Physics of the underdoped cuprates: Phenomenological synthesis and a microscopic theory

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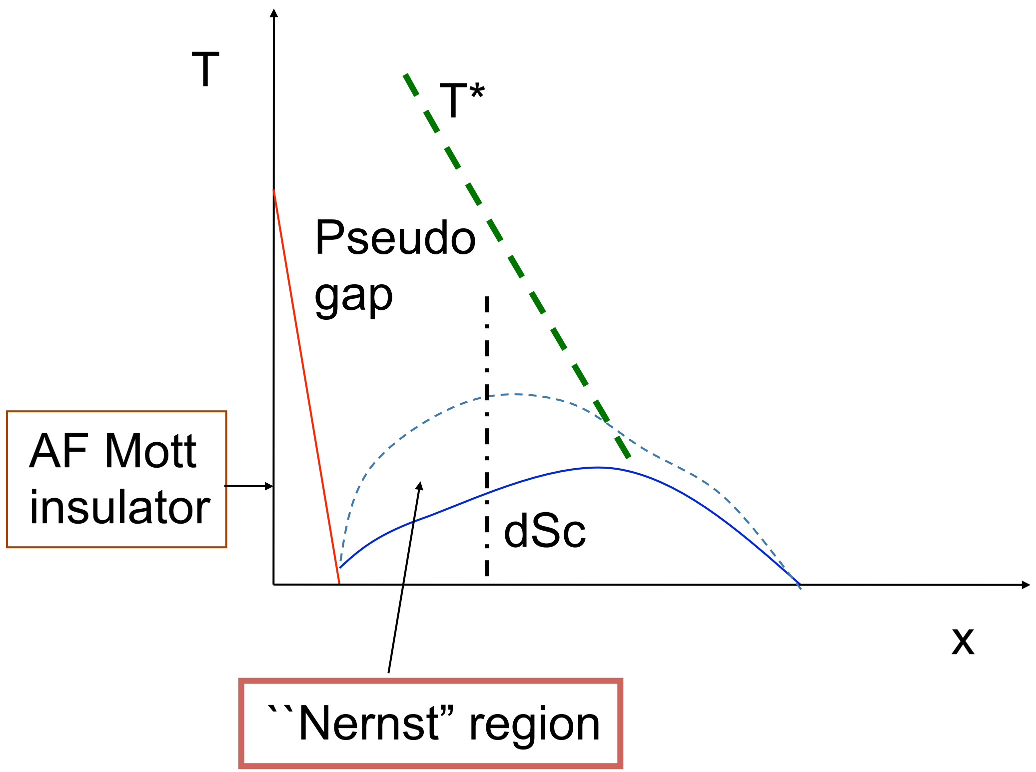
1. T. Senthil and P.A. Lee, PRB 09

2. T. Senthil and P.A. Lee, PRL (to appear), arxiv

Cuprate phase diagram



Focus on pseudo gap state: at not too low doping

Some important phenomena

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

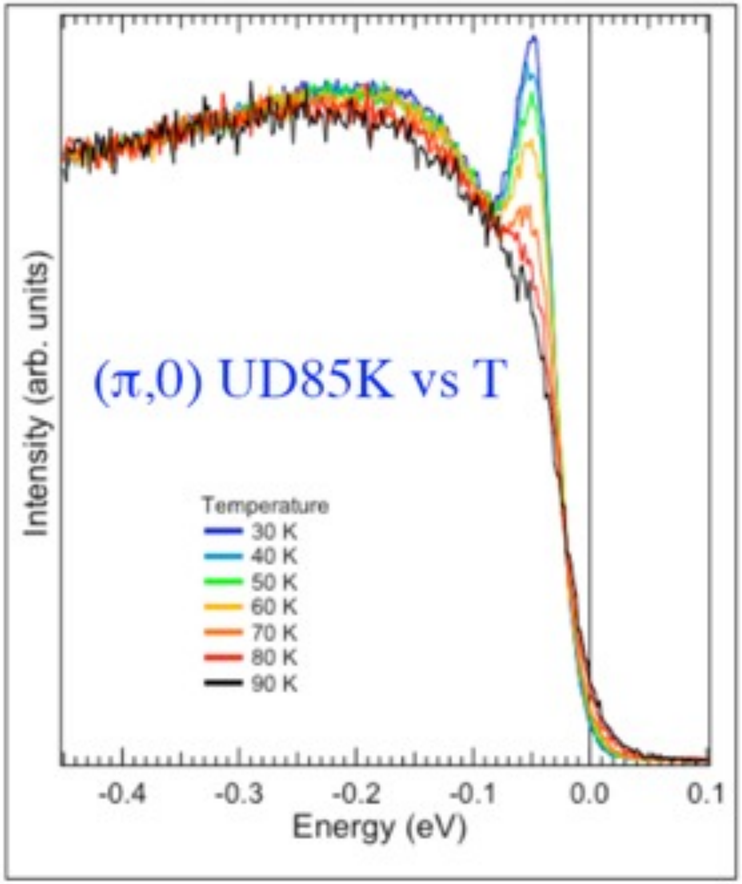
2. "Landau" quasiparticles emerge only below a low "coherence" scale $T_{coh} \approx T_c$

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

4. Other competing order (eg: SDW, CDW, ...)
Eg: At low-T SDW can be stabilized by magnetic field

Pseudogap state in ARPES

(Loeser et al '96, Ding et al '96)



