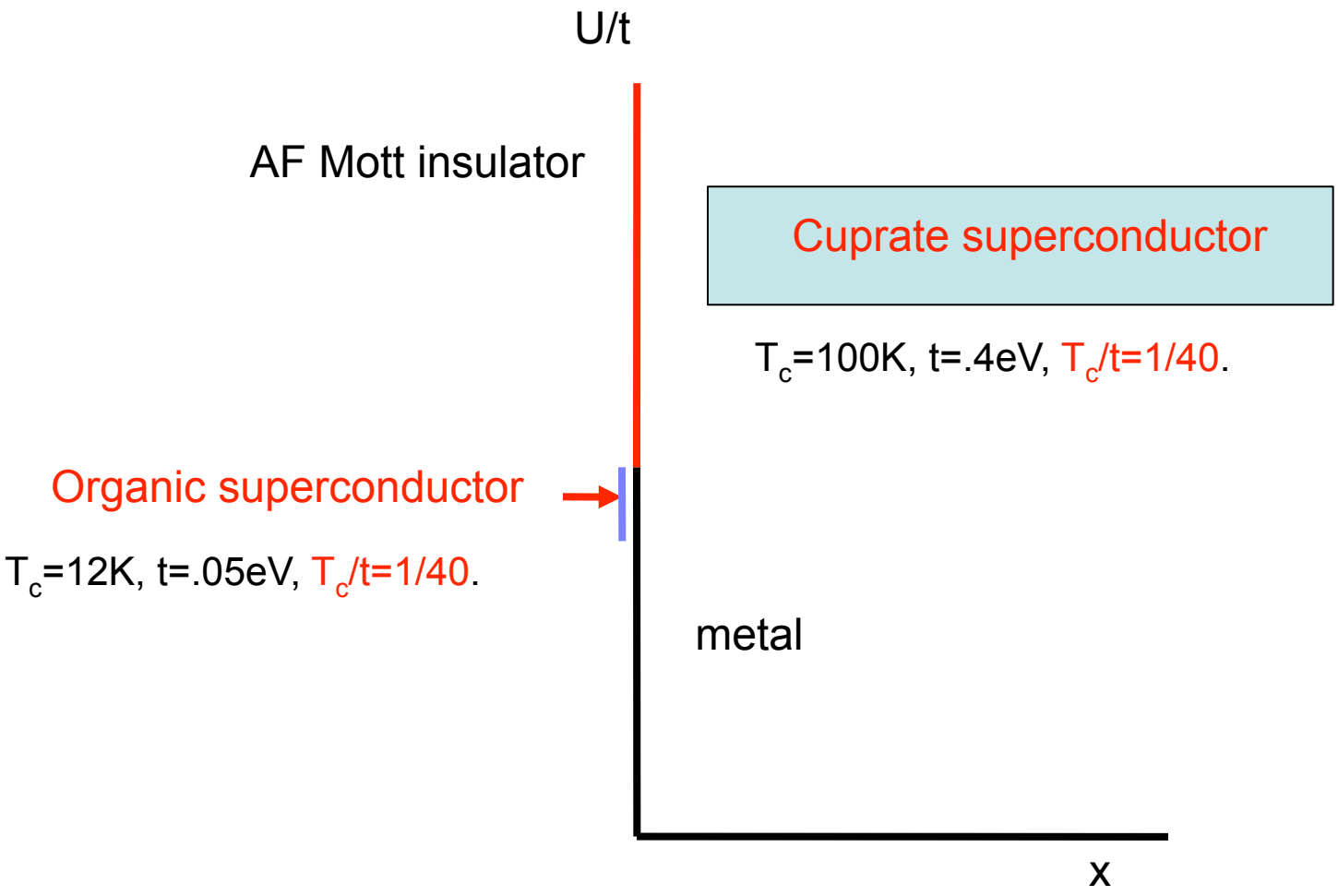
Metal- insulator transition by tuning U/t.



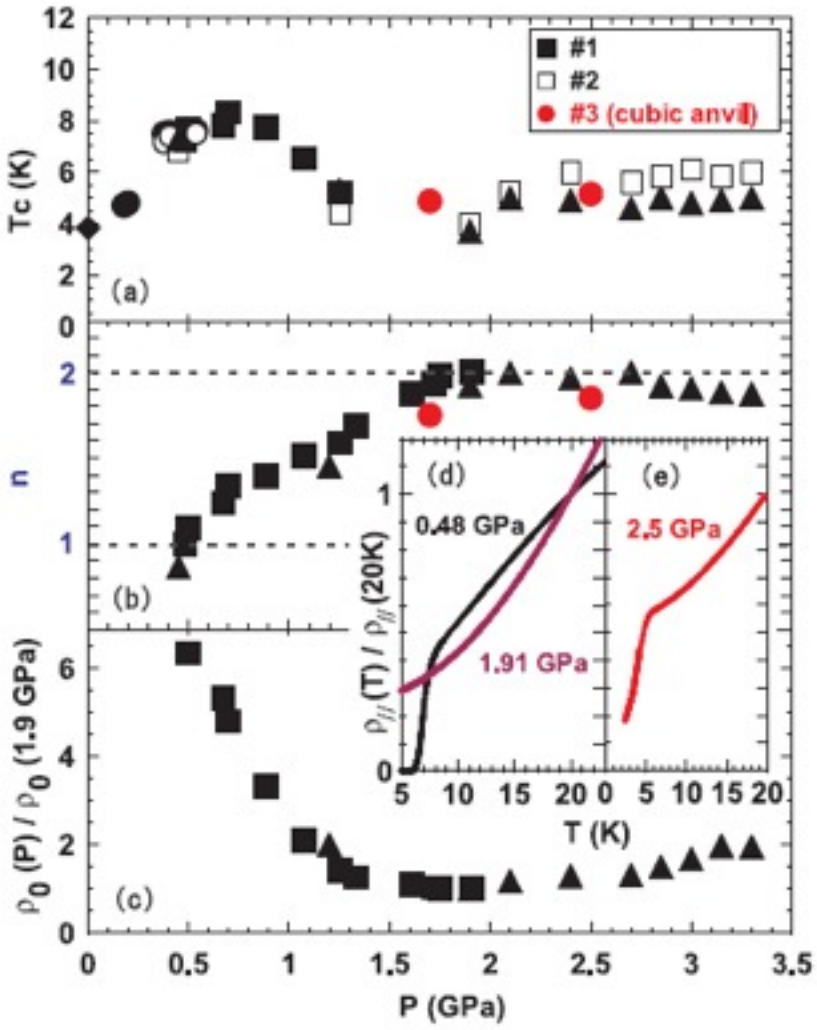
Metal- insulator transition by tuning U/t.

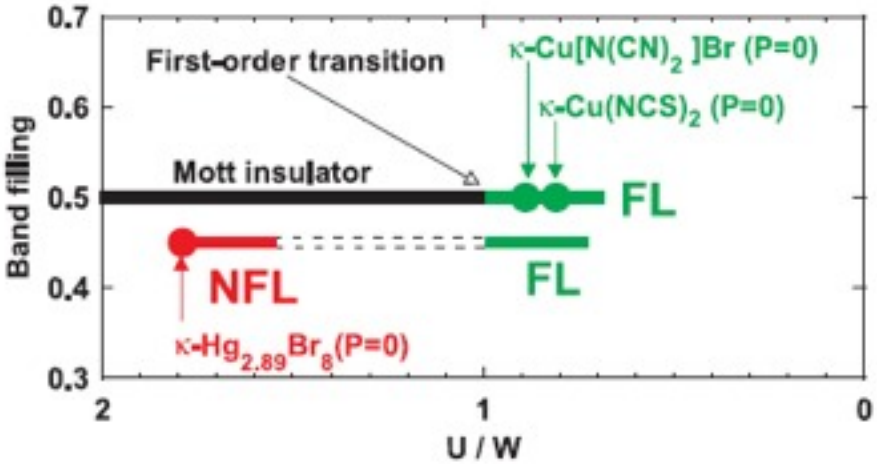


Metal- insulator transition by tuning U/t.



Doping of an organic Mott insulator.





κ-(BEDT-TTF)$_4$Hg$_{2.89}$Br$_8$

Superconductivity in doped ET, (ET)4Hg2.89Br8, was first discovered Lyubovskaya et al in 1987. Pressure data form Taniguchi et al, J. Phys soc Japan, 76, 113709 (2007).

Brief aside: Quantum spin liquids in the organics

Same family of organics also provide fascinating examples of quantum spin liquid Mott insulators.

Many interesting phenomena:

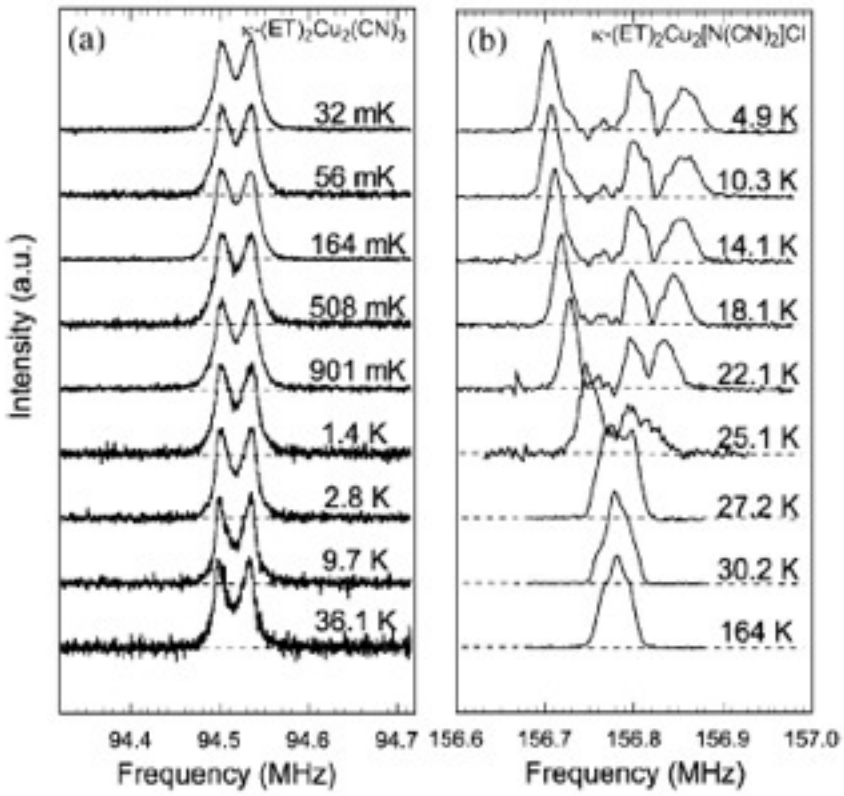
Insulator with specific heat, spin susceptibility like a metal.

Most dramatic: Metallic thermal transport in an insulator!

No magnetic order

(Expt : Kanoda , 2002 - present) κ-$(ET)_2Cu_2(CN_3)_2$

Weak Mott insulator close to Mott transition

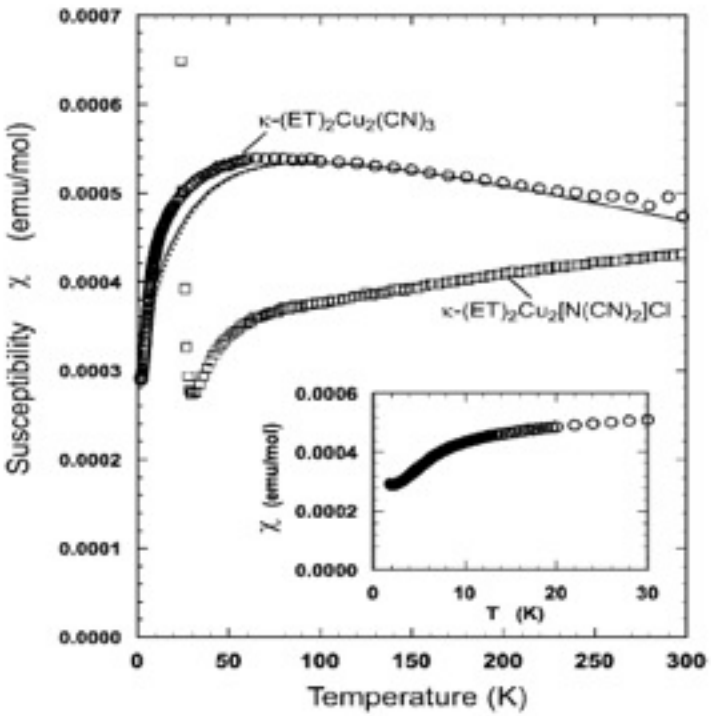


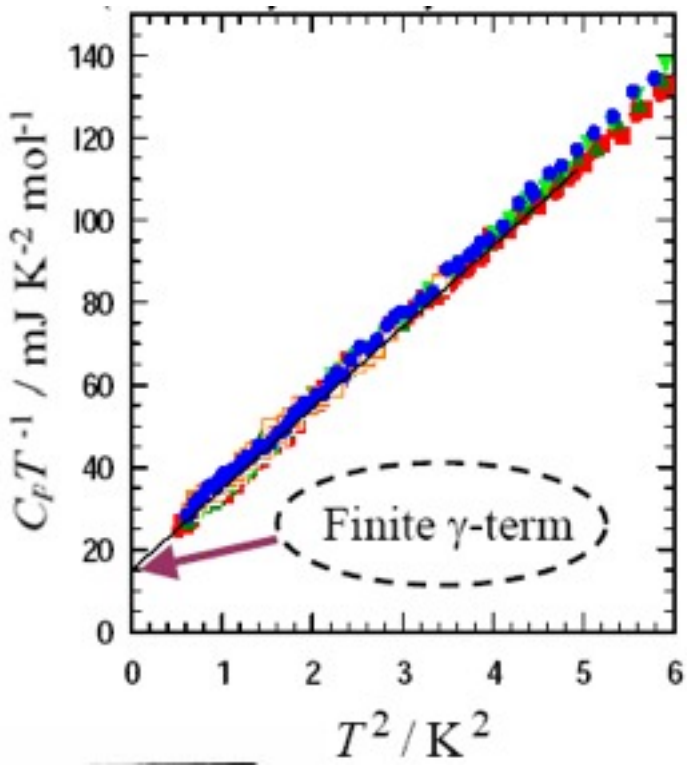
$\approx$ Isotropic Δ lattice

No ordering to 32 mK

$\ll J \approx 250$ K

A gapless spin liquid



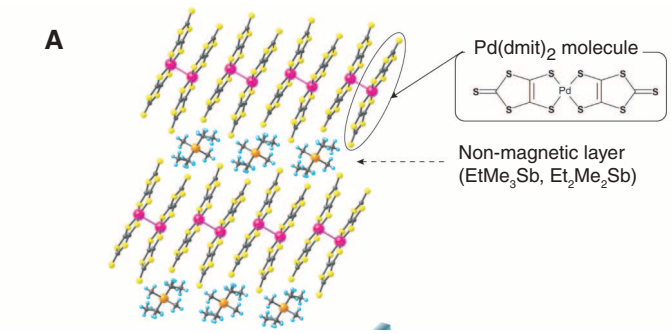


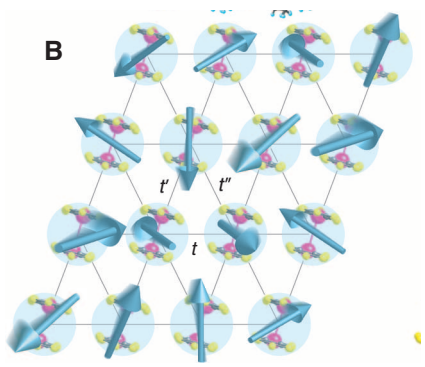
$\chi(T \to 0) \to$ const.
$C_T(T \to 0) \to$ const.

Wilson ratio $\frac{\chi T}{C}$ = const. $\sim O(1)$

Another candidate spin liquid on a triangular lattice

$EtMe_3Sb[Pd(dmit)_2]_2$



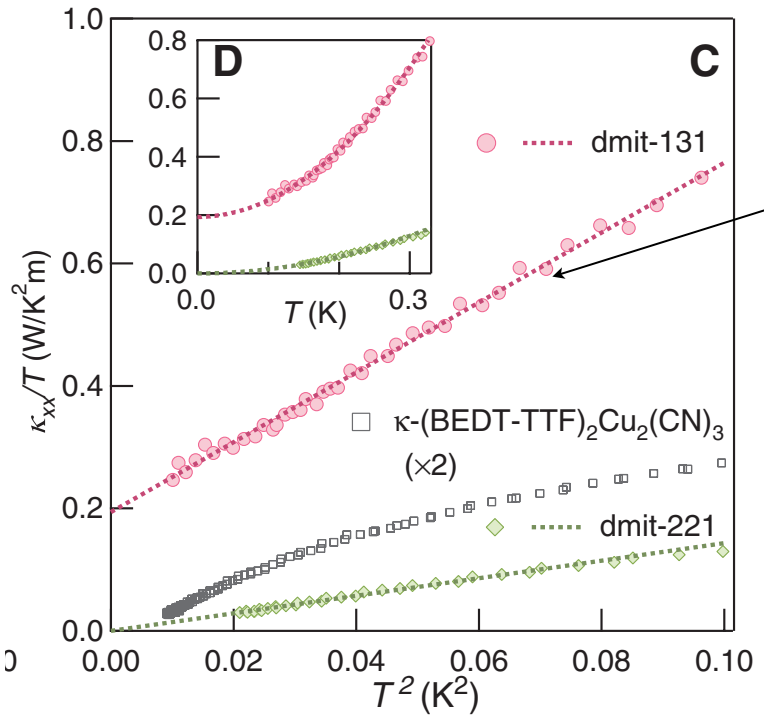


Phenomenology broadly similar to kappa-ET spin liquid.

Weak Mott insulator - close to pressure driven Mott transition.

No magnetic ordering to T << J
but gapless spin excitations (NMR, specific heat).

Metallic thermal transport in a Mott insulator



dmit quantum spin liquid

Gapless excitations are mobile in dmit spin liquid!

End of digression

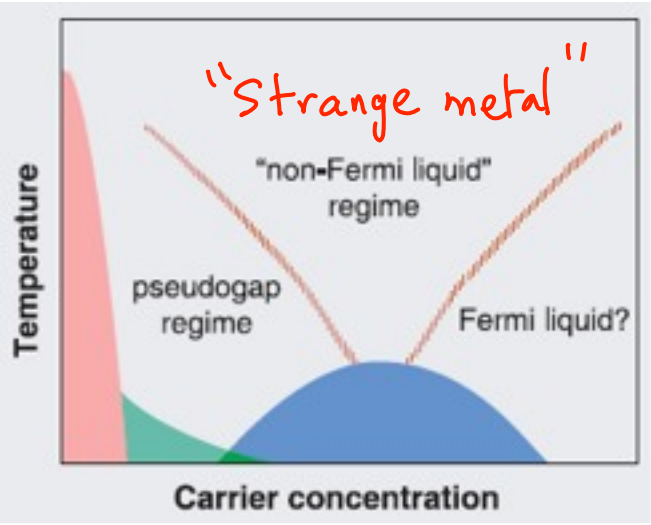
Quantum spin liquids near the Mott transition:

Growing number of experimental candidates - many dramatic phenomena.

A new chapter in condensed matter physics

Back to cuprates.....

High Tc Phase diagram

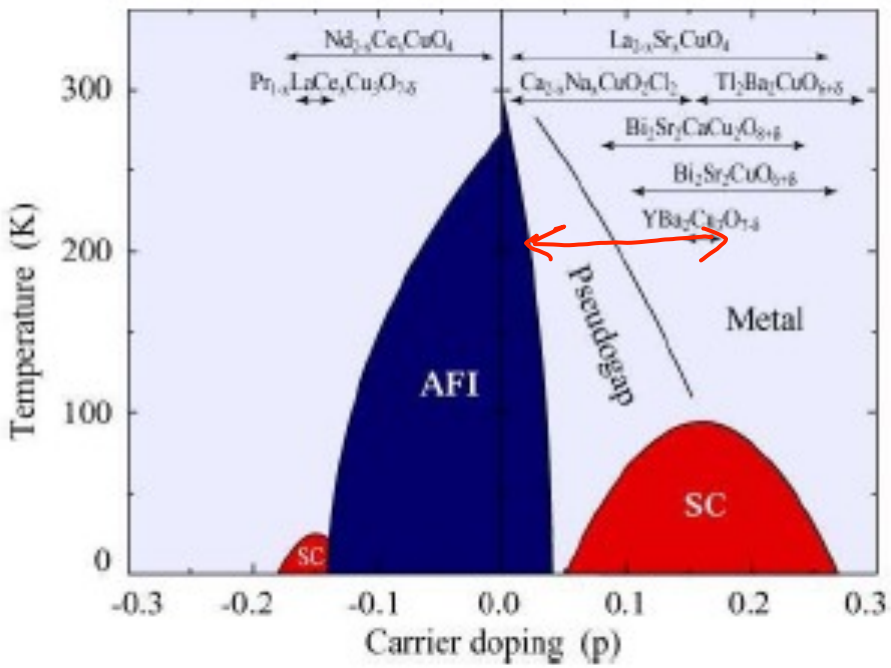


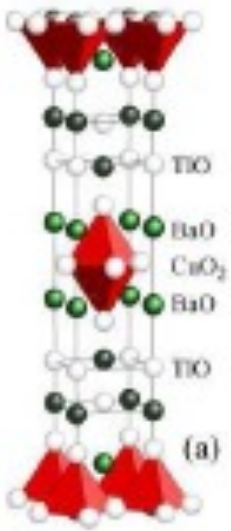
Plan

1.Overdoped – is it `conventional'?

2.What is strange about the strange metal?