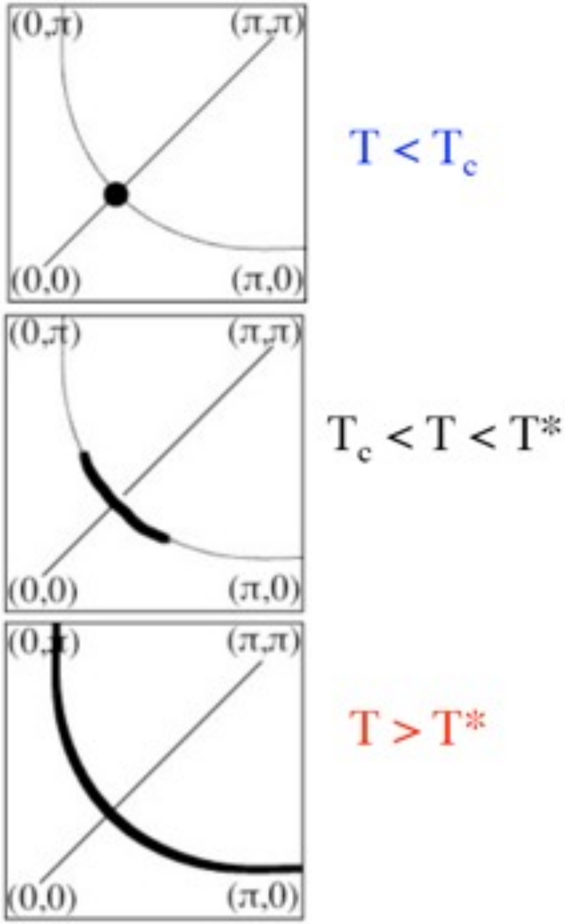
$T < T_c$: "d-wave" anisotropic SC gap $\Delta_{\vec{k}}$

$\Delta_{\vec{k}}$ largest near "antinodal" $(\pi, 0)$ points

$\to 0$ along diagonal "nodal" direction

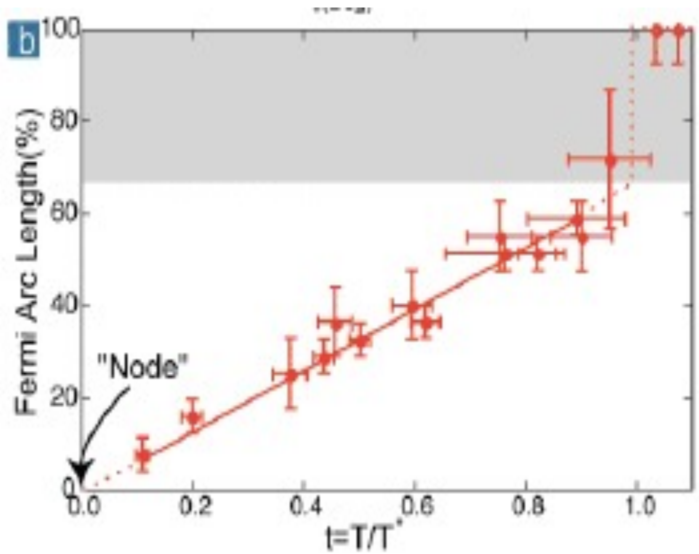
$T > T_c$: Antinodal gap does not close at T_c but persists up to a higher temperature T^*

Gapless Fermi arcs



Arc length decreases with decreasing T at fixed x

(possibily extrapolate to 0 at T→0)

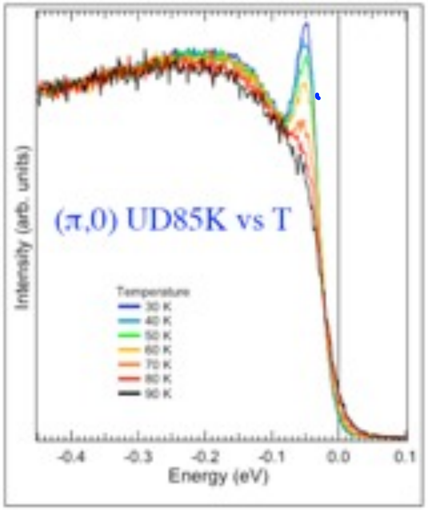


Kanigel et al, Nature Physics '06

Electron coherence crossover

Theory : fairly generic to proximity to Mott transition
(slave boson theory/DMFT)

Expt : 1. Evolution of antinodal spectra across T_c



2. Rapid suppression of scattering rate below T_c in microwave / thermal transport
(Bonn et al.) (Ong et al.)

- also nodal ARPES across T_c (P. Johnson et al)

Field induced incommensurate magnetism

H=0 : Dynamic incommensurate spin fluctuations in underdoped YBCO (Stock, Buyers et al '04)

Field induced SDW.

1. Direct evidence in LSCO family (Lake et. al.),

and in $YBCO_{6.45}$ (Keimer et. al. '09)

2. Indirect: No Zeeman splitting of high field quantum oscillations in $YBCO_{6.5}$

(Sebastian, Harrison, et al '09)