3. Theory interlude





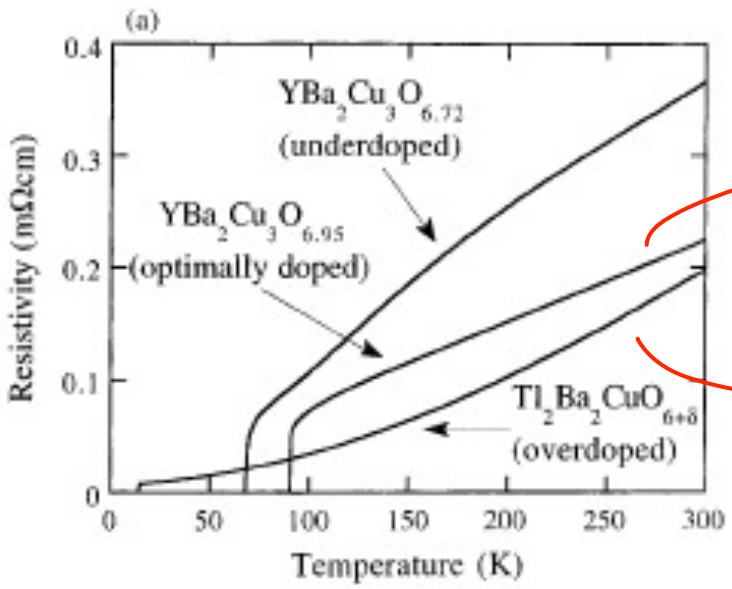
$Tl_2Ba_2CuO_{6+\delta}$

(Tl-2201)

Tl-2201: Clean single layer cuprate, no complications from CuO chains; go from optimal to extreme overdoped

Cons: Hard to grow, Tl toxic

A preliminary look: transport



$\rho(T) \propto T$ (optimal)

Overdoped looks more conventional.

Overdoped metal

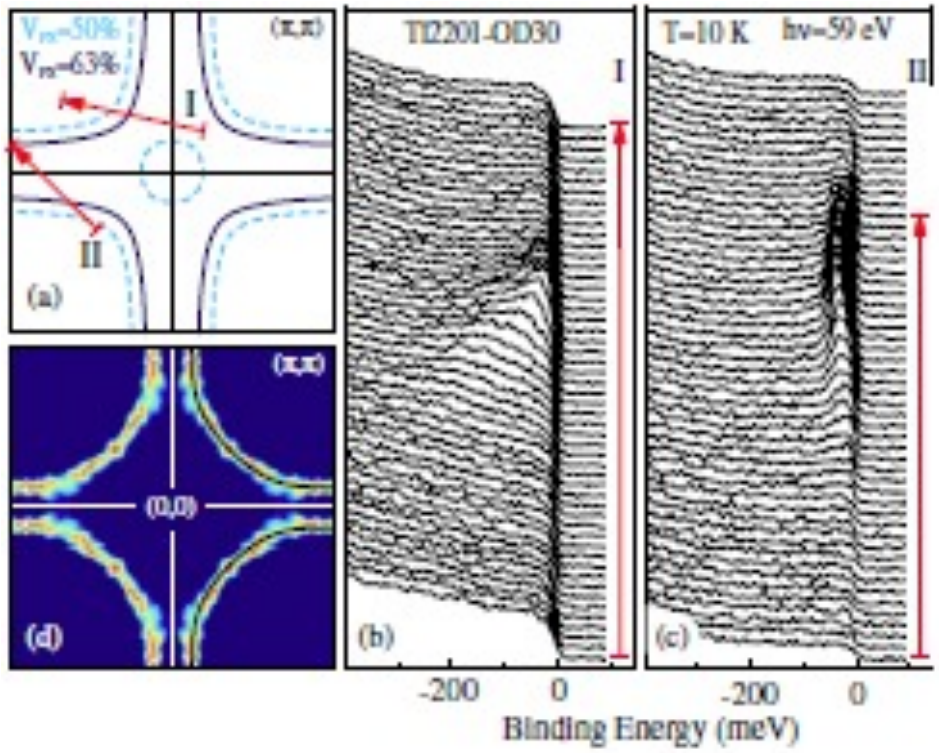
- Does it have a Fermi surface? Size and shape?

Methods to detect – ARPES, deHaas-van Alphen and related quantum oscillations, other….. eg Angle Dependant Magneto-Resistance (ADMR)

- Is it really a Fermi liquid with Landau quasiparticles?

Overdoped metal: Is there a Fermi surface?

ARPES : Yes !



Tl-2201

$T_c = 30$ K

Plate, ...,

Damascelli,

PRL 2005

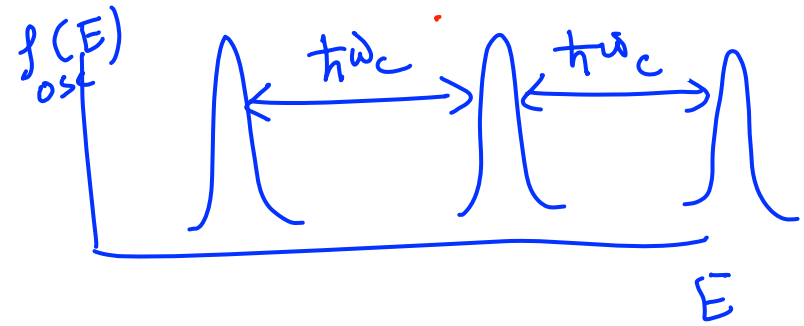
"Large" Fermi surface with area $\propto 1-x$

First measurement: "Angle dependant magnetoresistance"

(Hussey et. al., 2003)

deHaas van Alphen, other `quantum oscillations': classic Fermi surface determination methods

Oscillations of "everything" periodic in $1/B$ due to Landau level formation



Eg: $M_{osc} = B\, R_T R_D \sin\left(\frac{2\pi F}{B} + \gamma\right)$

Frequency $F = \frac{hc}{4\pi^2 e} A_k$ → "extremal" area of Fermi surface

"Lifshitz-Kosevich": $R_T = \frac{X}{\sinh X}$; $X = \frac{2\pi^2 k_B T}{\hbar\omega_c}$ $\left(\omega_c = \frac{eB}{m^* c}\right)$ (thermal supression)

"Dingle": $R_D = e^{-2\pi/\omega_c \tau_{imp}}$ (disorder supression)

Remarks on quantum oscillations

1. Need very clean materials $\omega_c \tau_{imp} \gtrsim 1$
   (exponential supression in Dingle factor)

2. Low-T, high B-fields : $k_B T \lesssim \frac{\hbar \omega_c}{2\pi^2}$

3. Oscillation frequencies $\longleftrightarrow$ area of Fermi surface

   T-dependance of amplitude $\longleftrightarrow$ effective mass m^*

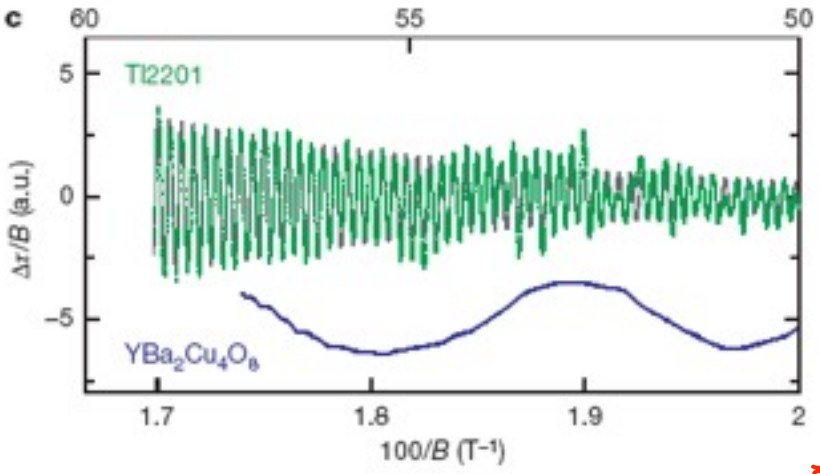
   B-dependance of " $\longleftrightarrow$ impurity scattering time τ_{imp}

4. Some non-Fermi liquids may also show quantum oscillations
   - amplitude possibly not described by Lifshitz-Kosevich

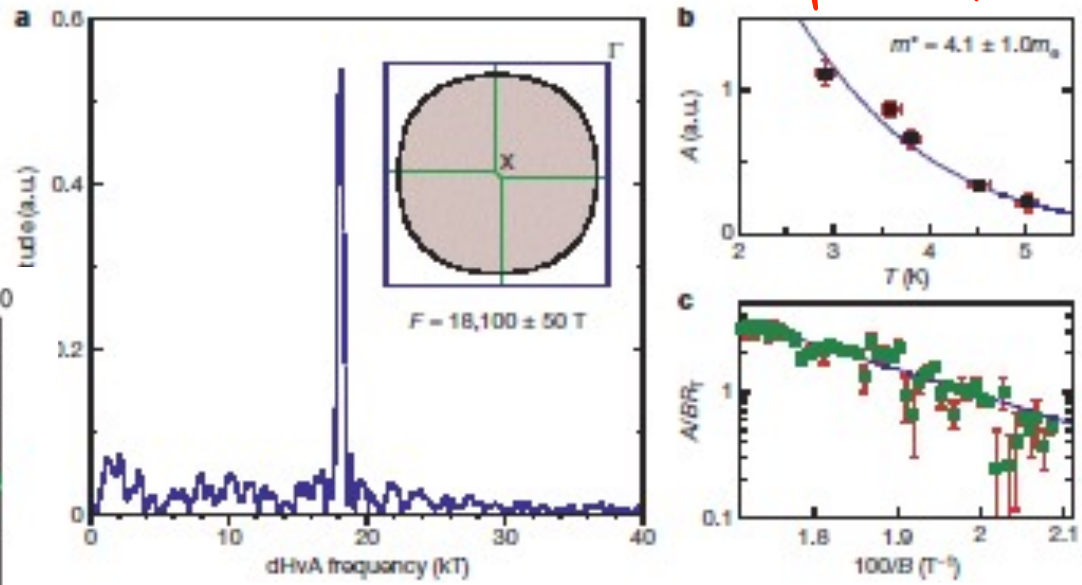
Vignolle, ..., Hussey, Nature 2008

Quantum oscillations in Tl-2201

Tc = 10 K, B upto 60 T; oscillations in both M and in c-axis ρ



"Amplitude plot"



"Dingle plot"

F = 18100 T consistent with "large Fermi surface"

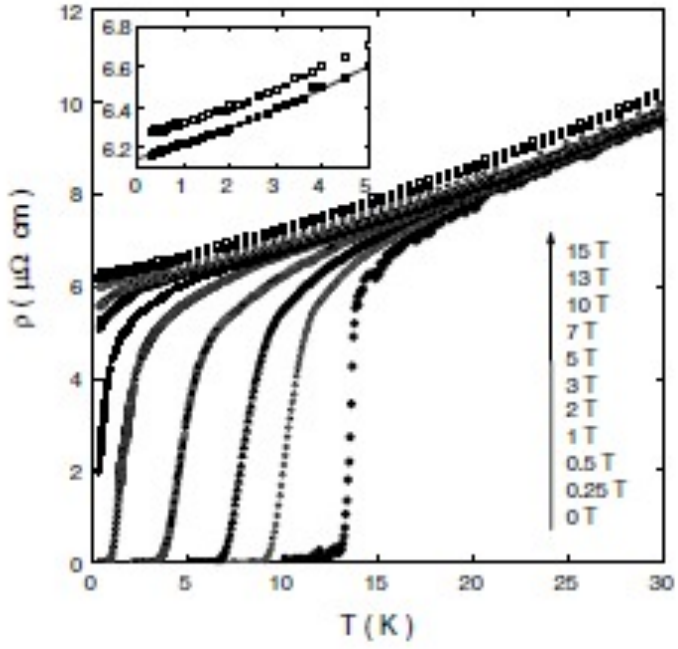
$m^*/m_e \simeq 4$ consistent with other probes

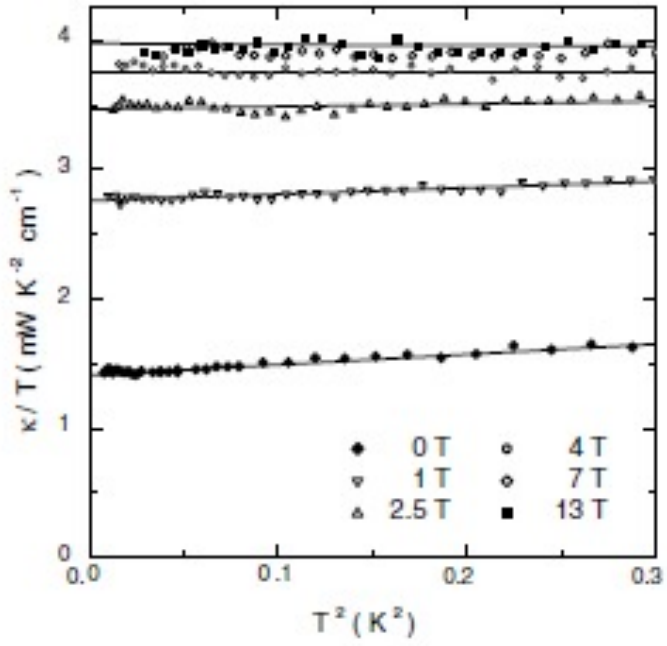
Proust, .. , Taillefer, PRL 2002

Thermal conductivity: Wiedemann–Franz law

Usual Fermi liquid : $\kappa = \underbrace{AT}_{\text{electrons}} + \underbrace{BT^3}_{\text{phonons}}$ as $T \searrow 0$

Wiedemann-Franz: $\lim_{T\to 0} \kappa/T\sigma = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 \equiv L_0$





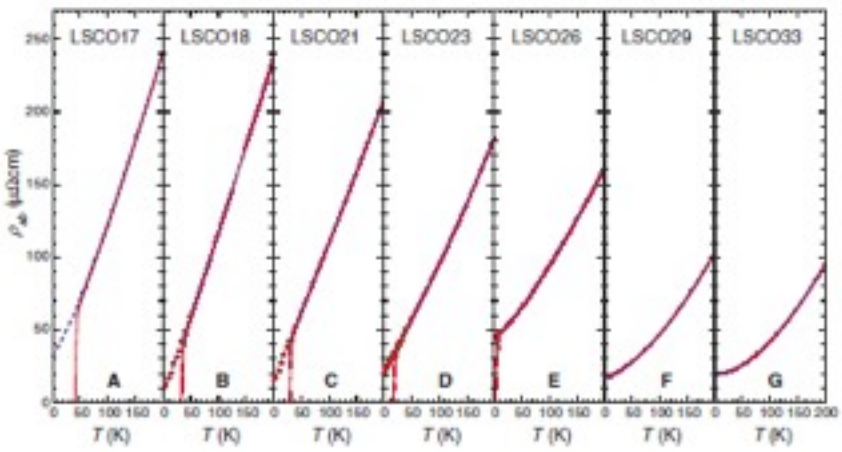
OD Tl2201 : $\kappa/T\sigma = 0.99\, L_0$ ✓

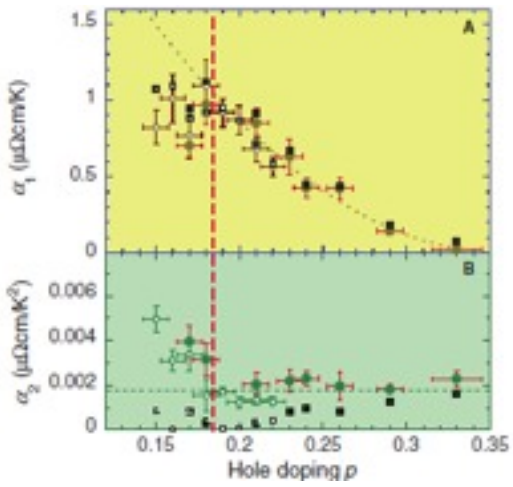
Is the OD state really a Fermi liquid?

Tl-2201 : $\rho(T \searrow 0, B) = \alpha_1 T + \alpha_2 T^2$ (Julian, Mackenzie, 1996)

Similar in extensive study of OD LSCO

Hussey et al, Science 2009

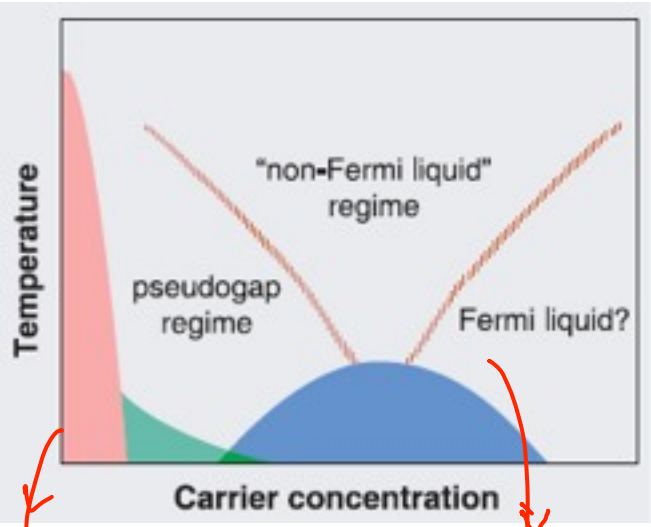




Other : Possibility of anisotropic quasiparticle scattering along Fermi surface $1/\tau = A + BT^2 + CT\cos^2 2\phi$

(detailed fits to magnetotransport data - Hussey et al, 2007)

High Tc Phase diagram



Mott insulator; no Fermi surface

Large Fermi surface

Plan

1.Overdoped – is it `conventional'?

2.<u>What is strange about the strange metal?</u>

3.Theory interlude

What is strange about the strange metal?

Mohit Randeria Lec 1

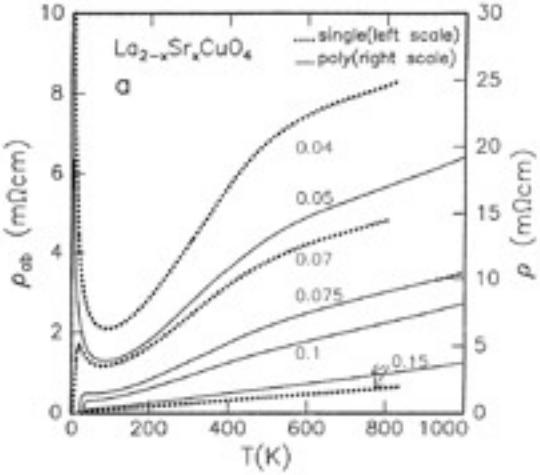
1. Photoemission

Sharp (upto thermal smearing) large Fermi surface but no Landau quasiparticles

2. Transport - linear T resistivity

This lecture - more discussion of transport and other anomalies in strange metal.

The strange metal: electrical transport

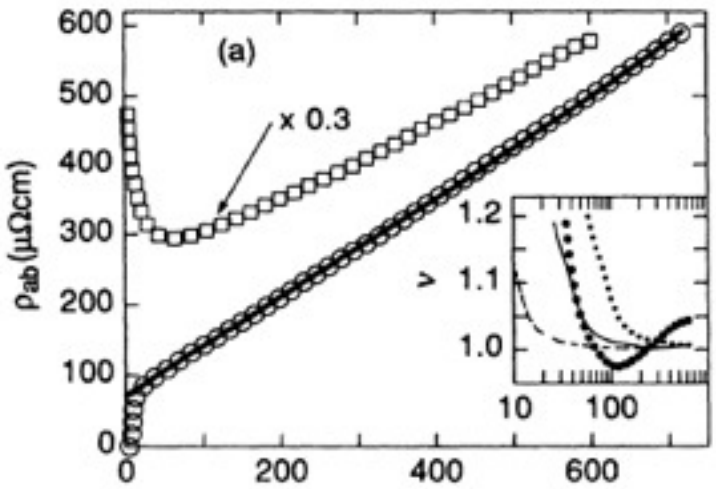


Linear-T resistivity near optimal doping with nearly zero intercept.

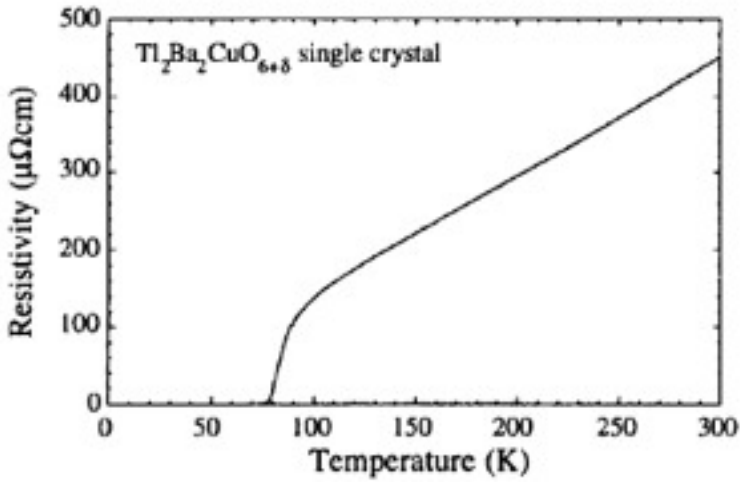
Slope of resistivity/layer roughly the same (1.5 μΩ cm/K) for all materials.

Sheet resistance = ρ/d ~ (h/e^2) T/J

"Bad metal": $k_F l \lesssim 2\pi$ at high T; no signs of phonons



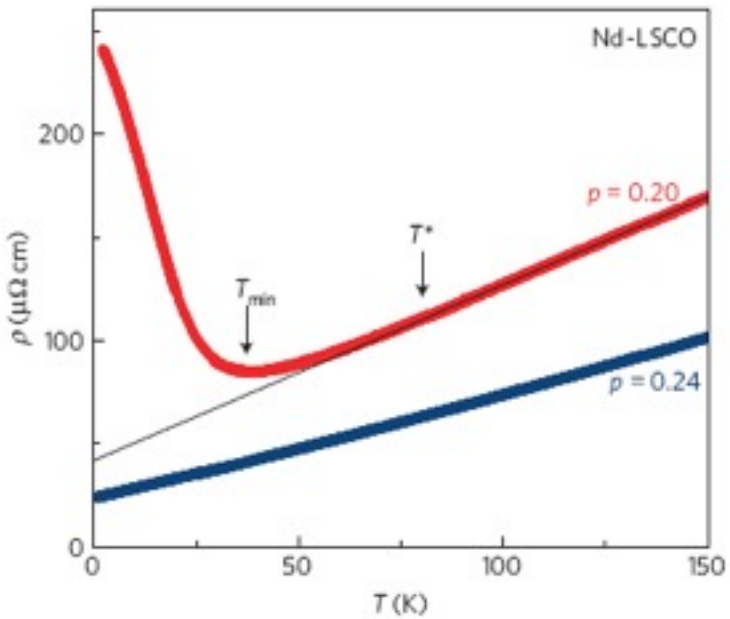
Bi-2201 Martin et.al '90

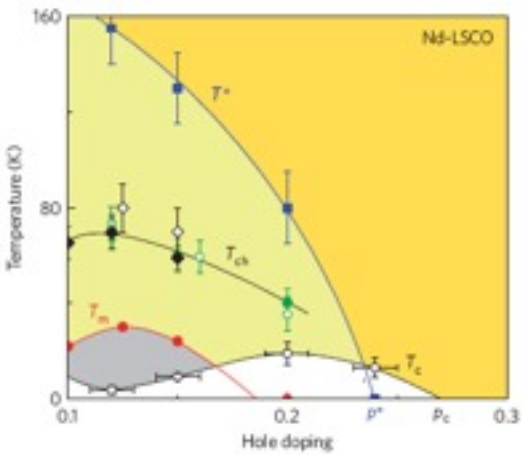


Mackenzie '97

Linear resistivity at very low-T

Daou, ..., Taillefer, Nat. Phys. 2008



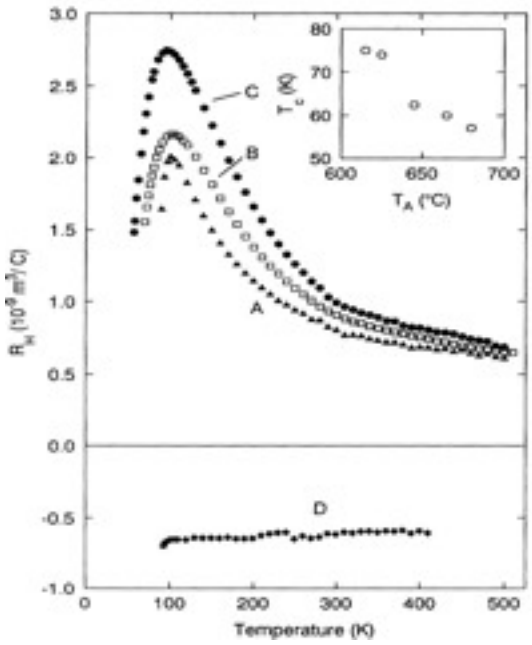


Tied to ``quantum criticality”?

Quantum critical point: second order phase transition at T = 0

Magnetotransport: Hall effect

Harris, ..., Ong '94

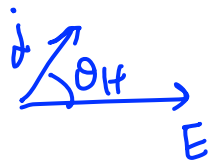


$R_H \nearrow$ as $T \searrow$

For Drude metal $\sigma_{xy} = (\omega_c \tau)\, \sigma_{xx}$

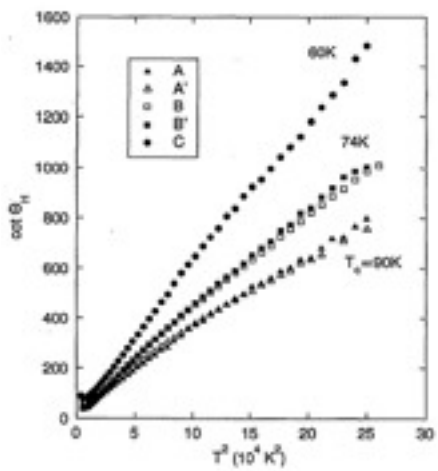
$\Rightarrow \cot \theta_H = \dfrac{\sigma_{xx}}{\sigma_{xy}} = \dfrac{1}{\omega_c \tau} \propto \rho$

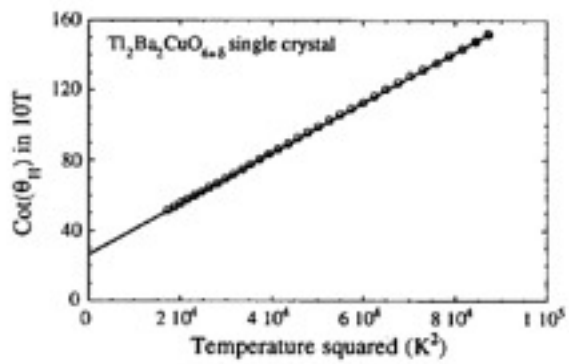
"Hall angle"



Here $\cot \theta_H \propto T^2$

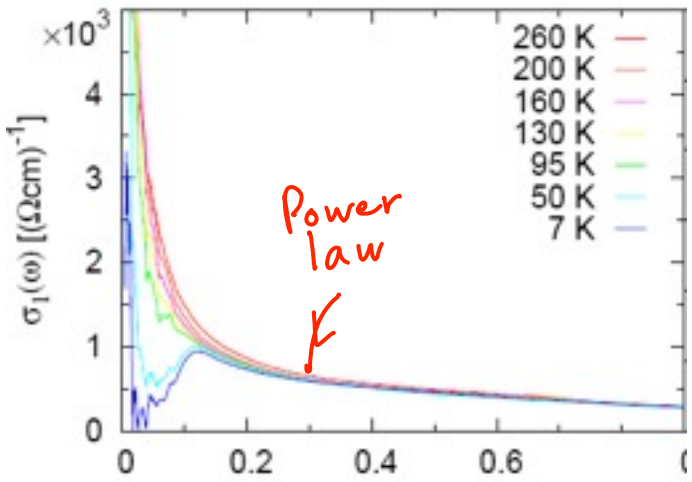
but $\rho \propto T$

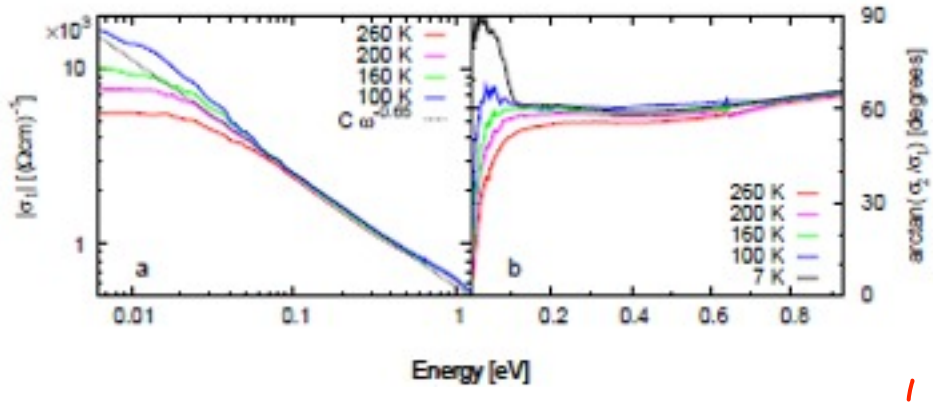




Mackenzie '97

Optical transport: high frequency tail





Van der Marel et. al., Science '03
(similar early data, Bontemps '94)

Power law tail at high frequency
($70\ \text{meV} \lesssim \omega \lesssim 1\ \text{eV}$)

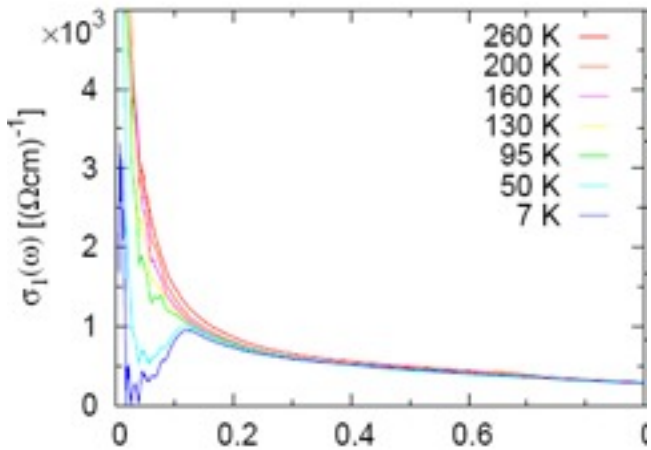
$$\sigma(\omega) = C(-i\omega)^{\gamma-2}$$

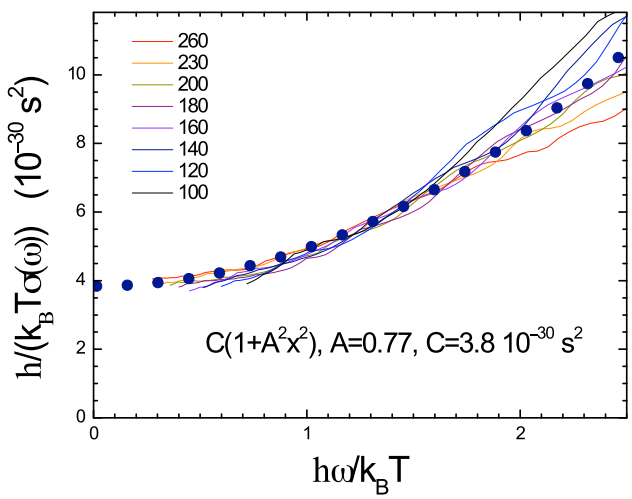
$$\gamma - 2 \approx -0.65$$

$$\Rightarrow |\sigma(\omega)| \sim \frac{1}{\omega^{0.65}}$$

and phase angle $\tan^{-1}(\sigma_2/\sigma_1)$
$= \pi/2\,(2-\gamma)$
independant of ω

Optical transport: low frequency peak





Roughly described by Drude form

$$\sigma_1(\omega, T) = \frac{\sigma_{DC}(T)}{1 + (\omega\tau(T))^2}$$

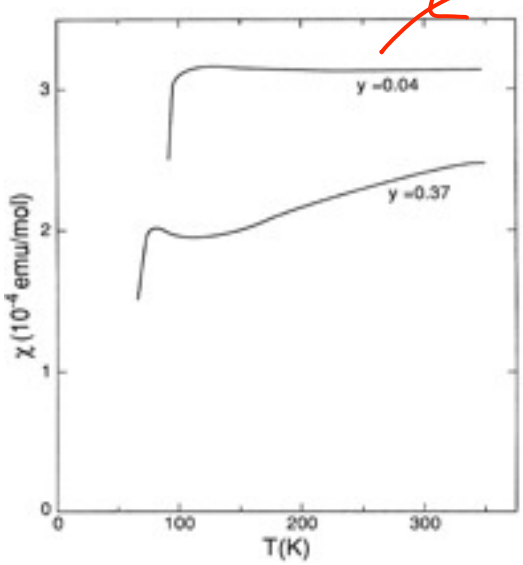
with "scattering time"

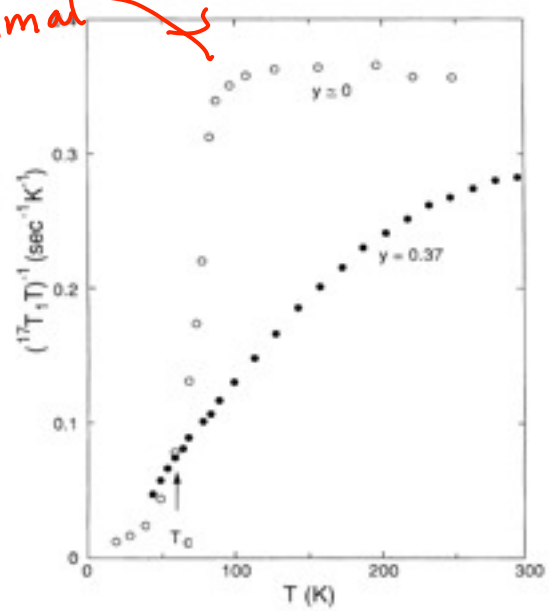
$$\tau(T) \propto \hbar / k_B T$$

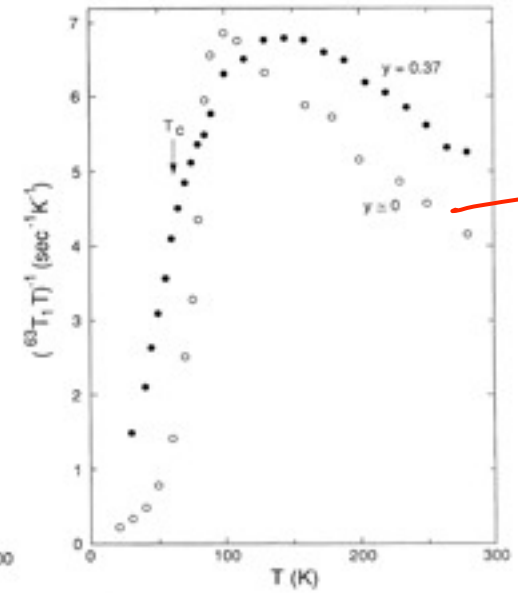
Spin physics: spin susceptibility and NMR relaxation

$YBCO_{7-y}$

optimal

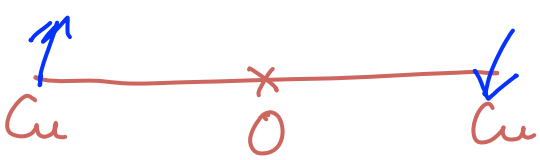






χ = const. for $T > T_c$;
(consistent with Knight shift)

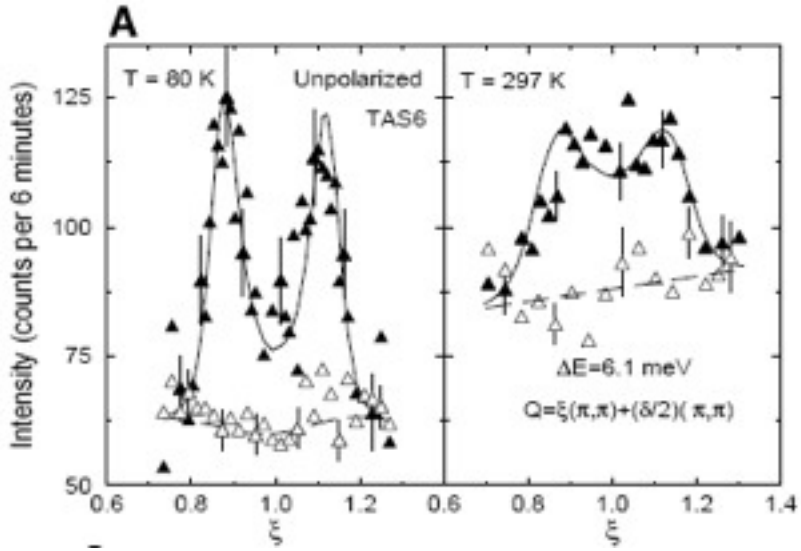
Striking difference between ^{17}O and ^{63}Cu in $1/T_1$;
"Korringa" $1/T_1 T K_s^2$ = const. violated at Cu site

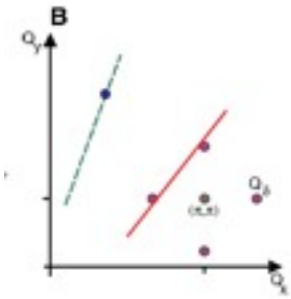


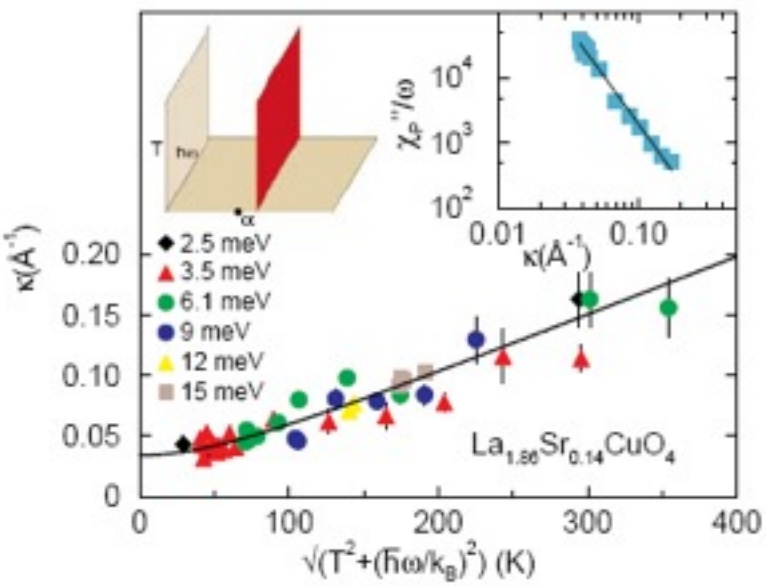
⇒ slow growth of AF correlations

Aeppli et. al., Science '97

Dynamic spin correlations: neutron scattering in LSCO







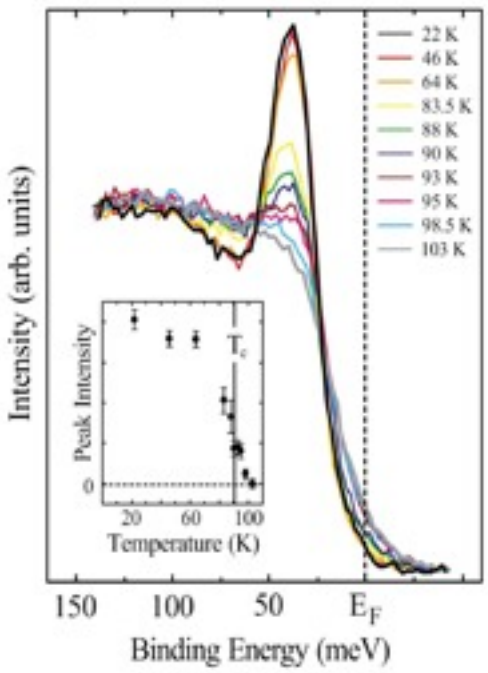
Nearly singular scaling of spin fluctuations at incommensurate wave vector near optimal doping.

However similar data apparently does not exist in YBCO

Transition to SC: onset of coherence

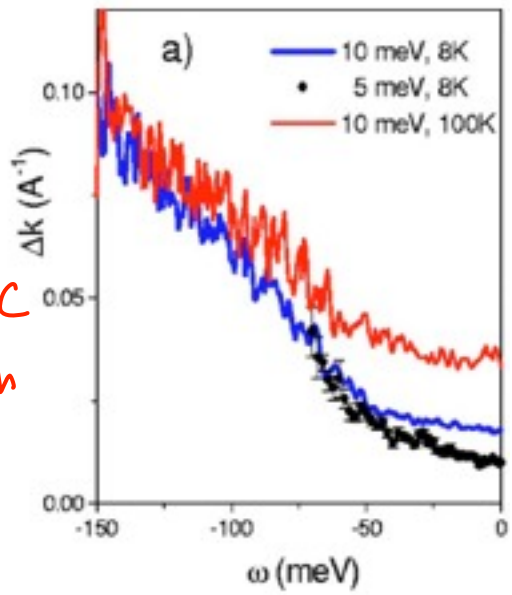
ARPES results

Anti node



Node

MDC width

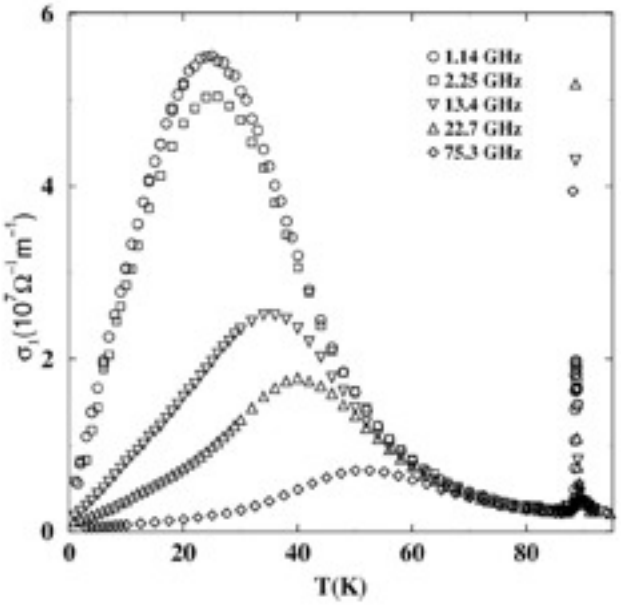


Sharp quasiparticles emerge for $T < T_c$.