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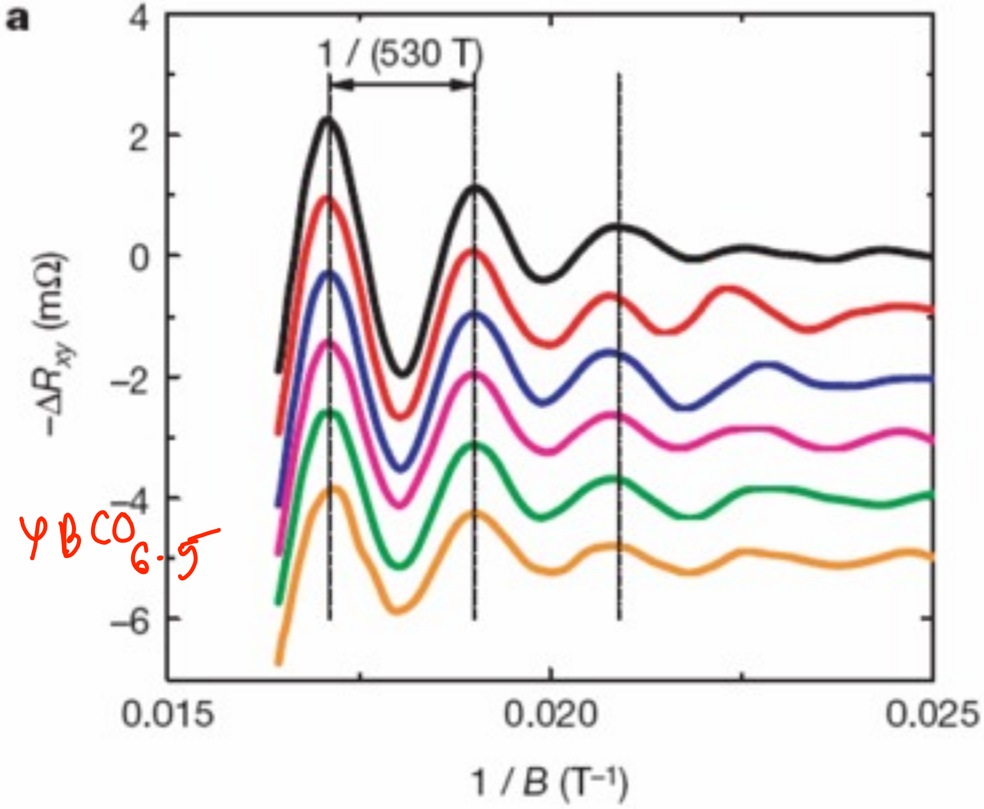
4. Other competing order (eg: SDW, CDW, ...)
Eg: At low-T SDW can be stabilized by magnetic field

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 $YBa_2Cu_4O_8$.

Dominant frequency 530T

$\Rightarrow$ small pocket.

(Proust, Taillefer, ... '07)

Other frequencies with lower amplitude,

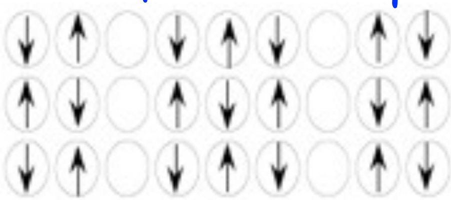
Eg: 1650T (Sebastian et. al. '08)

? Electron pockets ?

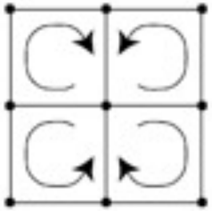
Le Bouef, Taillefer et. al. '08 ($R_H < 0$ at low-T)

Antinodal electron pockets?
- various density wave orderings

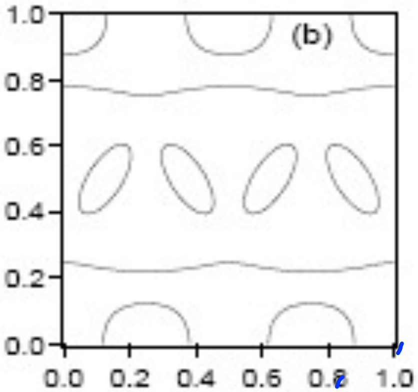
"Antiphase stripe"

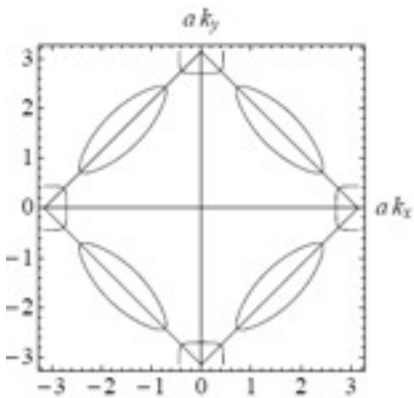


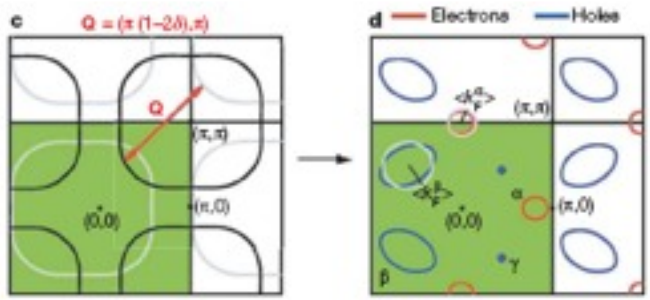
"d-density wave"



Incommensurate spin density wave







Millis, Norman '07

Chakravarty, Kee '08

Sebastian et. al. '08

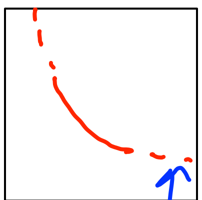
How do all this fit together?

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

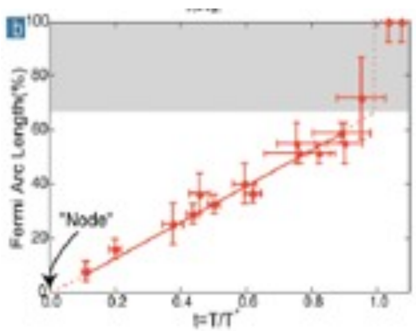
Low T, high H : closed Fermi pocket, possibly near antinode.