Onset of coherence in transport

Micro wave

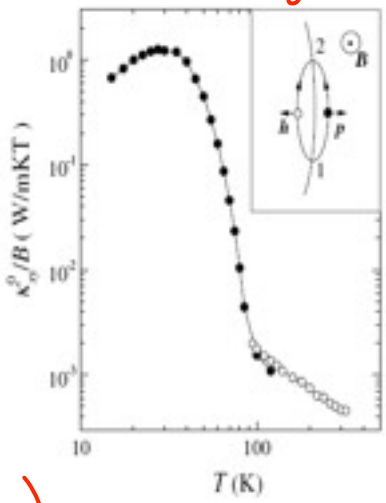
Bonn, Hardy, et. al. '93, '99

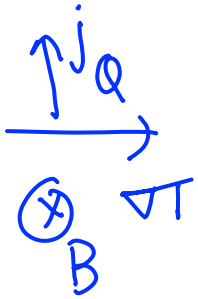


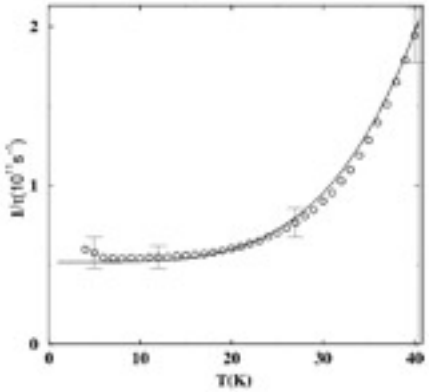
Thermal Hall effect

(Separate electron transport from phonon)

N. P. Ong '99



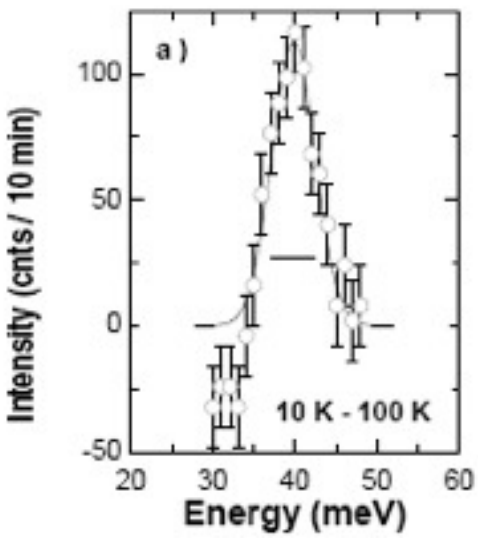




Collapse of scattering rate of nodal excitations for $T < T_c$.

Mean free paths ~ 1 micron

Neutron resonance



Keimer et. al. '95

Sharp magnetic excitation with gap of 41 meV (in YBCO) visible only for $T < T_c$.

Seen in almost all cuprates at various doping levels

Summary on strange metal

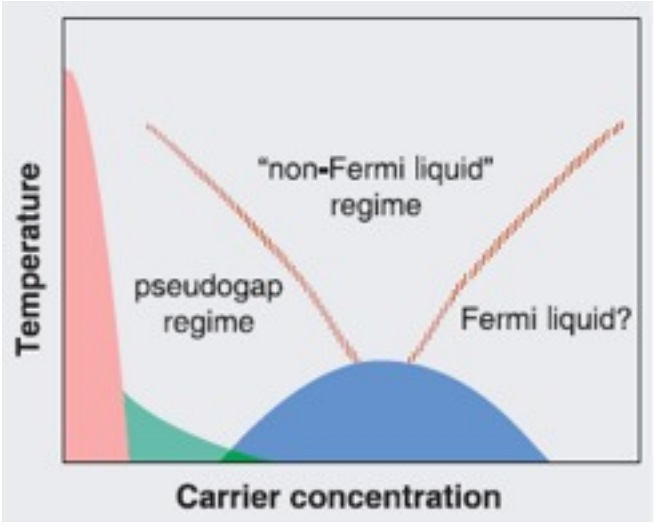
Strange metal: Power laws in many physical quantities;

Large Fermi surface but no Landau-like quasiparticles

Slow growth of antiferromagnetic spin correlations

Transition to superconductivity accompanied by appearance of coherent quasiparticles and a sharp spin triplet `resonance' mode.

Brief theory interlude



Some basic questions

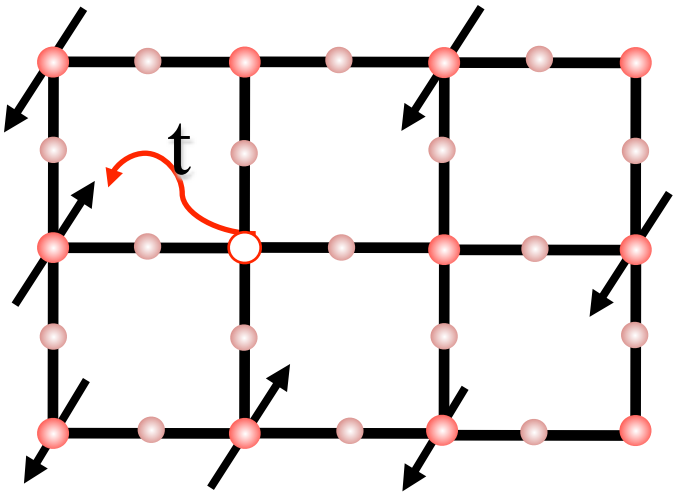
1.How does a
metal emerge from a Mott insulator?

2. Why superconductivity?

Simple physical picture (Anderson1987):
Superexchange favors formation of singlet valence bonds between localized spins.

Doped Mott insulator: Hole motion in background of valence bonds.

Cartoon pictures

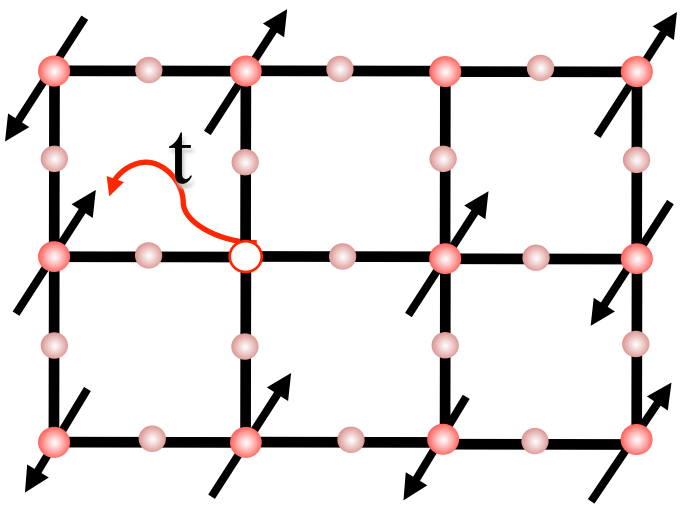


Large doping: Hubbard-U not very effective in blocking charge motion

Expect `large Fermi surface' with area set by 1-x.

What happens as doping is reduced to approach Mott insulator?

Cartoon pictures



Low doping: Most of the time most electrons unable to hop to neighboring sites due to Mott-blocking.

If electrons stay localized next to each other long enough, will develop superexchange which will lock their spins into singlets.

Electron configuration changes at long times – conveniently view as motion of holes in sea of singlets.

Resulting state: metallic but with a spin gap due to valence bond formation => `pseudogap metal".

Why superconductivity?

Crucial Anderson insight:

Singlet valence bond between localized spins: A localized Cooper pair.

`Pairing' comes from superexchange due to a repulsive Hubbard interaction.

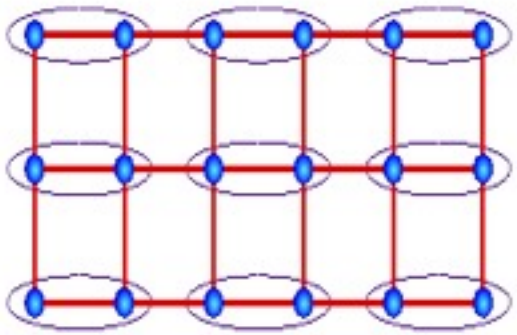
If spins were truly localized, Cooper pairs do not move => no superconductivity.

Nonzero doping: allow room for motion of valence bonds => superconductivity!

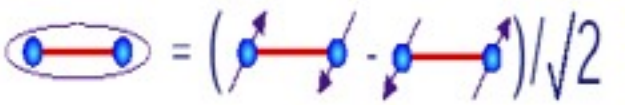
Hole picture: Coherent hole motion in valence bond sea

Fate of collection of valence bonds

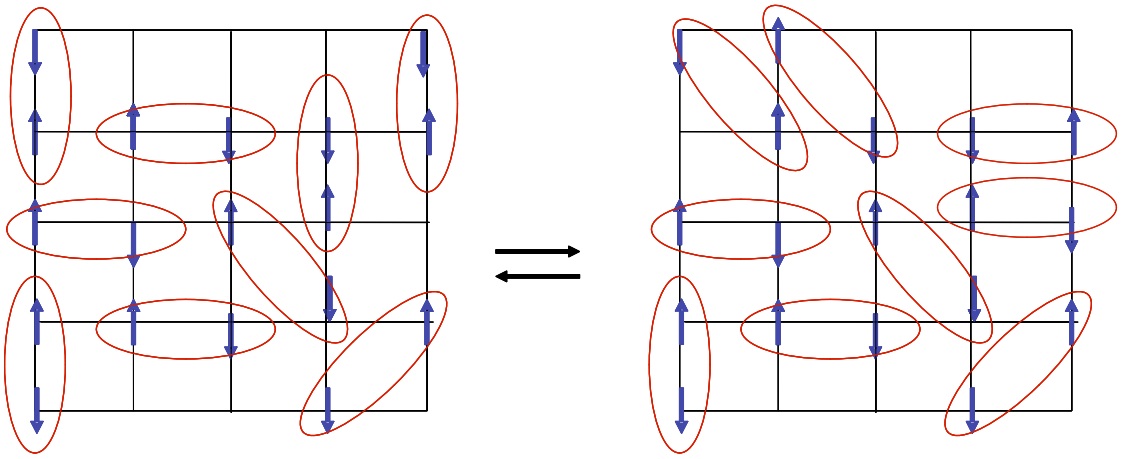
Two general possibilities:
Valence bonds can crystallize to form a solid
(``Valence Bond Solid”)
OR
Stay liquid to form a `Resonating Valence Bond’



VBS state (with doping a `bond centered’ stripe)



Ongoing debates on which one is more relevant but very formation of valence bond crucial ingredient in much thinking about cuprates.



RVB state = quantum spin liquid

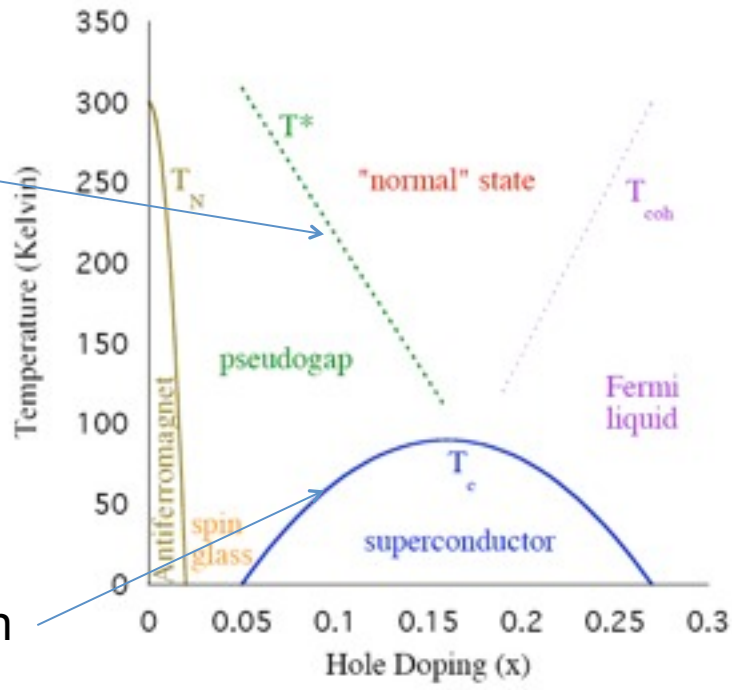
Doped Mott insulators and high Tc superonductivity

T. Senthil and Mohit Randeria

Lecture 3

Cartoon understanding of phase diagram

Formation of singlet valence bond



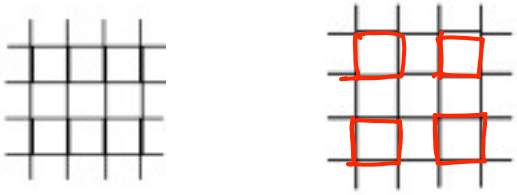
Coherence of hole motion

Does valence bond formation provide a legitimate <u>theoretical</u> route for superconductivity in a repulsive doped Mott insulator?

Many different kinds of studies: (work of large # of people over 20 yrs)

1.1d doped spin ladder:
Zero doping – spin gapped insulator due to valence bond formation.
Dope – (power law) superconductor .

2. Quasi-1d: Weakly coupled ladders



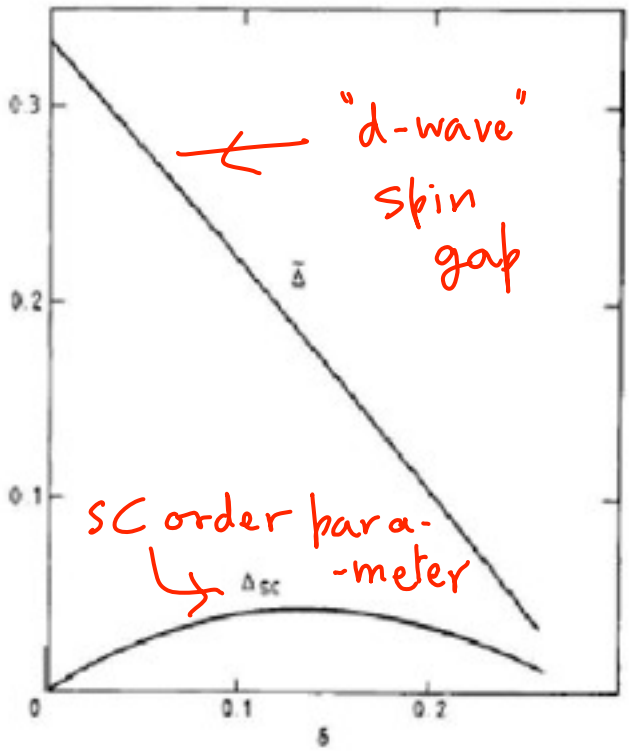
3. Inhomogenous 2d: Checkerboard Hubbard model

4. Superconductivity in doped VBS Mott insulators (`large-N' methods): spontaneously generate weakly coupled ladders.

5. Superconductivity in doped spin liquid Mott insulators (i.e insulators with one electron per site)

Superconductivity in doped spin liquids: mean field

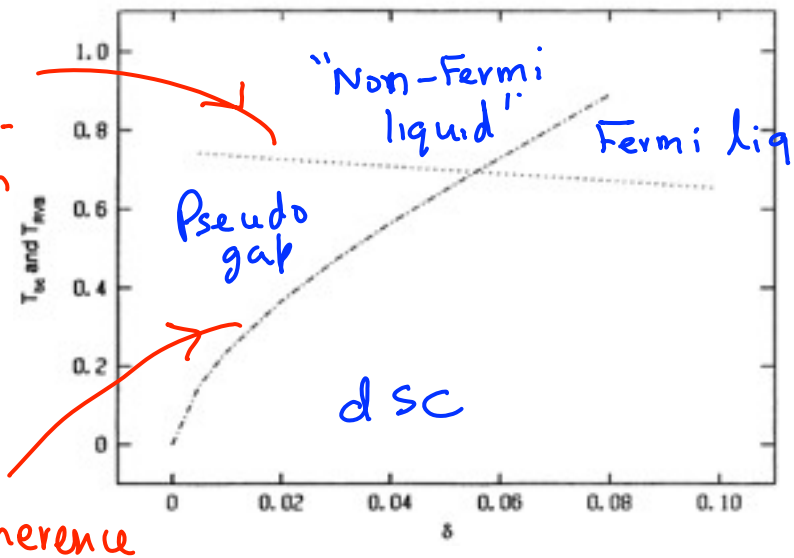
Incorporate no double occupancy constraint of t-J model in approximate "mean field"



f.c. Zhang, Gros, Rice, Shiba '88

"Gutzwiller" mean field

spin gap form-ation



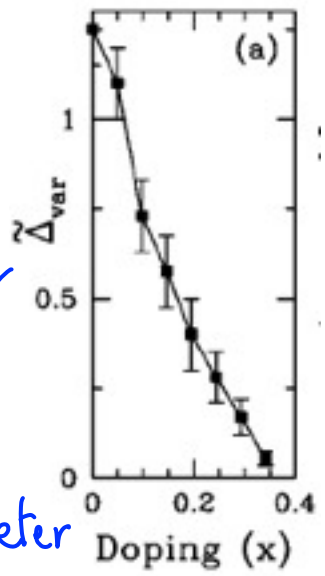
coherence of hole motion

Kotliar, Liu '88

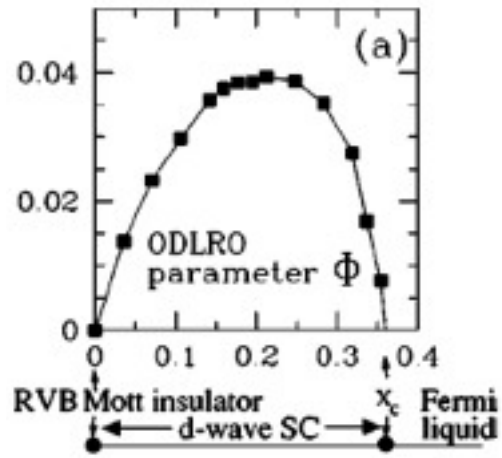
"Slave boson" mean field

Superconductivity in doped spin liquids: variational wavefunctions

$$|\Psi_{gd}\rangle = P_{\text{no double occupancy}} \, |dBCS\rangle$$



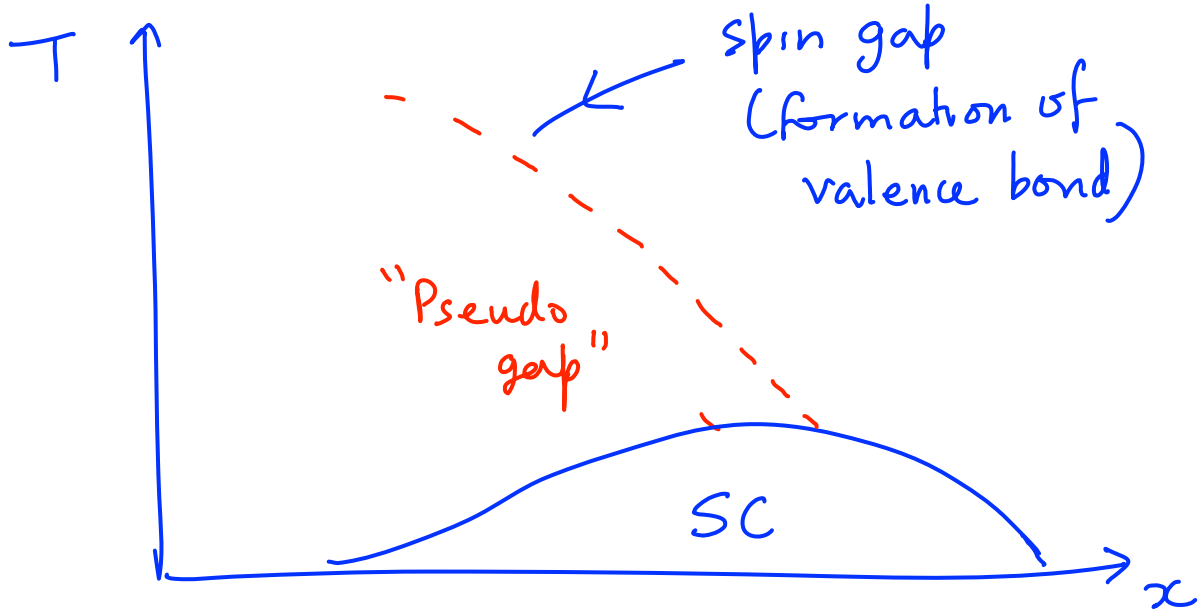
Gap parameter of $|dBCS\rangle$ in variational wave function



Paramekanti, Randeria, Trivedi 2001

Common features of superconductivity in doped (paramagnetic) Mott insulators

Generic phase diagram

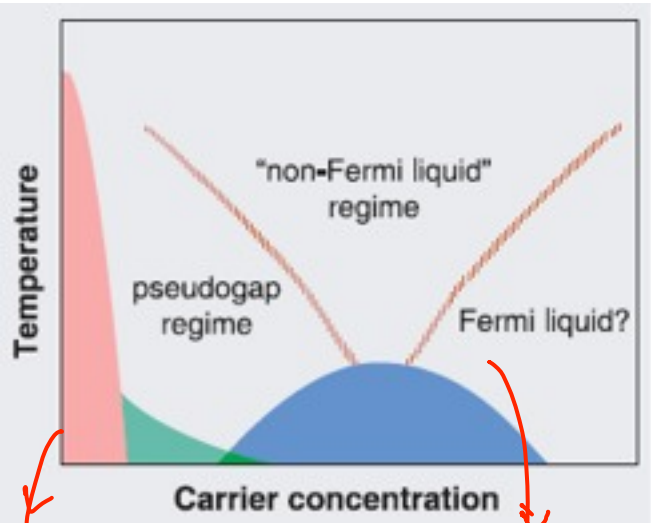


"Low" x : T_c controlled by phase stiffness ρ_s ($\to 0$ as $x \to 0$)