$T > T_c$

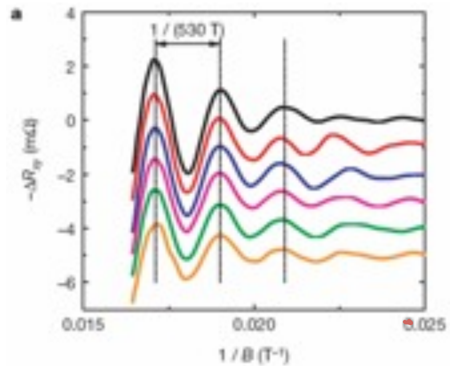
$T \to 0$, $H \approx 50$T



gap



versus



How to fit together?

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

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

H ~ 50 T is actually a small field

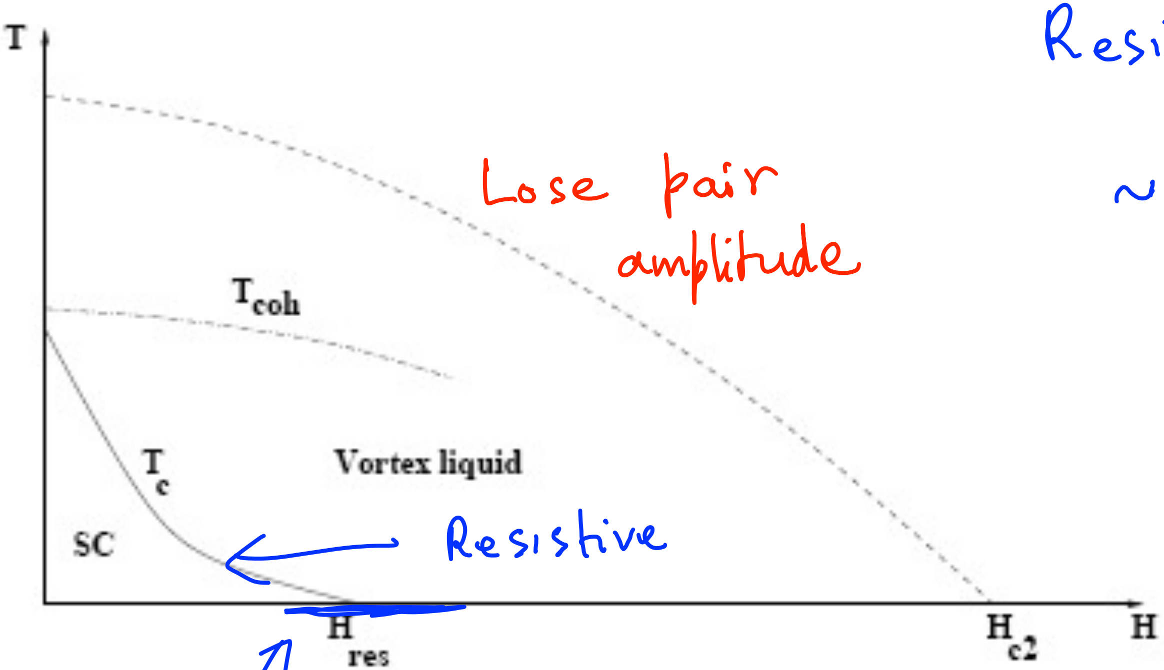
Eg: If Δ_{PG} = "pairing" gap, $H_{c2} \sim \dfrac{\Phi_0}{(\hbar v_F/\Delta)^2} \gg 50\,T$

Plan of this talk

1. A synthesis of the phenomenology
- a coherent picture to reconcile ARPES, Nernst/ magnetization with quantum oscillations.

2. A microscopic theory accessing key aspects of overall picture.

Ong `high' field phase diagram



$\approx 40T$

$\gtrsim 150T$ (conclusion of Ong et al)

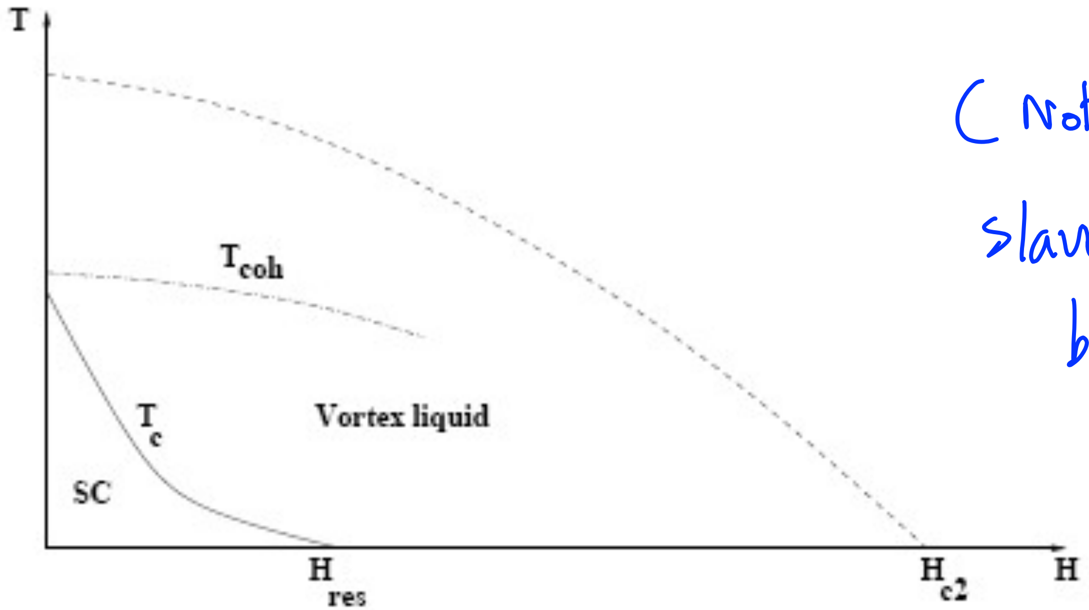
Resistive transition ~ melting of vortex solid

Quantum oscillation expts done here } $\Rightarrow$ Must understand within framework of "vortex liquid"

Key assumption: Electron coherence in a field

$H \sim o(H_{res})$ does not supress T_{coh} to 0

but only T_c.