Spins start gapping at higher temperature T^*

"High" x : T_c controlled by pairing gap $\searrow 0$

High Tc Phase diagram



Mott insulator; no Fermi surface

Large Fermi surface

Plan

1. Phenomenology of the pseudogap – review, quantum oscillations, and competing orders

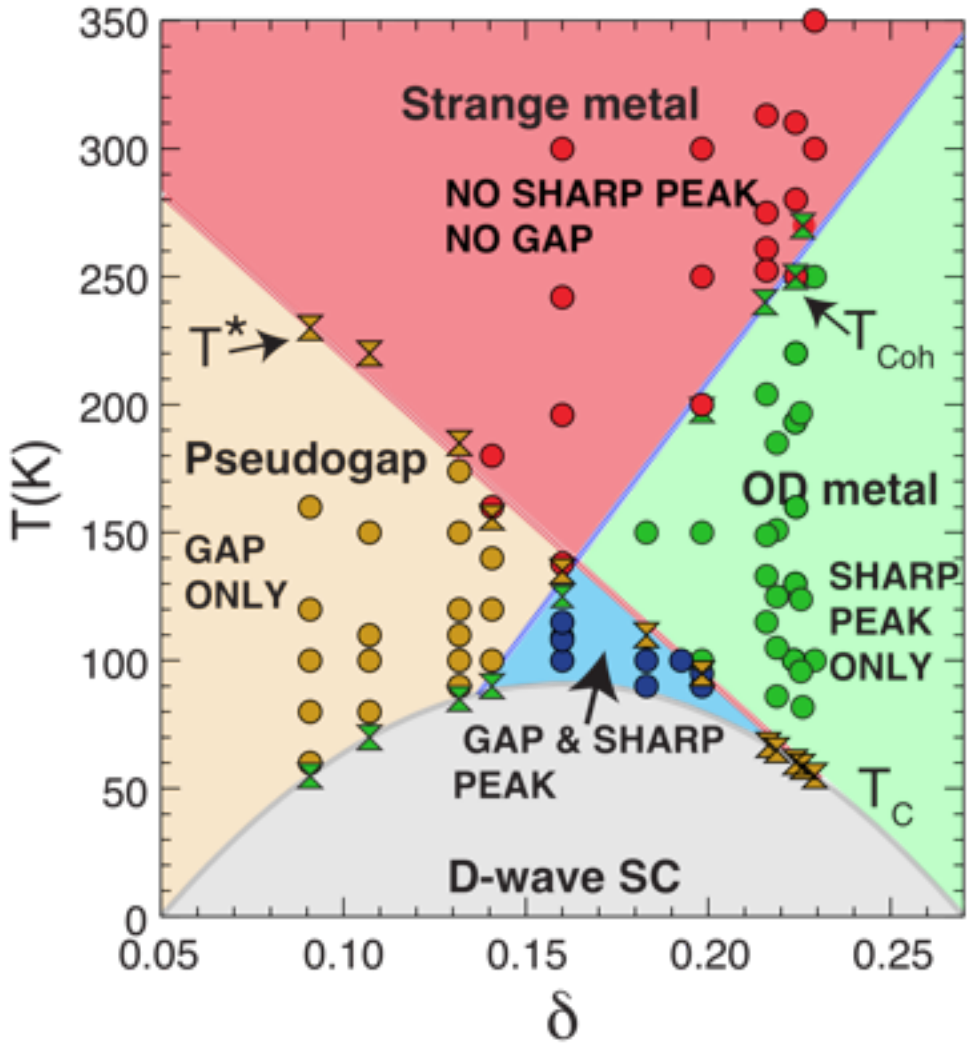
2. Some theory

3. Refined basic questions

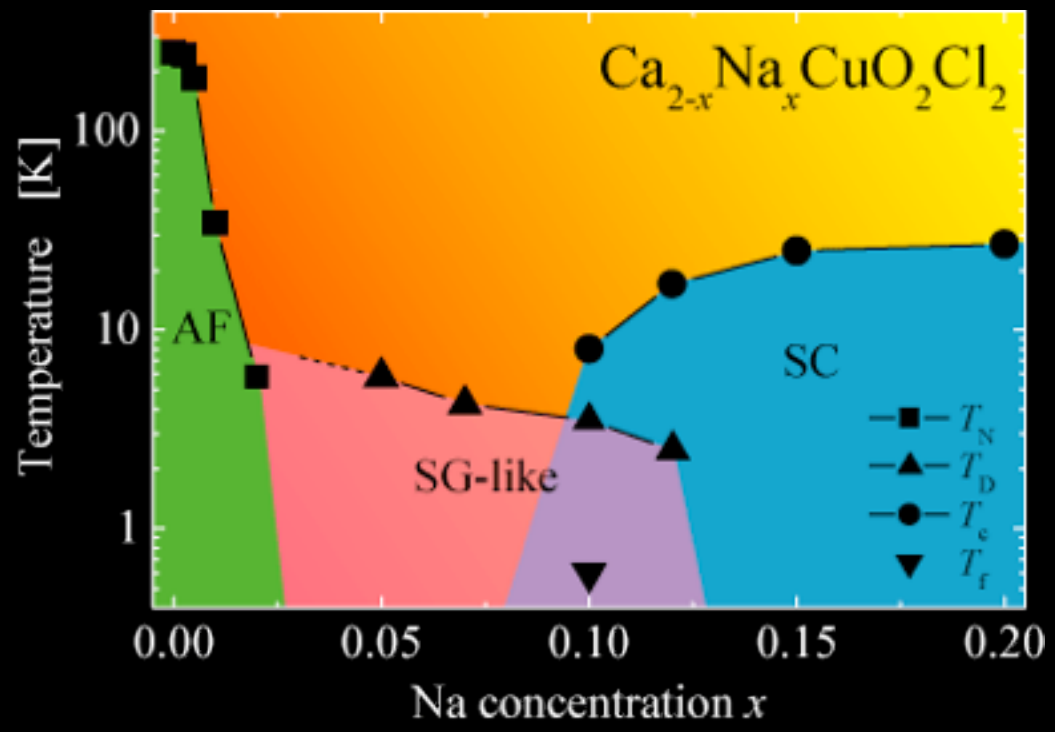
Pseudogap: loss of ``density of states" in spin, single particle properties

Some real high Tc phase diagrams

Bi2212



ARPES data from
U. Chatterjee et al (2010)
Courtesy: J.C. Campuzano



K. Ohishi et al., cond-mat/0412313

Courtesy: J. C. Davis

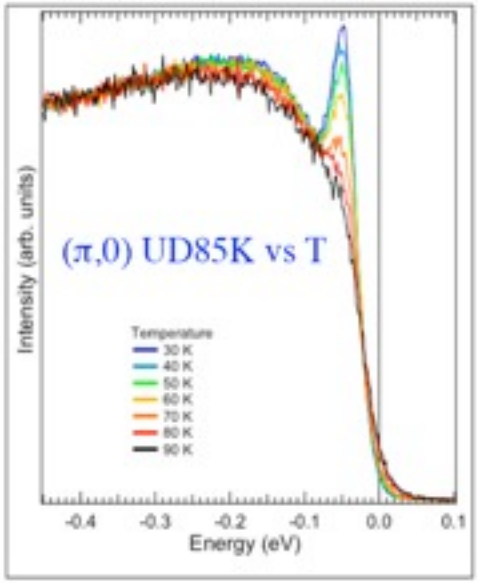
Summary of ARPES in underdoped pseudogap regime

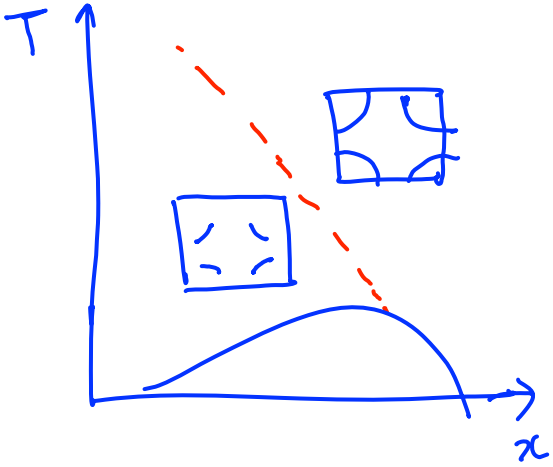
1. Big antinodal gap – 50 meV or bigger

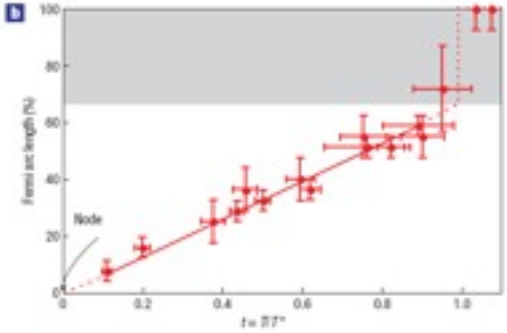
2. Gapless Fermi arcs near node that shrink as T is reduced;

possibly even extrapolate to 0 at T = 0.

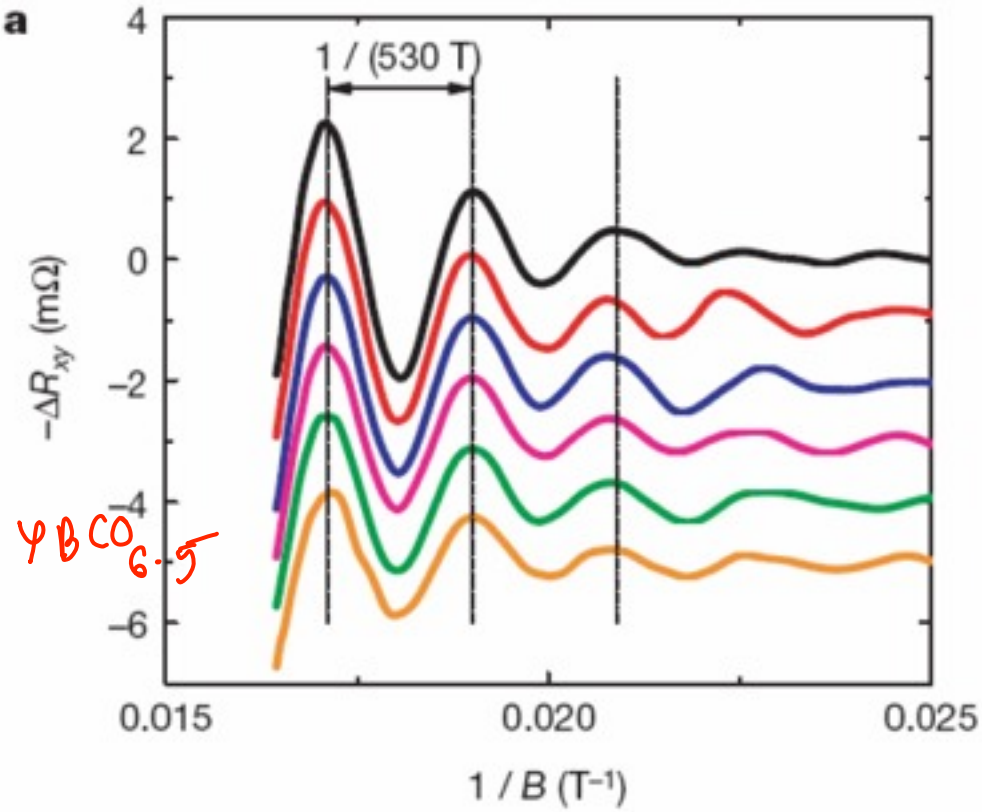
3. Gap is apparently centered on large Fermi surface







New mystery: quantum oscillations in a magnetic field at low T



deHaas-van Alfen, Shubnikov-deHaas oscillations in ultra-pure $YBCO_{6+x}$ ($x \approx 0.5$) and $YBa_2Cu_4O_8$ in B upto $\simeq 60T$

Dominant frequency 530T

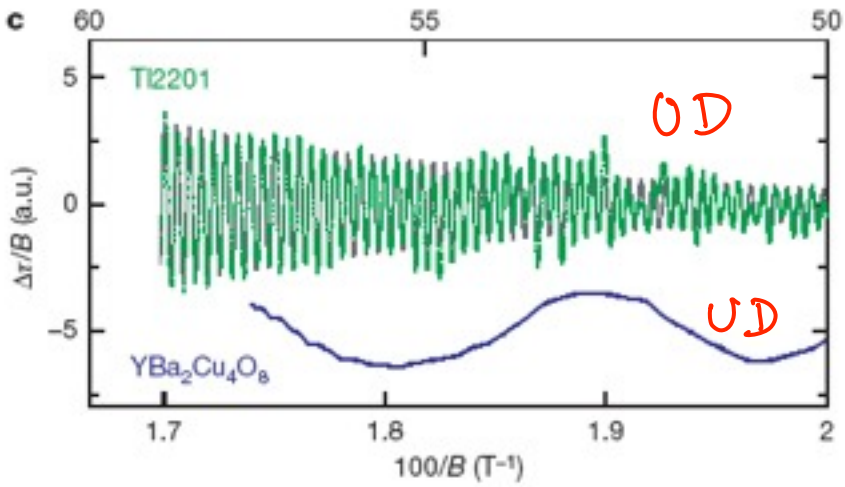
$\Rightarrow$ small pocket.

(Proust, Taillefer, ... '07)

Other frequencies with lower amplitude,

Eg: 1650T (Sebastian et. al. '08)

High field ground state: contrast between under and over-doped



OD Tl 2201 : F = 18100 T

⟺ 63 % of Brillouin Zone

UD $YBCO_{6.5}$: F = 530 T

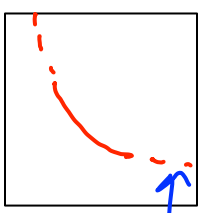
⟺ 3 % of Brillouin Zone

How do all this fit together?

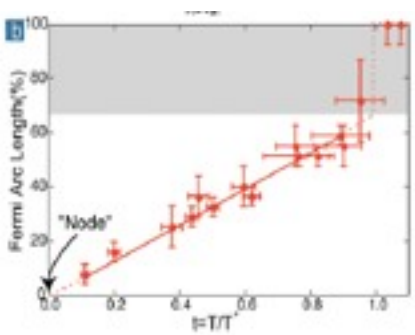
$T^* > T > T_c$, low H: "gapless Fermi arcs" that shrink as $T \searrow$, antinodal gap ≈ 50 meV

Low T, high H: closed Fermi pocket, possibly near antinode.

$T > T_c$

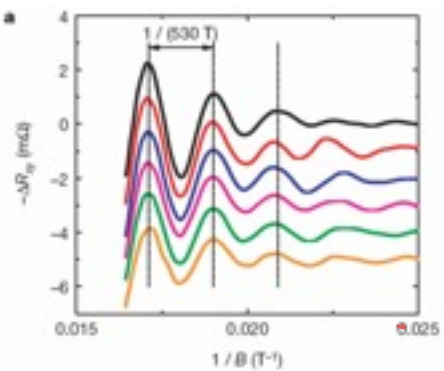


gap



versus

$T \to 0$, $H \approx 50$ T



How to fit together?

1. How can a closed Fermi surface emerge at low T ?

2. Can a 50T field really close the antinodal gap $\Delta_{PG} \simeq 50$ meV ?

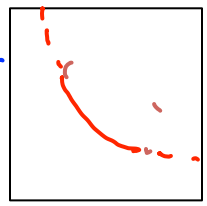
$H \sim 50T$ is actually a <u>small</u> field

Eg: If Δ_{PG} = "pairing" gap, $H_{c2} \sim \dfrac{\Phi_0}{(\hbar v_F/\Delta)^2} \gg 50T$

Arcs versus pockets

Could it be that the arcs are really just one side of a closed pocket near the nodal region?

1 quadrant of BZ



Fermi arc

or

Small hole pocket

(Back side invisible to ARPES for some reason?)

To be clarified in future experiments . . . .

Competing order and fluctuations

Apart from superconductivity, many other ordered or nearly ordered (i.e short range ordered) states have been reported in the underdoped cuprates.

Some prominent examples:

1. Antiferromagnetism/SDW/spin stripes
2. Charge order – charge stripes/CDW/checkerboard
3. Nematic order (breaking of lattice rotation symmetry without breaking translation symmetry).
4. Others – broken T-reversal, circulating currents,.....

Implication/importance of these for pseudogap/SC/ strange metal not currently understood.

Phase fluctuations above Tc: Nernst/ diamagnetism

If Tc controlled by phase stiffness, might expect region with enhanced superconducting phase fluctuations in the `normal' state above Tc.

Experiment: Microwave conductivity (Corson, …..Orenstein)

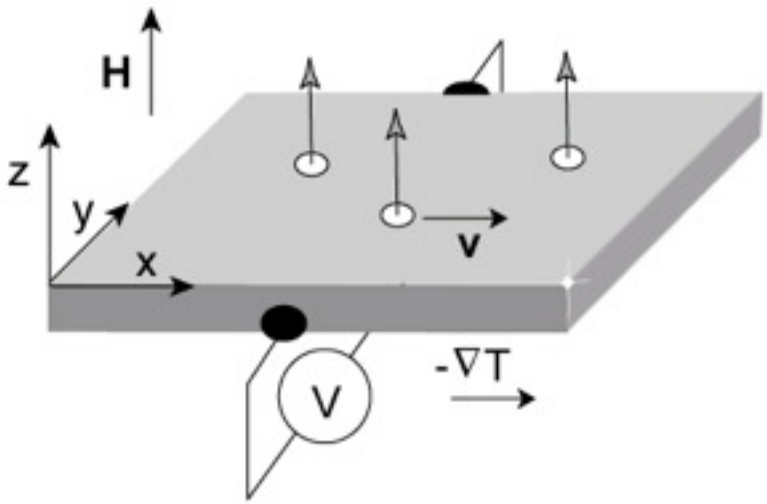
Nernst effect and diamagnetism (Wang, Li,……, Ong)

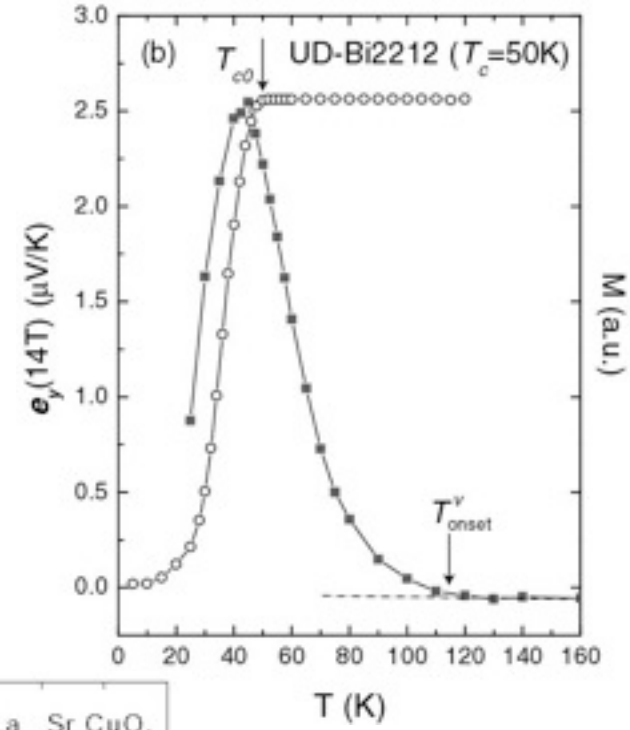
(next few slides courtesy of Lu Li)

This fluctuations regime surely exists but does not extend all the way to T*.

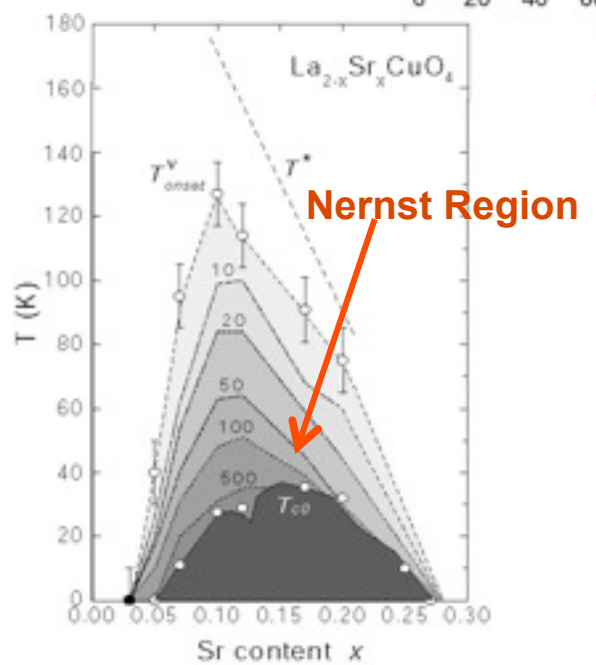
Vortex Nernst effect

Vortices move in a temperature gradient
Phase slip generates Josephson voltage





Wang et al. PRB(2001)



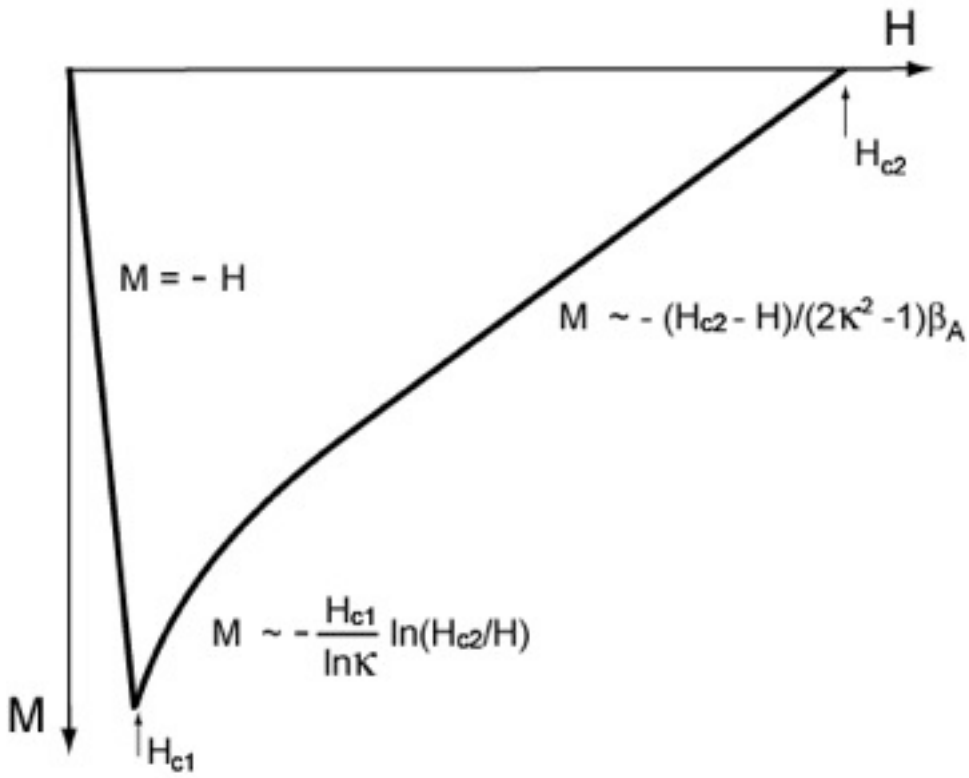
$$2eV_J = h\dot{\phi} = 2\pi h\,\dot{n}_v$$

$$\mathbf{E}_J = \mathbf{B} \times \mathbf{v}$$

Nernst signal: $e_y = E_y / |\nabla T|$

Diamagnetic signal: need high-resolution magnetometry !