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

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

Easier to weaken SC than to kill coherence peak

Low T, high H: emergence of large Fermi surface

Quasiparticle Hamiltonian

$T \ll T_{coh} \Rightarrow$ effective quasiparticle Hamiltonian

Let $q^{\dagger}_{\alpha}$ create low energy quasiparticle

Electron operator $c^{\dagger}_{\alpha} \approx \sqrt{Z_0}\, q^{\dagger}_{\alpha} + \dots$

$\left(Z_0 \sim O(x) \right)$

At $H = 0$,

$$\mathcal{H}_{eff} = \sum_k \epsilon_k q^{\dagger}_{k\alpha} q_{k\alpha} + \sum_k \Delta_k \left(q^{\dagger}_{k\uparrow} q^{\dagger}_{-k\downarrow} - q^{\dagger}_{-k\downarrow} q^{\dagger}_{k\uparrow} \right) + h.c$$

$\Delta_k \sim \Delta_0 \left(\cos k_x - \cos k_y \right)$

Model of a vortex liquid

In vortex liquid, d-wave pair order parameter

$$\rightarrow \Delta(\vec{R},\tau) = \Delta_0 \, e^{i\phi(\vec{R},\tau)}$$

($\Delta(\vec{R}\,\tau)$ couples to d-wave singlet pair with center of mass at $\vec{R}$).

Take $\langle \Delta^*(R\,\tau)\,\Delta(0\,0)\rangle = \Delta_0^2 \, F(\vec{R}\,\tau)$

with $F(0,0) = 1$

$$F(|\vec{R}| \to \infty, \tau) \sim e^{-|\vec{R}|/\xi_\phi} \; ; \; F(|\vec{R}|, \tau \to \infty) \sim e^{-|\tau|\Gamma}$$

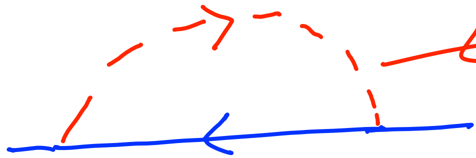
($\Gamma^{-1} \equiv \tau_\phi$ = pair phase memory time)

Electronic structure of the vortex liquid

Quasiparticles scatter off fluctuating pair field

Calculate self-energy in 2^{nd} order perturbation theory

$$\Sigma(\vec{k}, \omega) =$$



pair propagator

$\Rightarrow$

$$\Sigma(\vec{k}=\vec{k}_F, \omega) = \frac{\Delta_{0k}^2\, \omega}{\pi \Gamma^2}$$

for small ω (like in Fermi liquid)

$$\approx -\frac{\Delta_{0k}^2}{\omega + \epsilon_k}$$

for $|\omega| \gg \Gamma$ (like in dSC)

Approximate self-energy

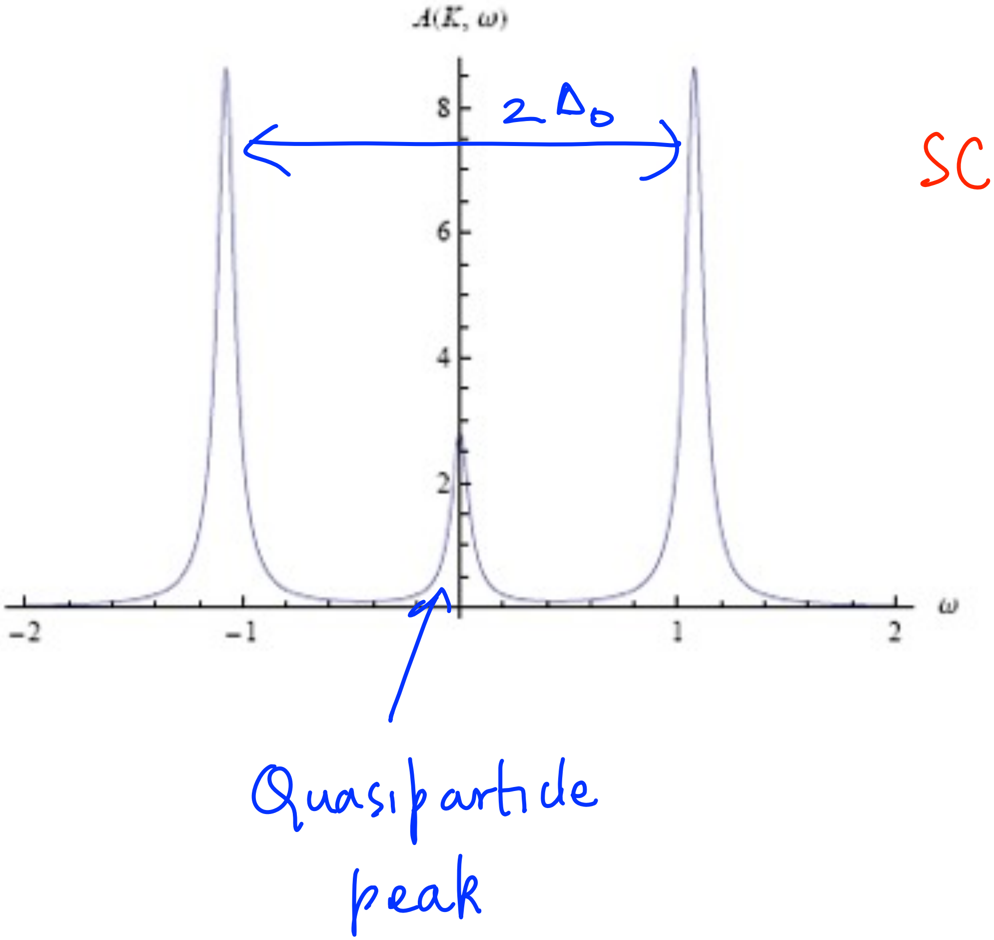
$$\Sigma(\vec{k}, i\omega) \simeq \frac{\Delta_{0k}^2 \left(-i\omega + \epsilon_k\right)}{-\omega^2 + \epsilon_k^2 + \pi\Gamma^2}$$ interpolates between both limits

Quasiparticle pole at "large" Fermi surface

with residue $Z_\Delta = \dfrac{1}{1 + \dfrac{\Delta_{0k}^2}{\pi\Gamma^2}}$.

$$\Rightarrow \quad Z_\Delta^{\text{nodal}} \simeq 1 \quad ; \quad Z_\Delta^{\text{anti-nodal}} \simeq \frac{\pi\Gamma^2}{\Delta_0^2} \ll 1$$

Antinodal spectral function



Physical picture :

SC for time scales $\ll \tau_\phi$

length scales $\ll \xi_\phi$

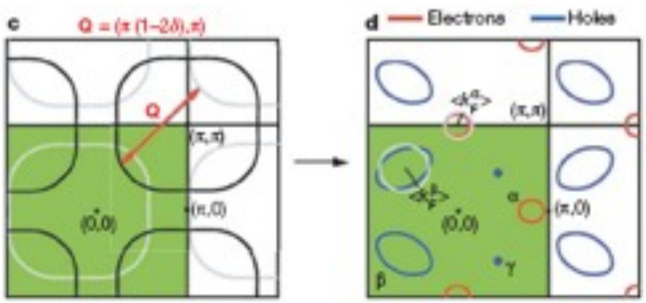
but metal with large Fermi surface at longer scales

Effect of magnetic field

1. Usual Landau quantization of orbits

2. Field induced SDW ordering

$\Rightarrow$ reconstruction of emergent large Fermi surface into electron & hole pockets



Can now follow previous papers (Millis, Norman, Sebastian, ...) to understand quantum oscillations

Picture at low T, high H

Emergence of large Fermi surface metal in vortex liquid at low-T.

Pseudogap does not close but mid-gap states with low spectral weight are produced.

Large Fermi surface metal — precondition for field induced SDW to do the job of reconstruction to produce electron/hole pockets

Crucial question: how to reconcile with high T, low H phenomena?

Physics across Tc

<u>TWO</u> things happen upon crossing T_c (at $H=0$).

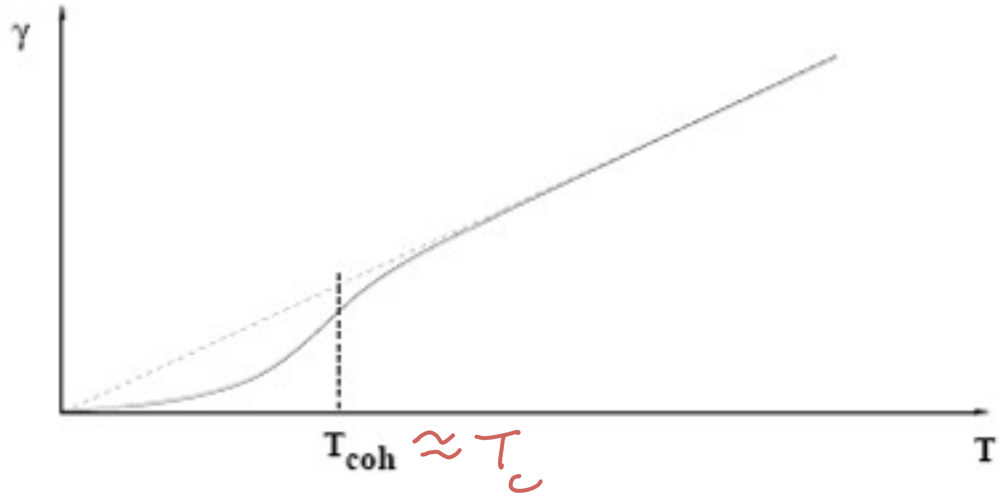
(i) Lose phase coherence of pair order parameter

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

Take vortex liquid self energy from before and let $\omega \to \omega + i\gamma$

$$\Rightarrow \Sigma_R(\vec{k}, \omega) \simeq \frac{\Delta_{0k}^2 (\omega - \epsilon_k + i\gamma)}{(\omega + i\gamma)^2 - \epsilon_k^2 - \pi \Gamma^2}$$