Magnetization curve of type-II superconductors



Magnetization study:

Advantage

- Clear determination of H_{c2} and H_{c1}
- Area = Condensation energy U

Difficulty

- In cuprates, H_{c2} ~ 50-150 T
- M < 1000 A/m (~ 12 G)
- **HARD** to resolve with commercial SQUID magnetometers (H_{max} = 5 T or 7 T)

Torque magnetometry

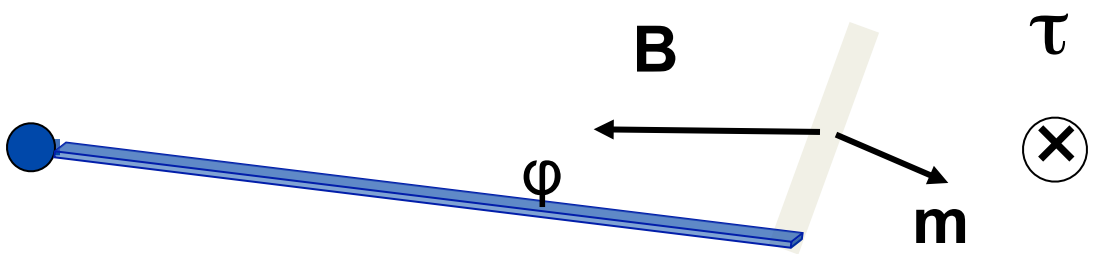
Torque on moment: $\tau = \mathbf{m} \times \mathbf{B}$

Deflection of cantilever: $\tau = k\,\varphi$

$$M_{eff} = \tau / \mu_0 HV\sin(\varphi)$$

Torque magnetometry

Torque on moment: $\tau = m \times B$



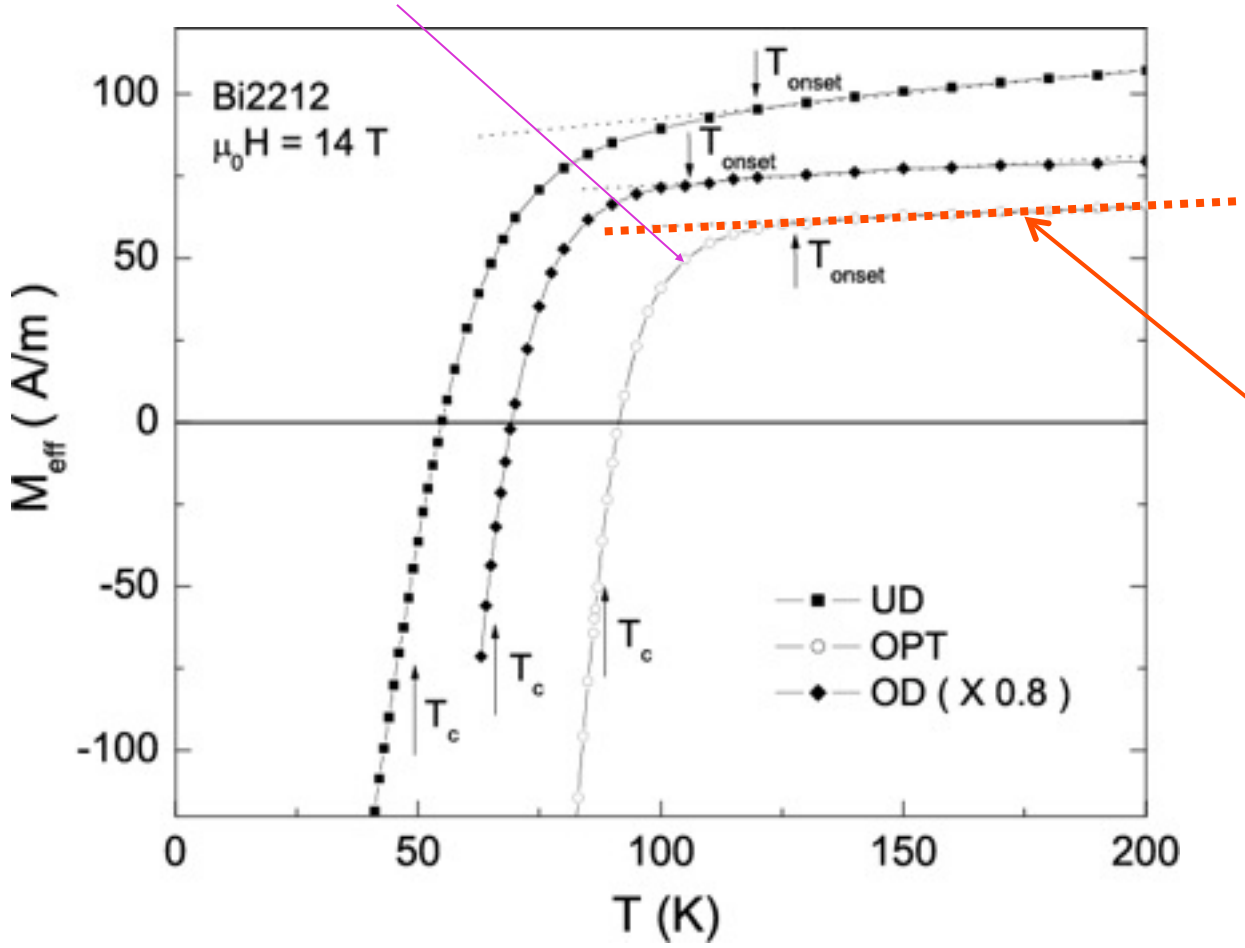
Deflection of cantilever: $\tau = k\,\varphi$

$$M_{eff} = \tau / \mu_0 HV\sin(\varphi)$$

Examples of Magnetization curves (I): M vs. T and the onset temperature T_{onset}

Enhanced diamagnetic signals above T_C

$M_{eff} = \tau / \mu_0 HV\sin(\theta)$

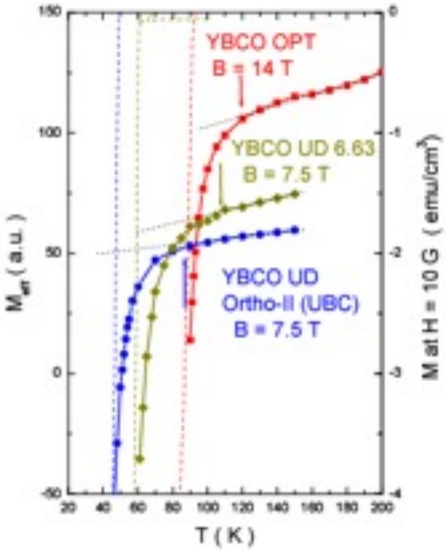


Weakly linear orbital background $\Delta\chi_{orb}H$

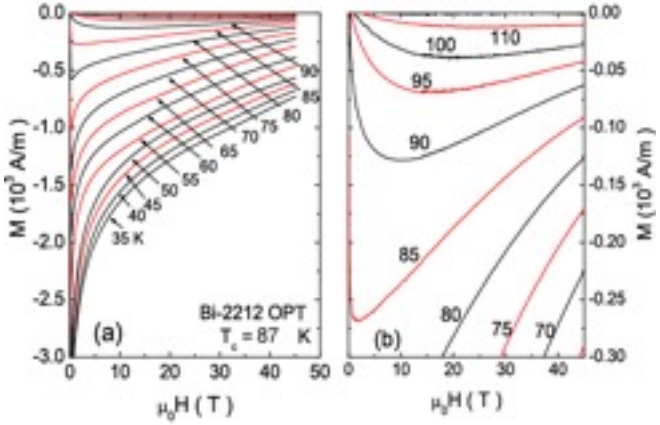
Lu Li, Thesis

Conclusion

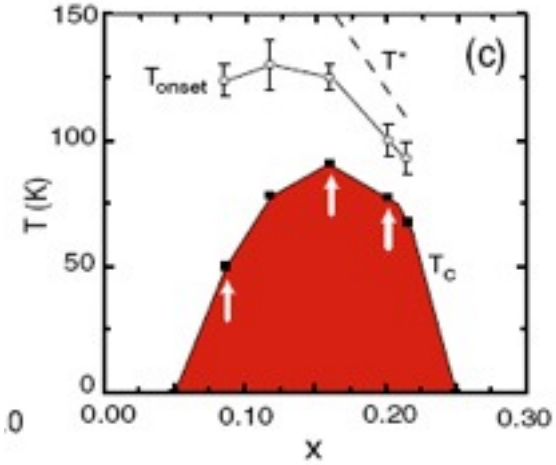
Diamagnetism up to 130 K



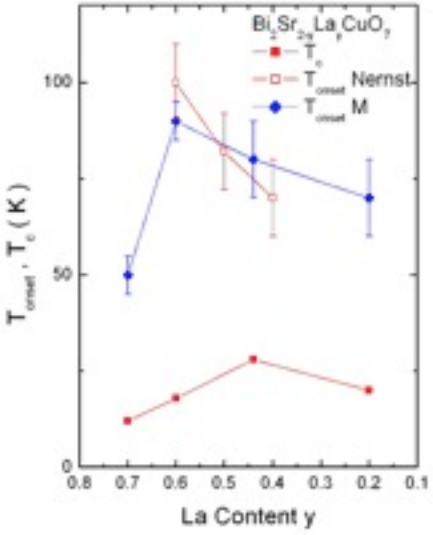
Non-linear M-H

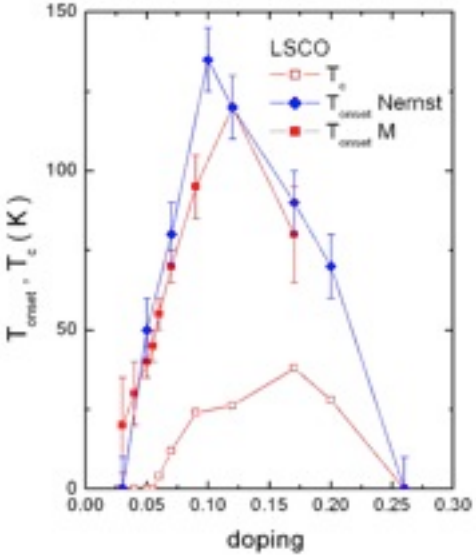


A universal SC fluctuation onset temperature vs x?



Bi2212



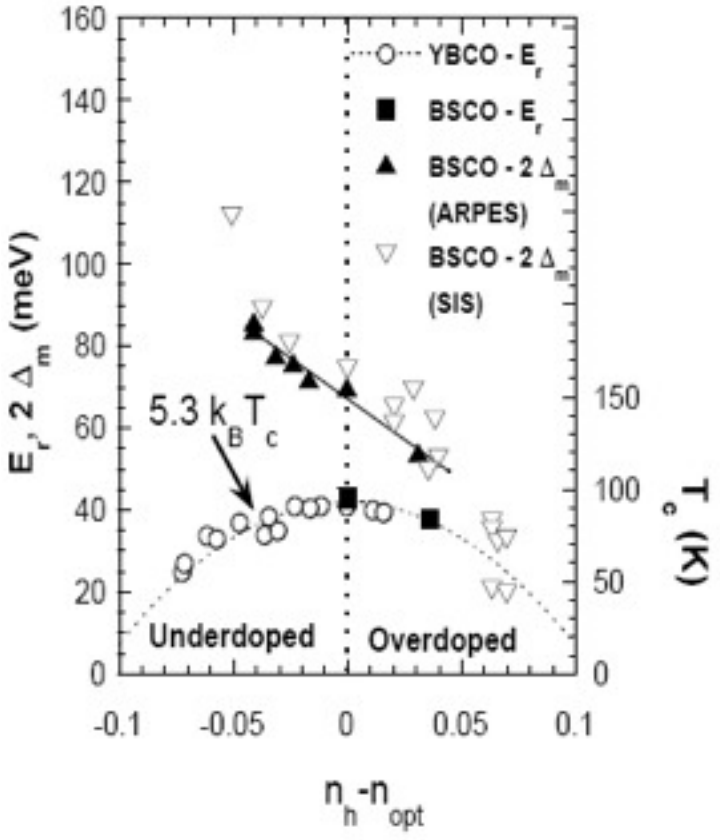


Other order and fluctuations: Antiferromagnetism

AF LRO disappears at very low doping but some soft spin fluctuations persist to high doping.
Eg: Neutron resonance in SC state seen in most cuprates.

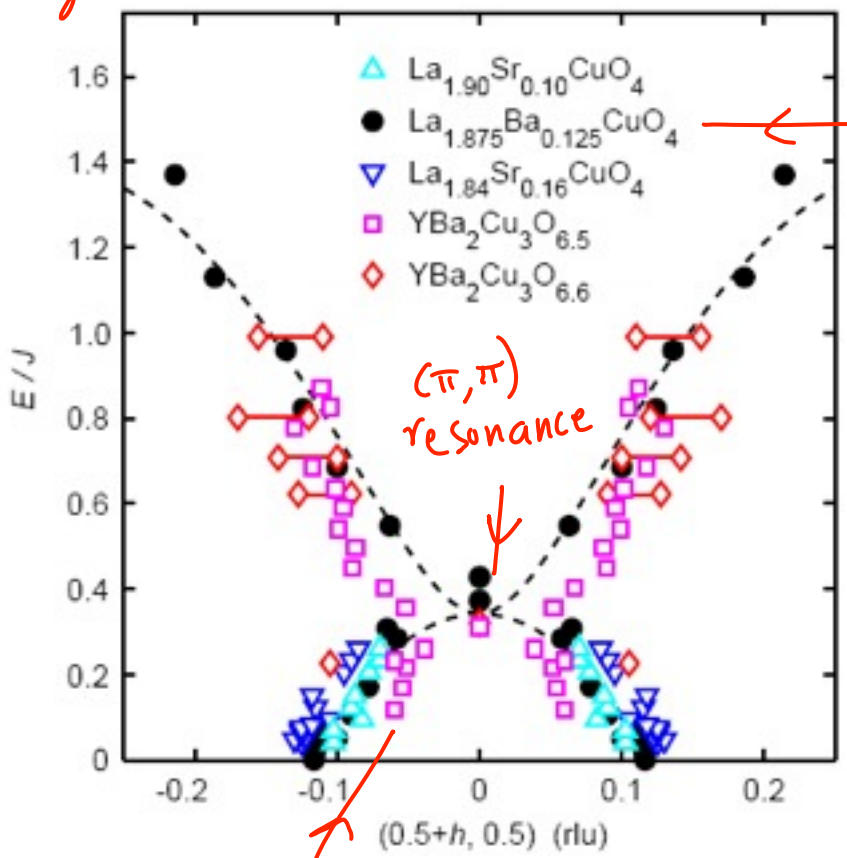
Resonance frequency decreases with Tc in underdoped.

Soft mode of AF LRO?



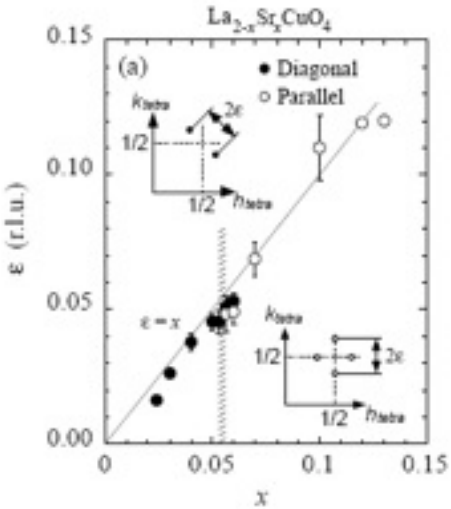
`Universal' spin fluctuation spectrum of superconducting cuprates

"Hourglass"



stripe ordered

(π,π) resonance

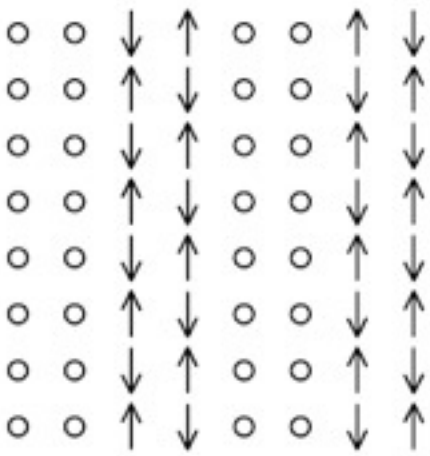


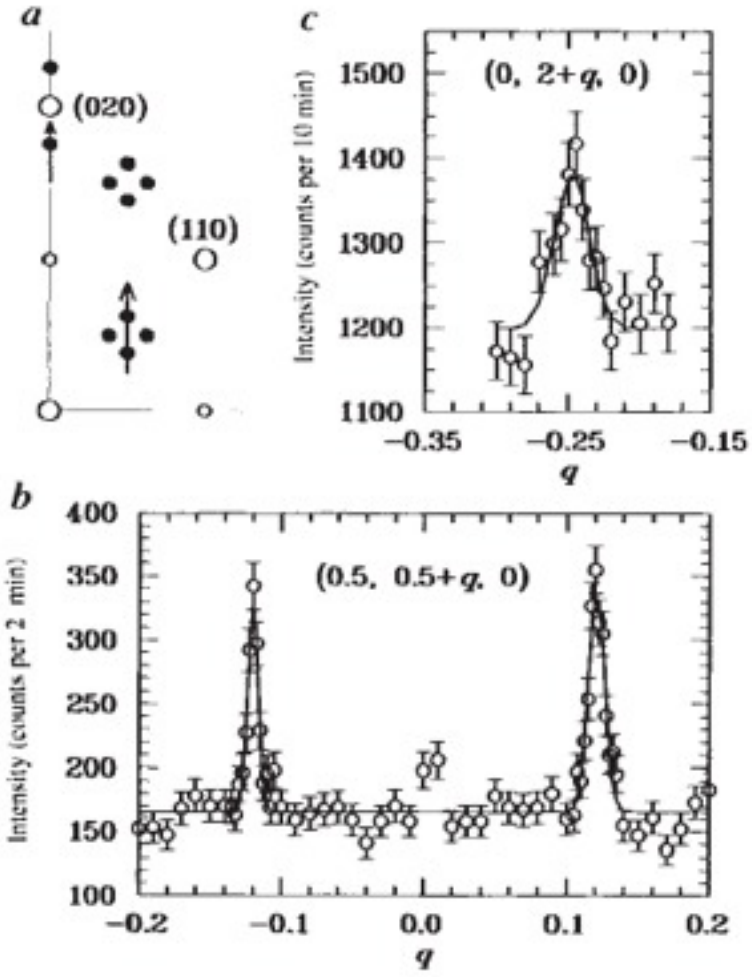
Yamada plot for LSCO

Low frequency dynamic incommensurate spin fluctuations in YBCO but apparently not in Yamada plot (dynamic "spin stripes")

Broken translation symmetry I: charge stripes

Static charge stripes seen in Nd-doped $La_{2-x}Sr_xCuO_4$, and $La_{1.5/8}Ba_{.1/8}CuO_4$





Broken translation symmetry in STM: methods

Tunnel current $I \approx \underbrace{\frac{4\pi e}{\hbar} e^{-s\sqrt{\frac{8m\varphi}{\hbar^2}}}}_{\text{unknown prefactor}} \rho_t(0) \int_{-eV}^{0} \rho_s(\varepsilon) d\varepsilon$

Exploit asymmetry of spectrum

(i) R-map: $R(\vec{r}, V) = \dfrac{I(\vec{r}, s, +V)}{I(\vec{r}, s, -V)}$

[Theory: No double occupancy $\Rightarrow R \sim \dfrac{2x(\vec{r})}{1-x(\vec{r})}$]

(ii) Z-map: $Z(\vec{r}, V) = \dfrac{\frac{dI}{dV}(\vec{r}, s, +V)}{\frac{dI}{dV}(\vec{r}, s, -V)}$

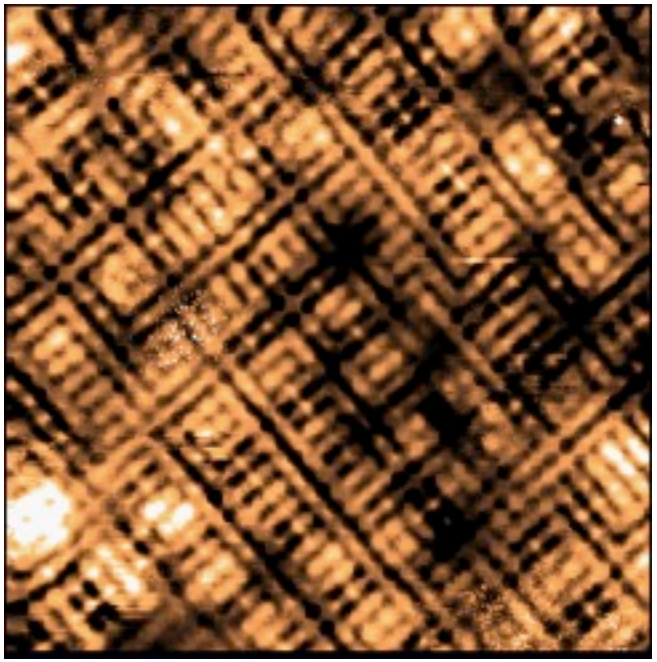
Alternate:

Fourier transform real space $\frac{dI}{dV}$, look for V independant Fourier peak.