γ: electron decay rate

Γ: Pair decay rate

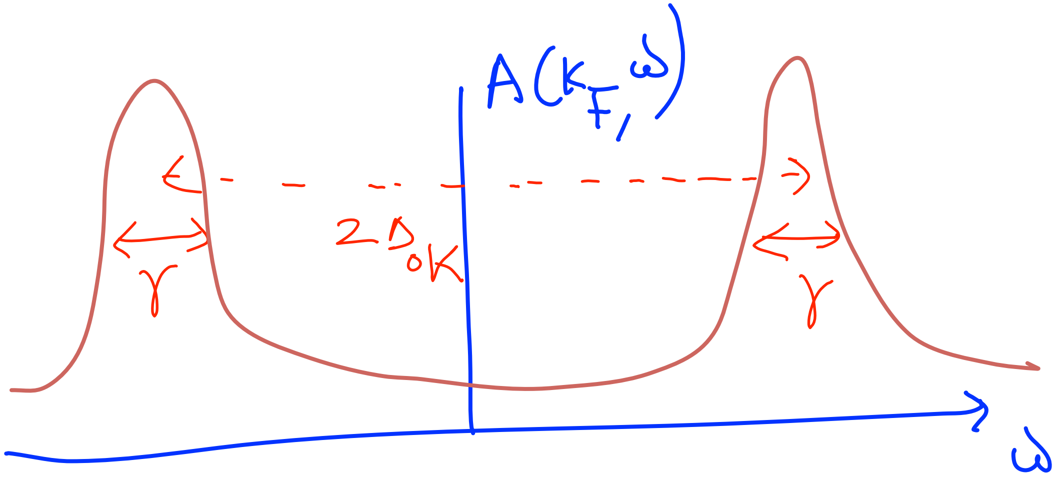
For $\Gamma \ll \min(|\omega|, \gamma)$

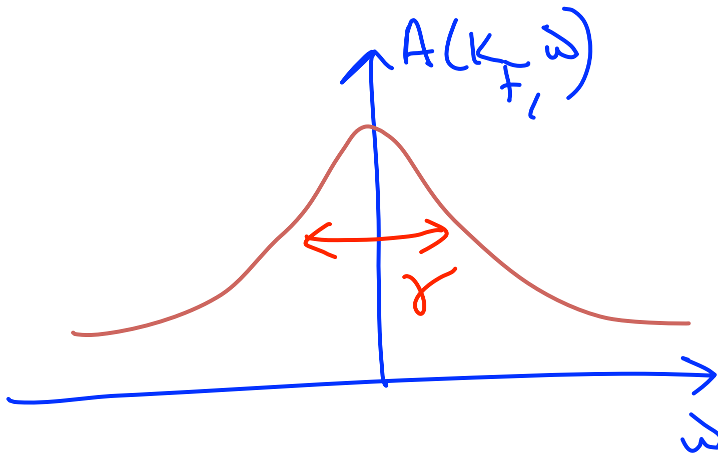
$$\Sigma_R(\vec{k}, \omega) \approx \frac{\Delta_{0k}^2}{\omega - \epsilon_k + i\gamma}$$

= self-energy similar to Norman et al '98, '07 to fit ARPES data

Pseudogap and Fermi arcs

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





"Pseudogap" like "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 part 1

1. Quantum oscillations in $T=0$ vortex liquid

- emergence of large FS
- reconstruction by field induced SDW

2 Pseudogap / Fermi arcs at $T > T_{coh} \approx T_c$:

Incoherent single particle excitations + pairing / other order fluctuations

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

Part 2: A microscopic theory

Revisit slave boson theory of doped t-J model.

$$\mathcal{H} = -t \sum_{\langle ij \rangle} \left(c_i^\dagger c_j + h.c \right) + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

$c_i^\dagger c_i \leq 1$. $\Rightarrow$ solve by $c_{i\alpha} = b_i^\dagger f_{i\alpha}$

holon spinon

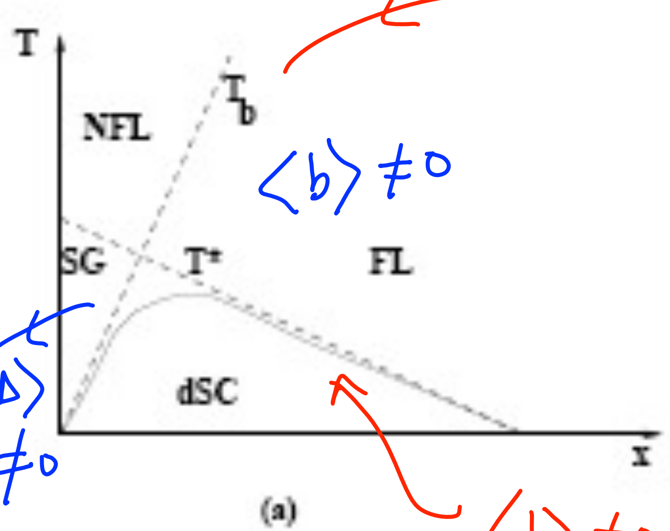
U(1) phase redundancy

$\Rightarrow$ action $S = S[b, f, a_\mu]$

U(1) gauge field

``Standard" slave boson RVB theory of doped Mott insulator

coherence scale $T_{coh} \simeq$ "Higgs" condensation of b



$\langle b \rangle \neq 0$

$\langle \Delta \rangle \neq 0$

$\langle b \rangle \neq 0$, $\langle \Delta \rangle \neq 0$

$\Delta \sim f^\dagger f^\dagger$

Old problem: T_{coh}, T_c far too <u>high</u>.

Fluctuations: Gauge theory; Landau-damped dynamics for transverse gauge field

$$S_{eff}[a] = \int d^2q \, d\omega \left(\frac{|\omega|}{q} + q^2 \right) |a(q\omega)|^2 \quad (\text{at high-}T)$$

True coherence scale: Anderson is different

(TS '08)

"Naive" coherence scale: Higgs condensation of b

For $T \ll T_b$, $S_{eff}[a] \simeq \int_{q,\omega} \left(\frac{|\omega|}{q} + q^2 + \rho_{bs} \right) |a(q,\omega)|^2$

phase stiffness of b $\sim O(T_b)$

Landau-damped dynamics

$\Rightarrow$ Anderson "plasmonization" scale $\approx \rho_{bs}^{3/2} \ll T_b$

$\Rightarrow$ Anderson differs from Higgs parametrically!