Broken translational symmetry in STM: bond-centered `glass'

"R - map"

Kohsaka, ..., Davis
Science'07



12 nm

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$

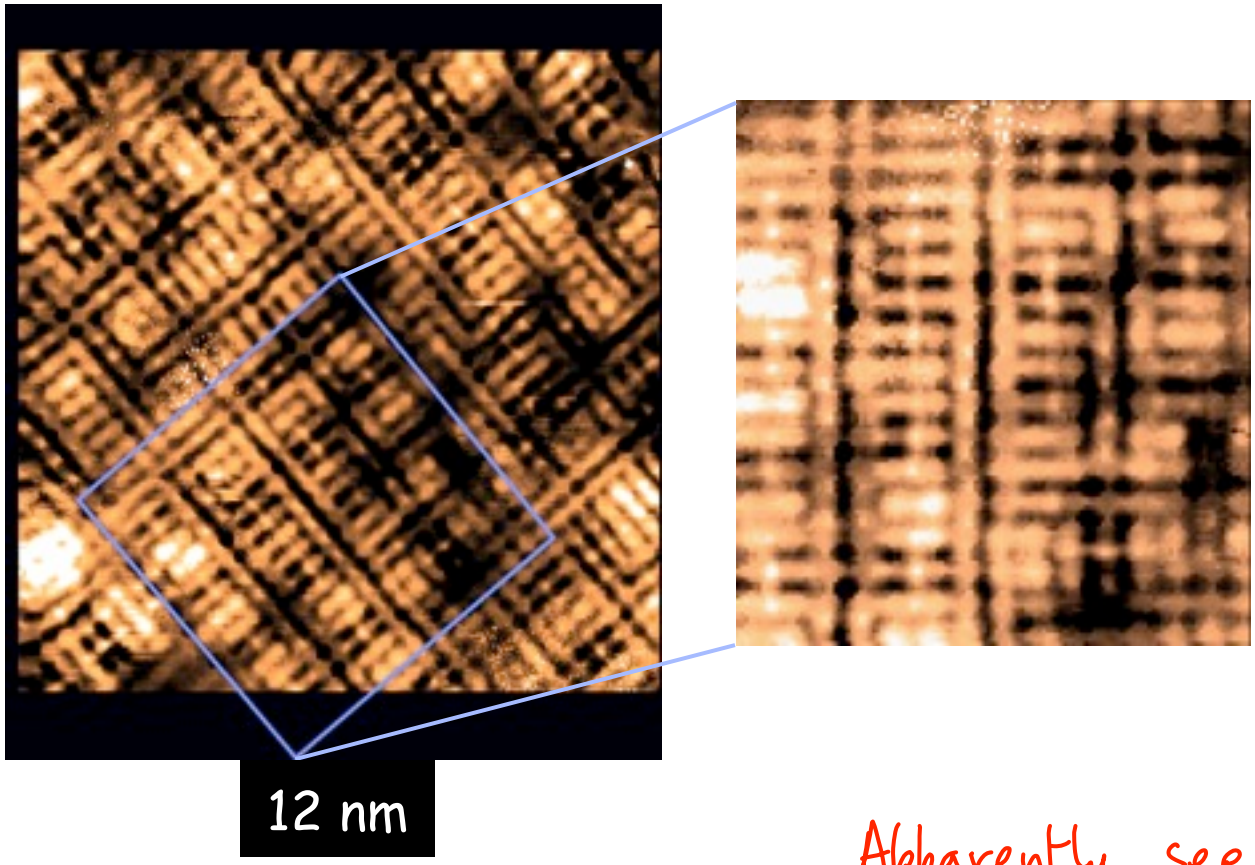
Similar data in Bi-2212

Apparently seen only at very low doping $\lesssim 12\%$

Broken translational symmetry in STM: bond-centered `glass'

"R - map"

Kohsaka, ..., Davis Science'07



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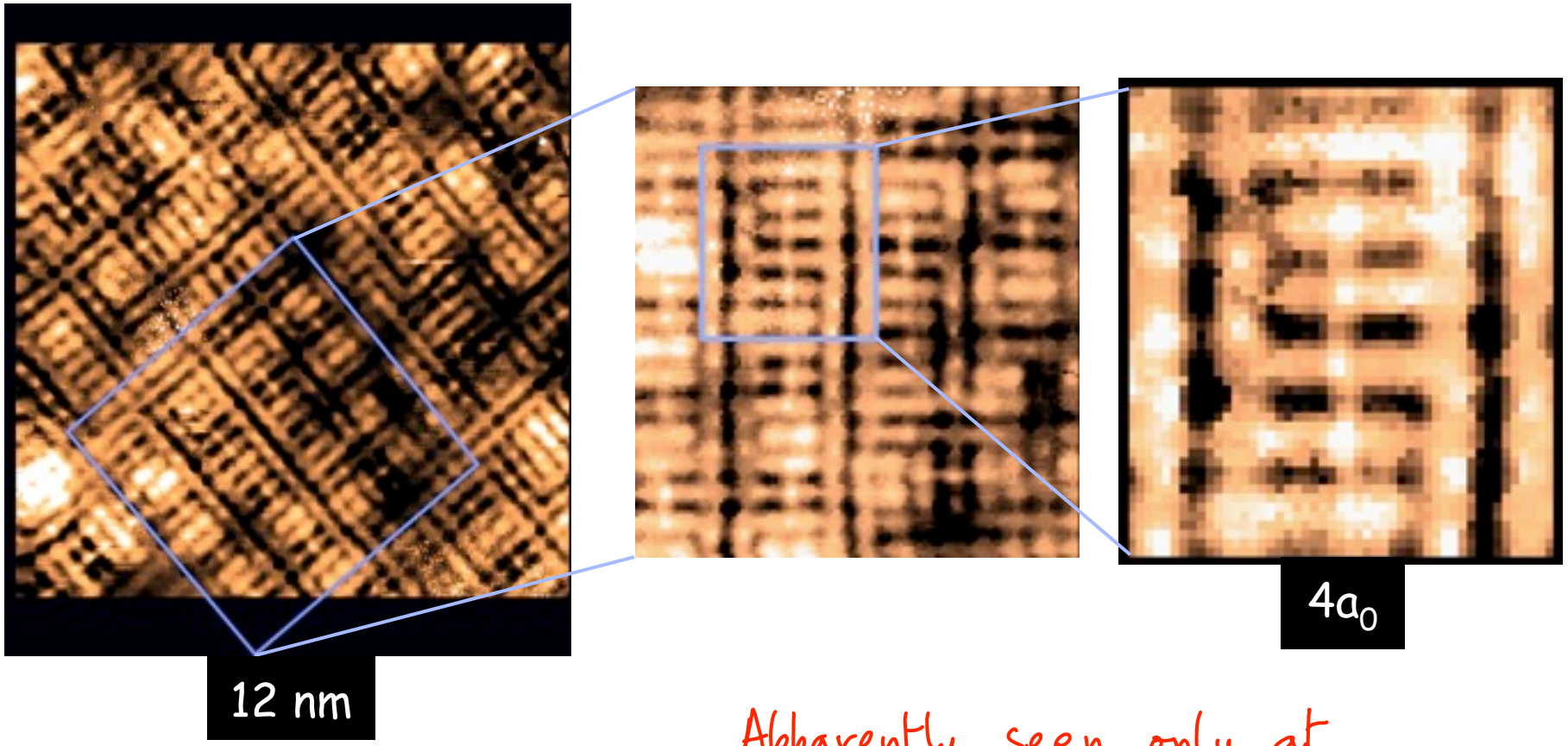

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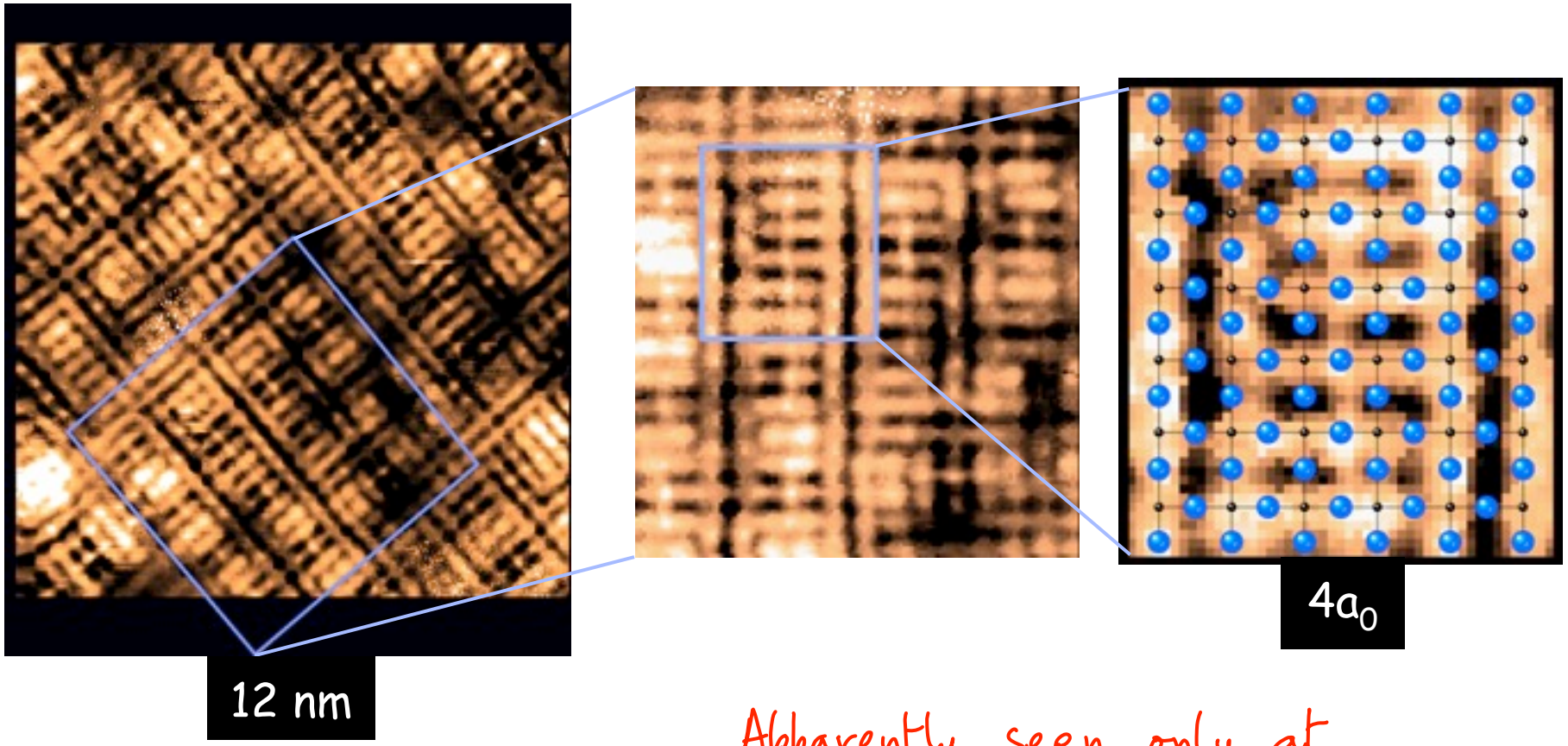

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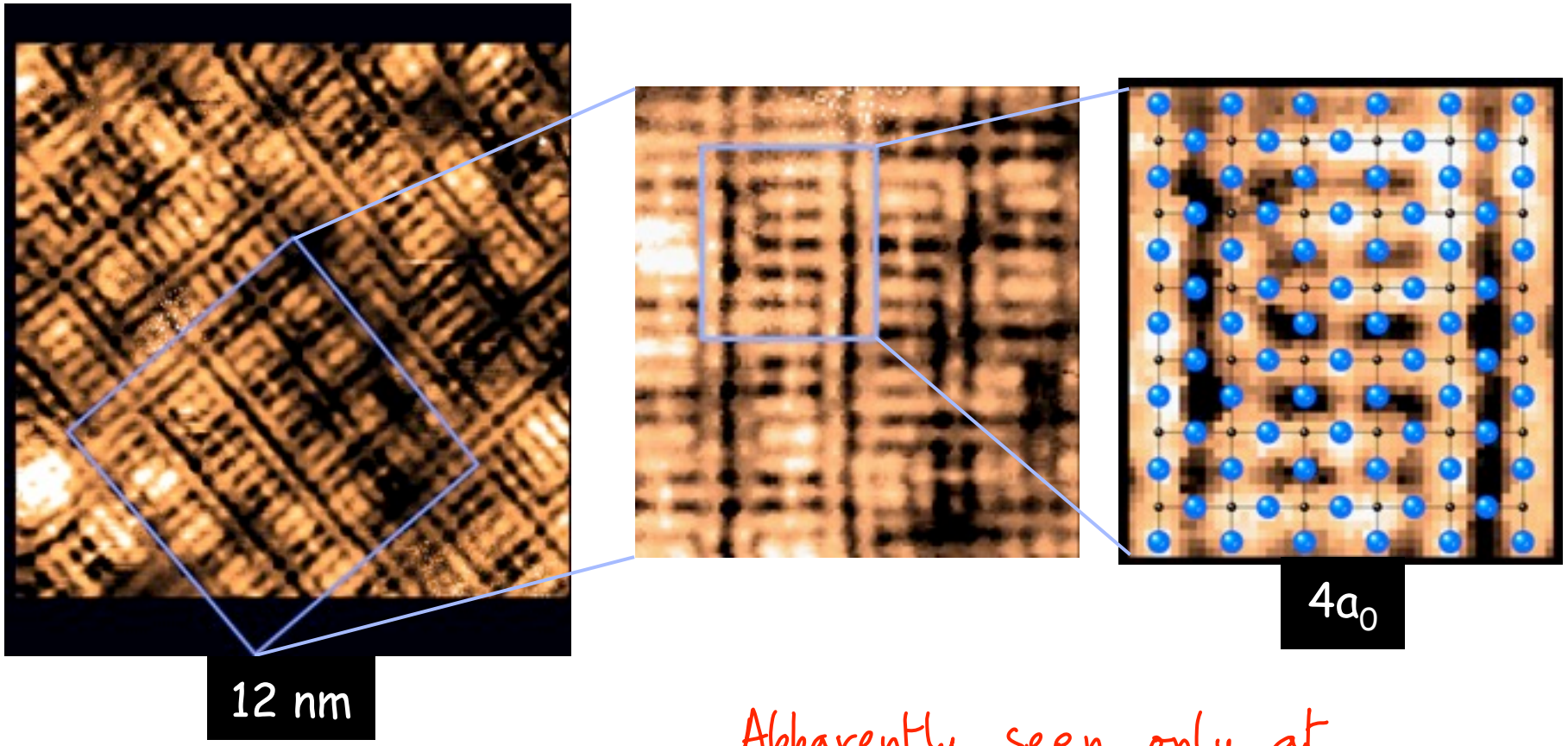


$Ca_{1.88}Na_{0.12}CuO_2Cl_2$

Similar data in Bi-2212

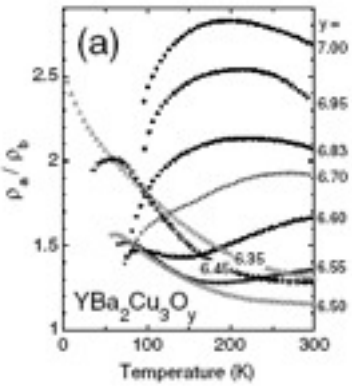
Apparently seen only at very low doping $\lesssim 12\%$

Electronic nematics

Break lattice rotation symmetry without breaking translation symmetry

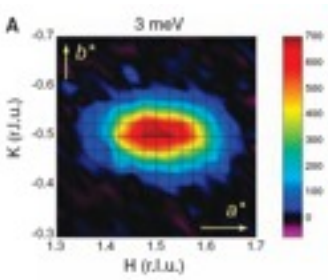
YBCO has no static stripes but seems to develop enhanced "nematic" order below T^*

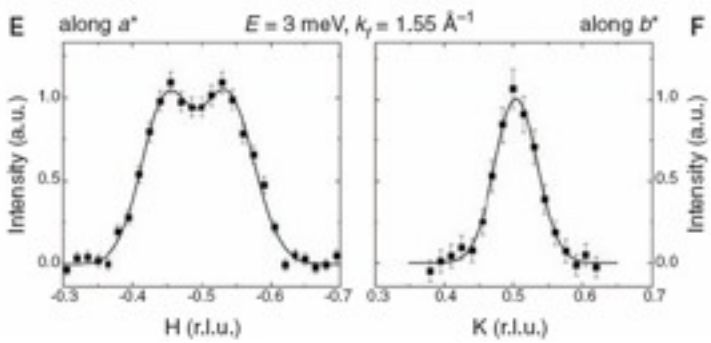
Resistivity anisotropy

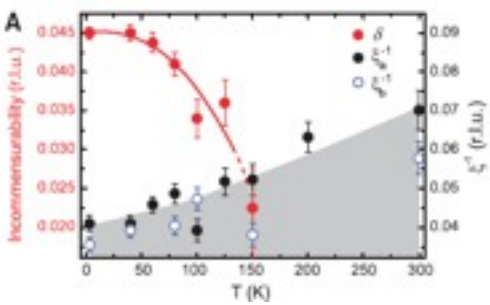


Ando et. al., 2002

Spin fluctuation spectrum $YBCO_{6.45}$ (Hinkov, ..., Keimer, Science 2008)



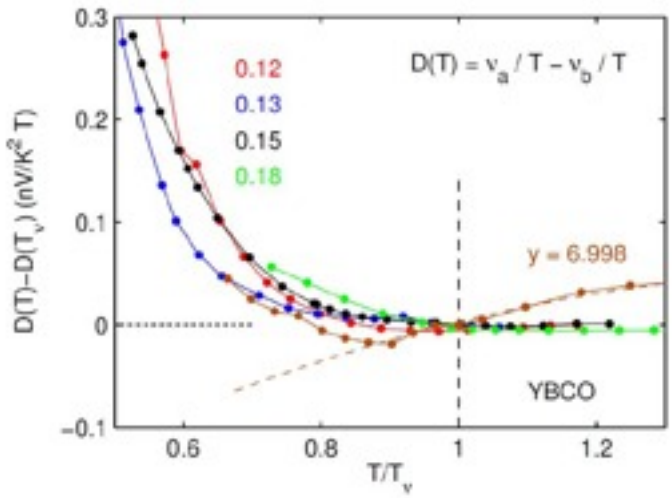


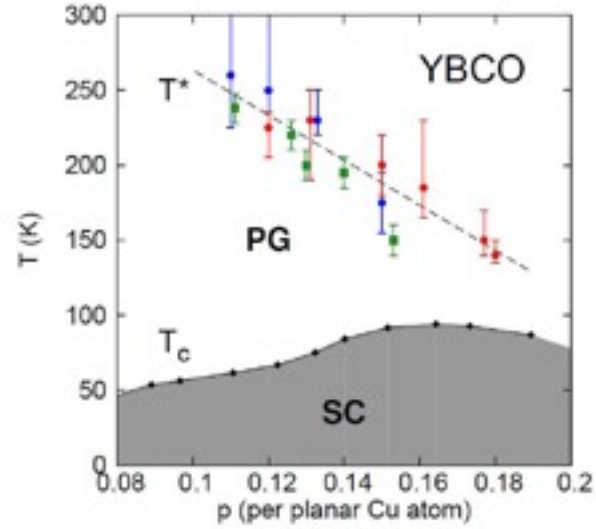


Correlation with T*

Daou, ..., Taillefer, arXiv:0909.4430

Nematic onset roughly at T^*





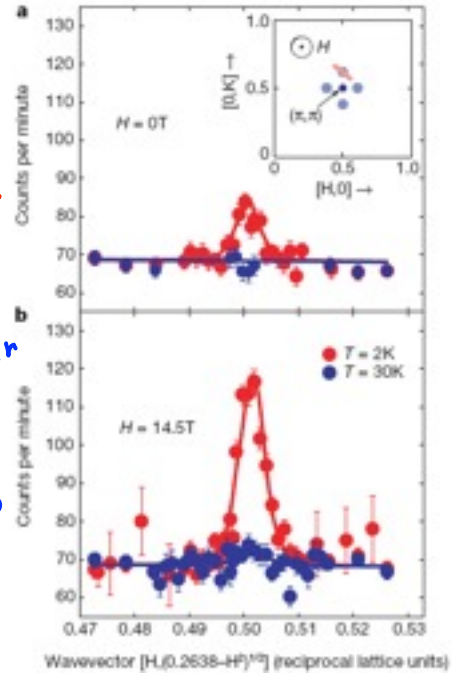
ν = Nernst coefficient

$= E_y / (\nabla T)_x B$

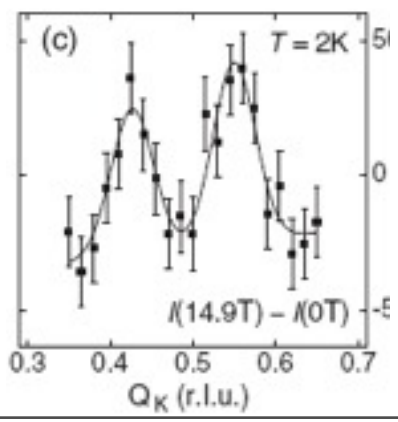
$D(T)$ = anisotropy in ν/T

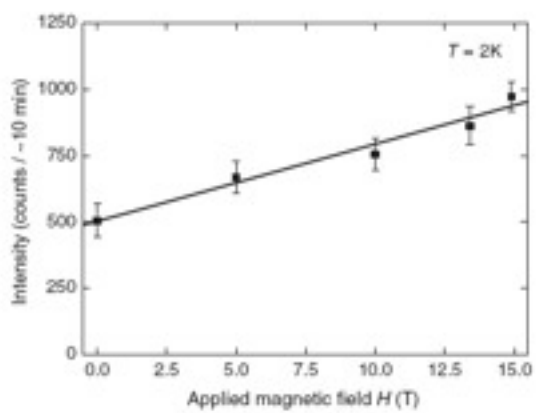
Field induced magnetic ordering at low-T

LSCO
Lake et. al. '02
(Similar data: Khaykovich, et. al. '02)



Magnetic field stabilizes SDW order in favor of superconductivity.





YBCO 6.45
Haug, ..., Keimer, PRL 2009.

SHOULD THE PSEUDOGAP BE UNDERSTOOD AS VALENCE BOND FORMATION OF NEARLY LOCALIZED SPINS WITH MANY COMPETING ORDERS AS CONSEQUENCE ?

OR

IS SOME COMPETING (FLUCTUATING) ORDER THE CAUSE OF PSEUDOGAP ?

Summary of some important underdoped phenomena

1. Antinodal gap ($\gtrsim 50$ meV), gapless. T-dependent Fermi arcs near node

2. "Landau" quasiparticles emerge only below a low "coherence" scale $T_{coh} \approx T_c$

3. Persistence of SC amplitude without phase coherence above T_c (microwave, Ong Nernst/magnetization)

4. Quantum oscillations in a field.

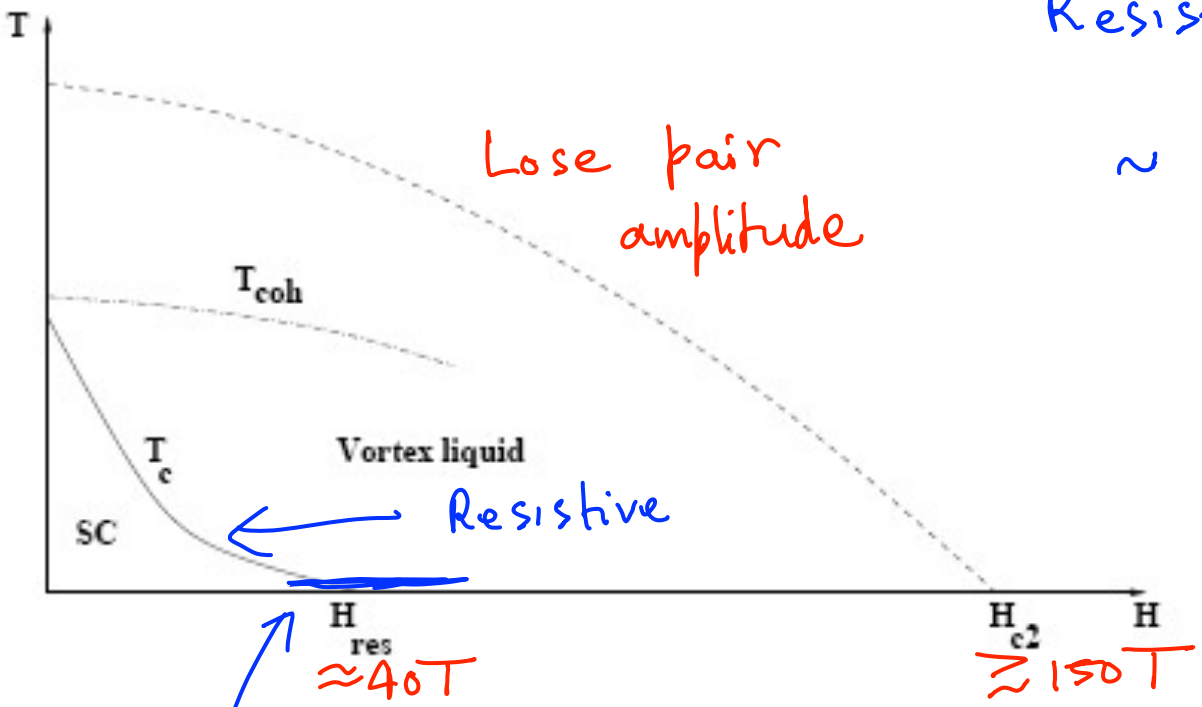
5 Other competing order (eg: SDW, CDW, ...)

Eg: At low-T SDW can be stabilized by magnetic field

A phenomenological synthesis

Coherent picture of results of ARPES, Nernst/magnetization, and quantum oscillations (TS, PAL, 2009)

Ong `high' field phase diagram



Lose pair amplitude

Resistive transition

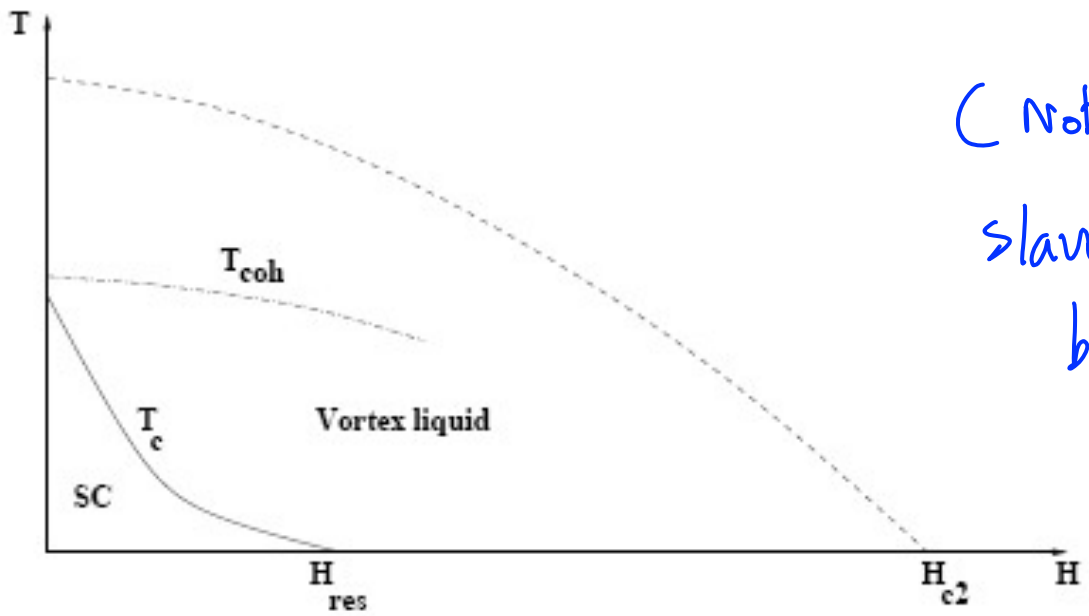
~ melting of vortex solid

(conclusion of Ong et al)

Quantum oscillation expts done here } ⇒ Must understand within framework of "vortex liquid"

Key assumption: Electron coherence in a field

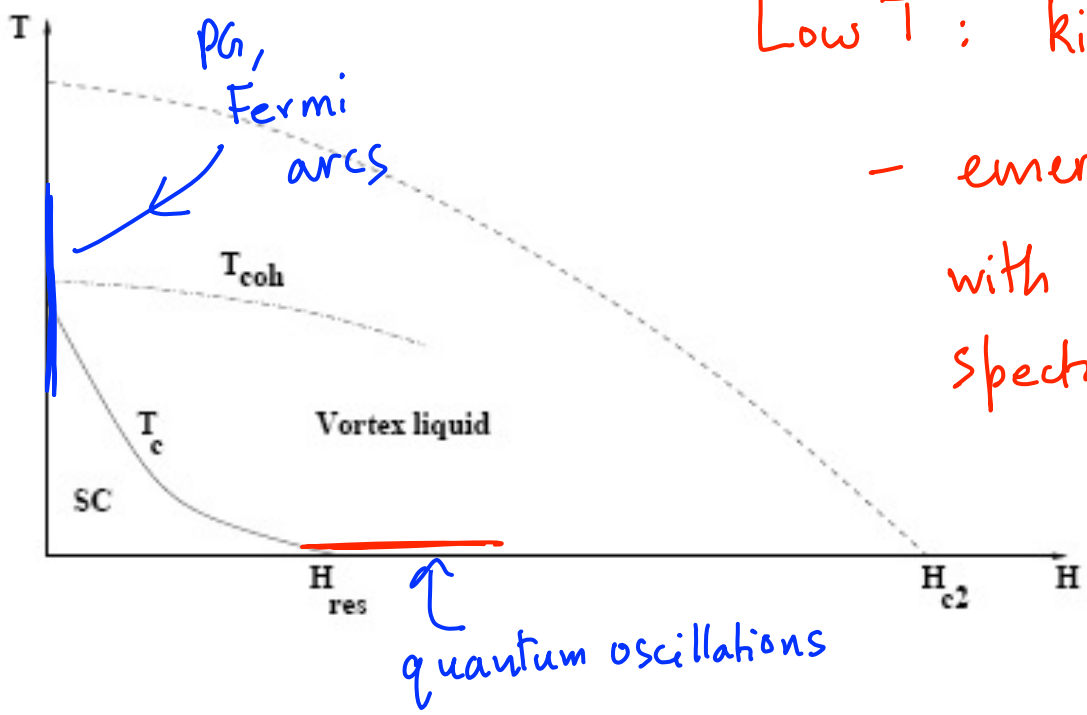
$H \sim 0$ (H_{res}) does not supress T_{coh} to 0 but only T_c.



(Not valid in simplest slave boson theory; need better justification)

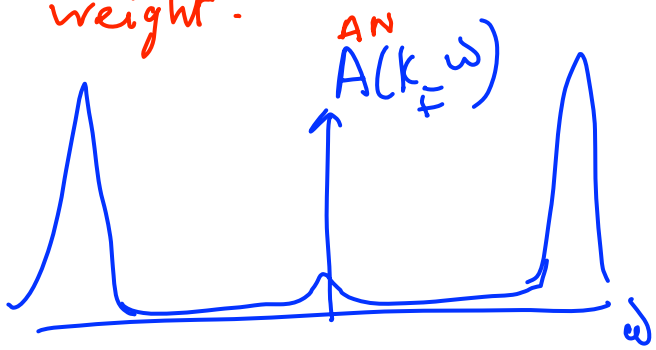
Exptl support: STM tunneling into vortex core (Hudson, Davis 2000)

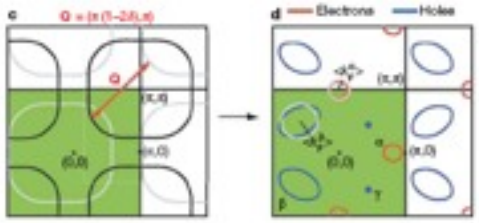
Easier to weaken SC than to kill coherence peak



Low T: kill SC by phase fluctuations

– emergence of large FS with quasiparticles with small spectral weight.





Effect of B-field: induce SDW order to reconstruct Fermi surface

Physics across Tc at zero field

TWO things happen upon crossing T_c (at $H=0$).

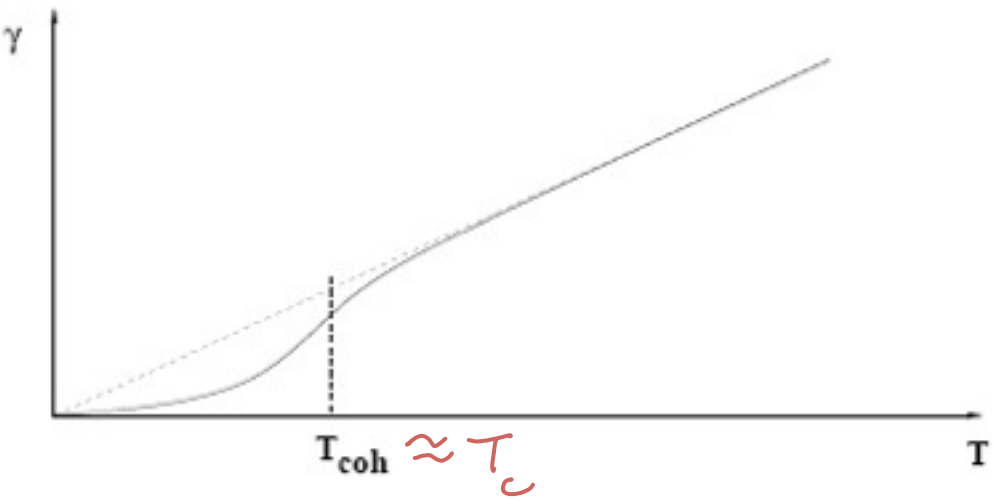
(i) Lose phase coherence of pair order parameter

BUT ALSO

(ii) Lose single particle coherence (as $T_{coh} \approx T_c$)

T_c - not just a phase disordering transition of SC but also a "coherence" transition for electrons

Modeling single particle incoherence



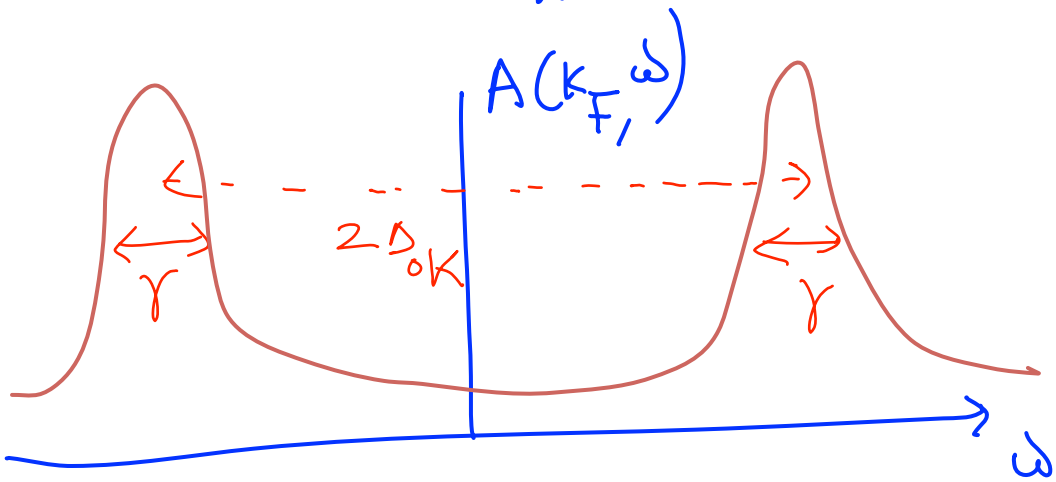
Simplified model: take single particle scattering rate γ = large, $\propto T$ for $T > T_{coh} \simeq T_c$

γ = small, $\lesssim T^2$ for $T < T_c$

Model SC phase disordering as before with a phase decay rate $\Gamma \ll \Delta_0$

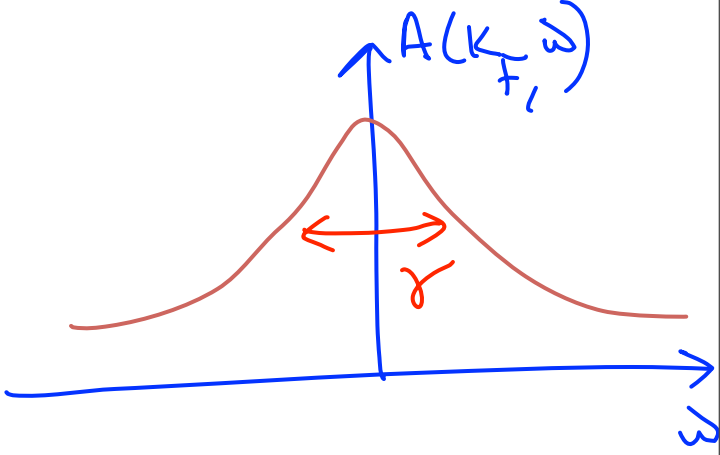
Pseudogap and Fermi arcs

For $\gamma \ll \Delta_{0K}$



"Pseudogap" like

For $\gamma \gg \Delta_{0K}$



"Fermi arc" like

$\gamma \gg \Delta_{0K}$ always satisfied near nodal $\vec{K}$ $\Rightarrow$ get Fermi arcs AND pseudogap

Arc length set by $\gamma \approx \Delta_{0K}$ $\Rightarrow$ decrease as $T \searrow$

(Norman et. al. '98, '07; Chubukov et. al. '08)

Summary of ``synthesis"

1. Quantum oscillations in $T=0$ vortex liquid
   - emergence of large FS
   - reconstruction by field induced SDW

2 Pseudogap / Fermi arcs at $T > T_{coh} \simeq T_c$:
Incoherent single particle excitations + pairing / other order fluctuations

KEY issue for microscopic theory : single particle (in) coherence & interplay with ordering

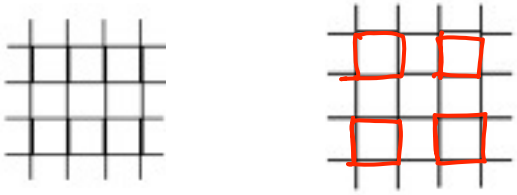
Back to basic theory questions

IS SUPERCONDUCTIVITY POSSIBLE IN A DOPED MOTT INSULATOR?

Many different kinds of studies:

1.1d doped spin ladder:
Zero doping – spin gapped insulator due to valence bond formation.
Dope – (power law) superconductor .

2. Quasi-1d: Weakly coupled ladders



3. Inhomogenous 2d: Checkerboard Hubbard model

4. Superconductivity in doped VBS Mott insulators (`large-N' methods): spontaneously generate weakly coupled ladders.

5. Superconductivity in doped spin liquid Mott insulators (i.e insulators with one electron per site)

ONLY THIS GIVES A ROUTE TO A GAPLESS SUPERCONDUCTOR

Refined basic theory questions

Is superconductivity with gapless nodal excitations possible in a doped Mott insulator?

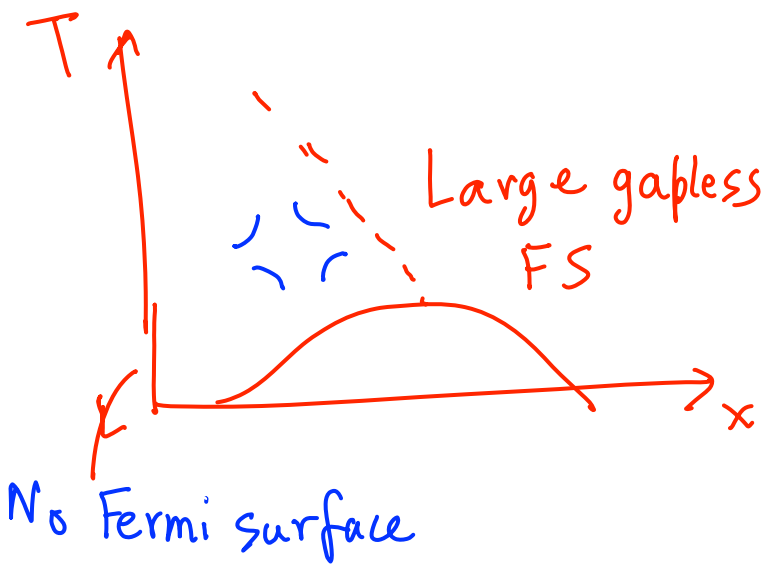
Only currently known route is by doping a gapless spin liquid Mott insulator.

Does this force us to a spin liquid based approach to cuprates?

More questions

More generally, large Fermi surface visible (at least at short time scales) already in underdoped.

How should we understand the emergence of the large Fermi surface in a doped Mott insulator?



Theory: How does the Fermi surface die?

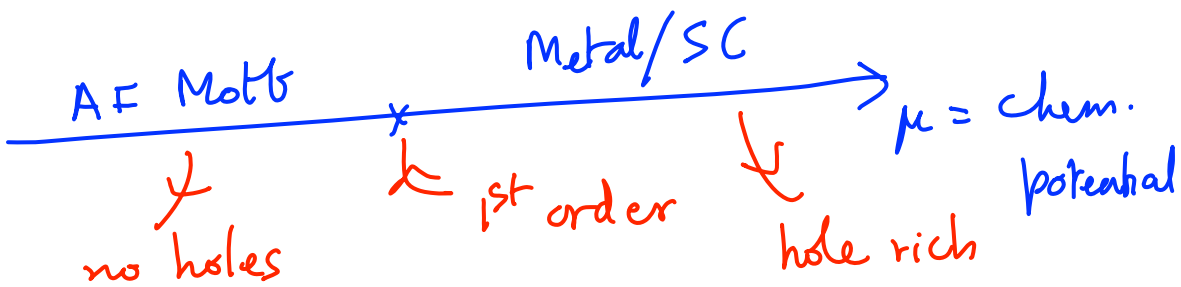
Even more questions

What about antiferromagnetism?

Doped systems have short ranged AF which grows as $x \searrow$

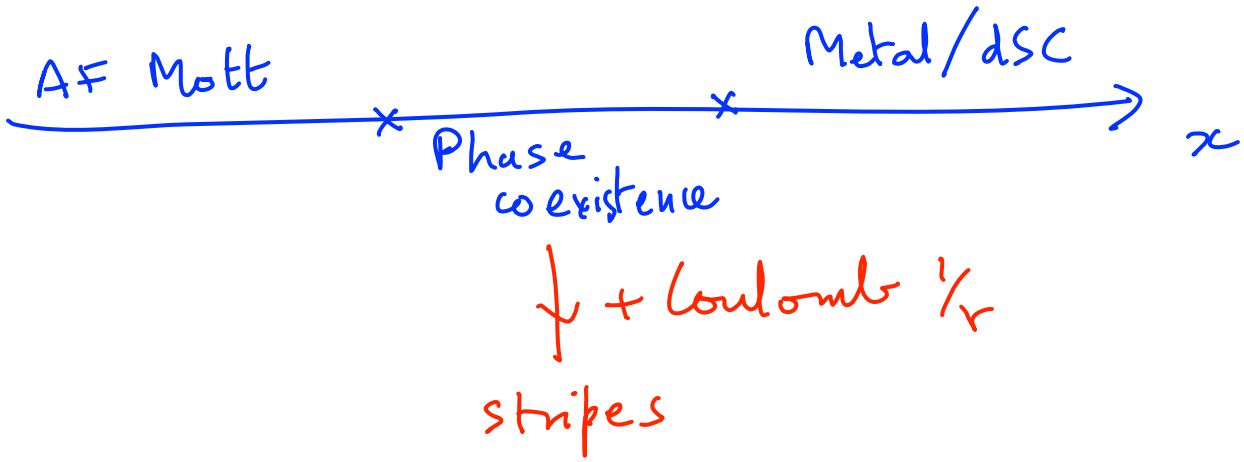
$\Rightarrow$ Did not completely forget origin as doped AF Mott insulator

Likely possibility:



$\Rightarrow$ As function of x, phase separation (stripes)

Last question



Are stripes essential to the story or are they a complication?