True coherence scale: Anderson is different

(TS '08)

Intermediate energies - holons "condensed" but a_μ "gapless"

$\Rightarrow$ Electrons strongly scattered by a_μ fluctuations

True coherence scale = Anderson scale

$$T_{coh} \sim T_b^{3/2} \ll T_b \; (= \text{"Higgs" scale})$$

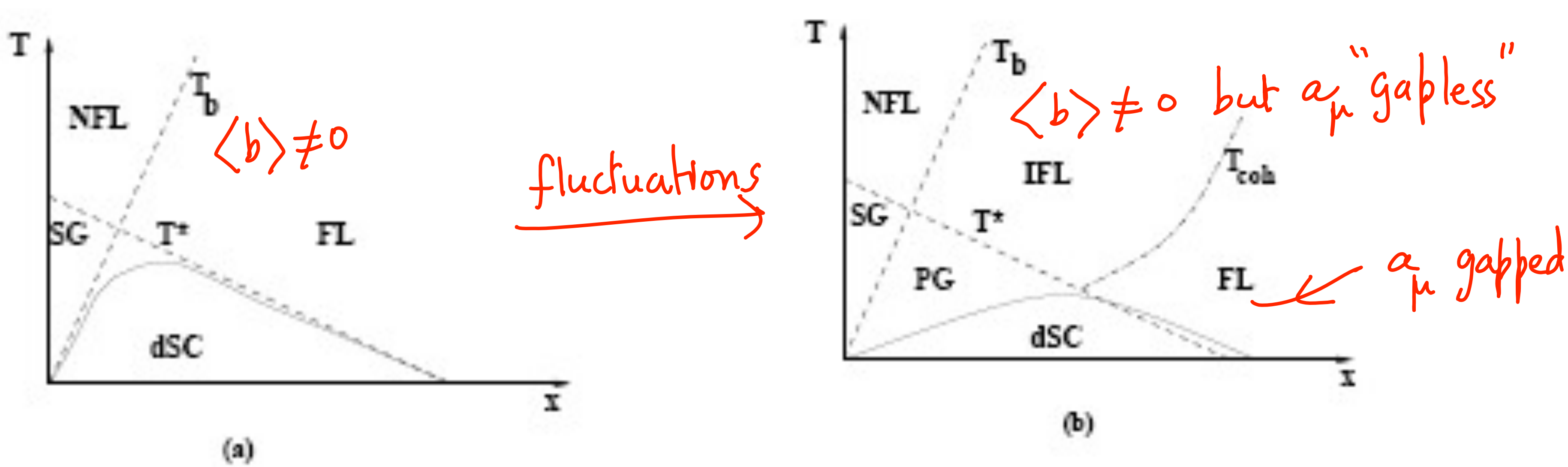
"INCOHERENT FERMI LIQUID" (IFL)

for $T_{coh} \ll T \ll T_b$ as a description of "strange optimal doped metal"

Modified slave boson gauge theory

(TS, Lee '09)

IFL regime: linear-T single particle scattering rate
+ other non-fermi liquid properties



Underdoped: IFL $\rightarrow$ pseudogap (PG) state

Underdoped: theory of a pseudogap state

$$S = S_{IFL} + \int_{x\tau} \Delta^*(x\tau)\,(\psi_\uparrow \psi_\downarrow) + h.c$$

fluctuating d-wave pair field

Pair amplitude gaps out antinode of IFL ($\Rightarrow$ pseudogap)

but nodal Fermi arc and linear-T scattering rate survive down to $T \approx T_c$

($\Rightarrow$ in underdoped $T_{coh} \approx T_c$, and not supressed by H-field)

Problems with the theory

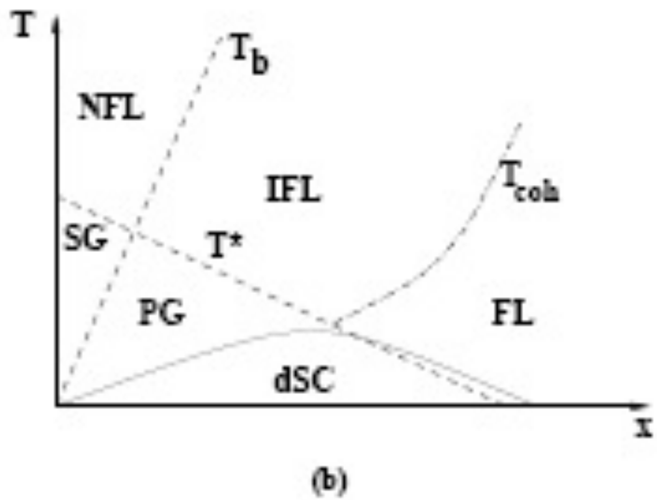
Biggest difficulty : In IFL, transport scattering rate $\gamma_{tr} \sim T^{4/3}$ ($\neq$ single particle scattering rate $\propto T$)

$\Rightarrow$ Resistivity $\rho \sim T^{4/3}$ in this theory

in disagreement with famous linear resistivity.

?? Is there a fix ??

Summary: Part II



New non-fermi liquid regimes overlooked in standard slave boson gauge theory: updated phase diagram

Interesting description of a candidate strange metal and a descendant pseudogap state with gapless Fermi arcs.

But some difficulties with experiments persist.