Fermi surface symmetry breaking and Fermi surface fluctuations

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1. Pomeranchuk instability
   (symmetry-breaking Fermi surface deformations)
2. Soft Fermi surface and Non-Fermi liquid behavior
3. Experimental signatures – cuprates

Collaborators:

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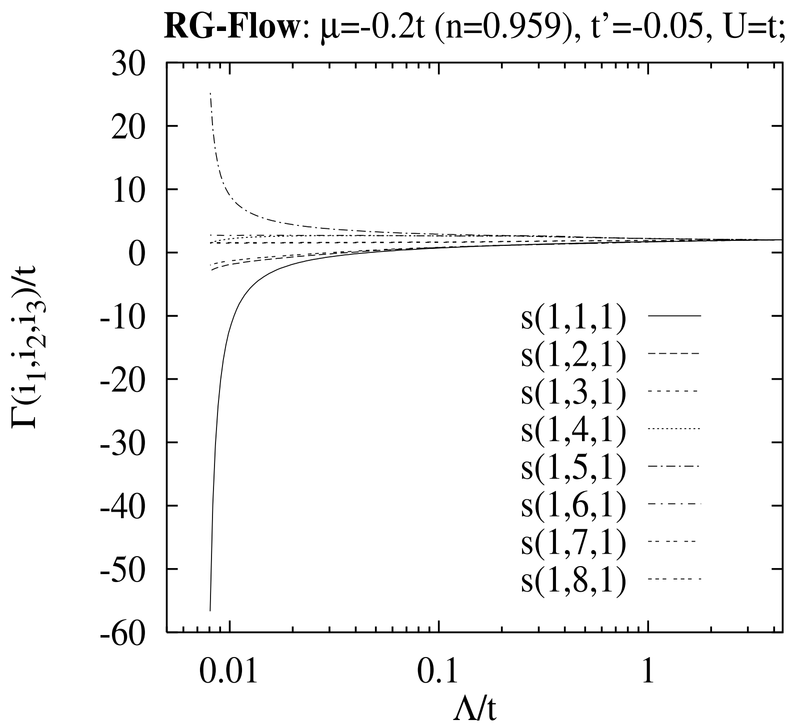
1. Pomeranchuk instability

RG flow of forward scattering interactions (singlet part) in 2D Hubbard model

Halboth + wm '00

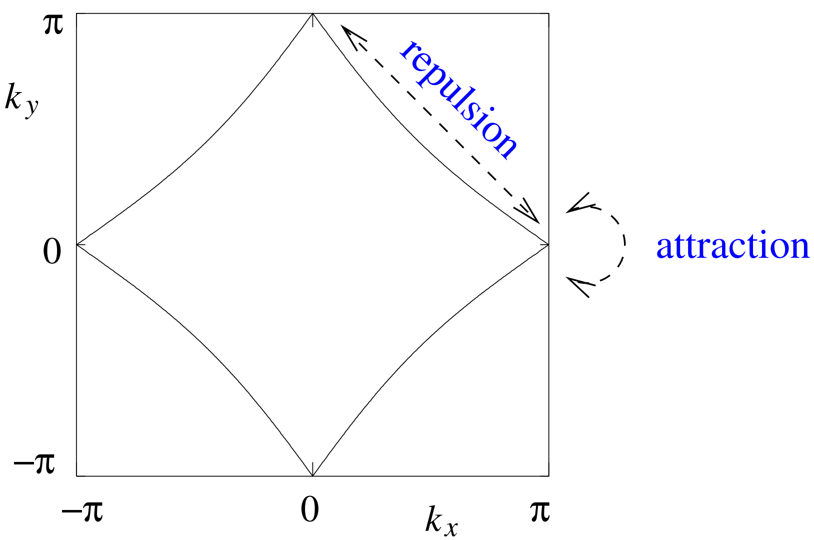


Forward scattering interaction $f_{\mathbf{k}_F\mathbf{k}'_F}$ with attractive d-wave component; small Fermi velocity $\mathbf{v}_{\mathbf{k}_F}$ near saddle points of $\epsilon_{\mathbf{k}}$

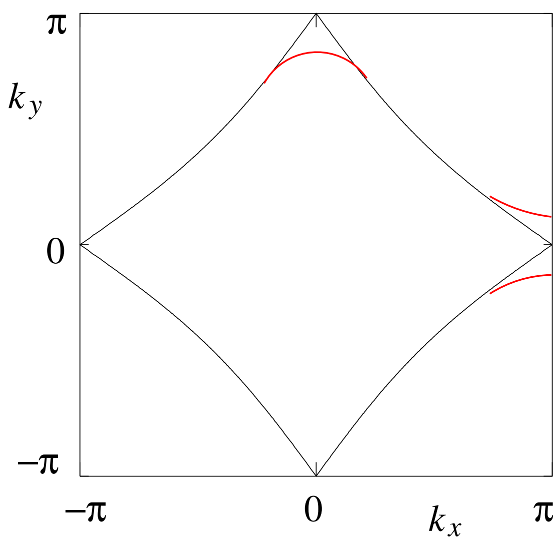
$\Rightarrow$ d-wave Fermi surface deformations easy (low energy cost)

Symmetry-breaking Fermi surface deformation ("Pomeranchuk instability")

Quasi-particle interactions:



Reshaping of Fermi surface



Tetragonal symmetry broken !

Realization of "nematic" electron liquid (→ Kivelson et al. '98)

See also: Yamase, Kohno '00 (tJ-model)

Phenomenological 2D lattice model:

$H = H_{\rm kin} + \frac{1}{2V} \sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} f_{\mathbf{k}\mathbf{k}'}(\mathbf{q})\, n_{\mathbf{k}}(\mathbf{q})\, n_{\mathbf{k}'}(-\mathbf{q})$

where $n_{\mathbf{k}}(\mathbf{q}) = \sum_\sigma c^\dagger_{\mathbf{k}-\mathbf{q}/2,\sigma}\, c_{\mathbf{k}+\mathbf{q}/2,\sigma}$

and only small momentum transfers $\mathbf{q}$ contribute (forward scattering)

Interaction with uniform repulsion and d-wave attraction:

$f_{\mathbf{k}\mathbf{k}'}(\mathbf{q}) = u(\mathbf{q}) + g(\mathbf{q})\, d_{\mathbf{k}}\, d_{\mathbf{k}'}$

with $d_{\mathbf{k}} = \cos k_x - \cos k_y$ and $u(\mathbf{q}) \geq 0$, $g(\mathbf{q}) < 0$

(*qualitatively* as from RG)

yields Pomeranchuk instability

Similar model without u-term for *isotropic* (not lattice) system
by Oganesyan, Kivelson, Fradkin '01

Mean-field phase diagram ($u = 0$):

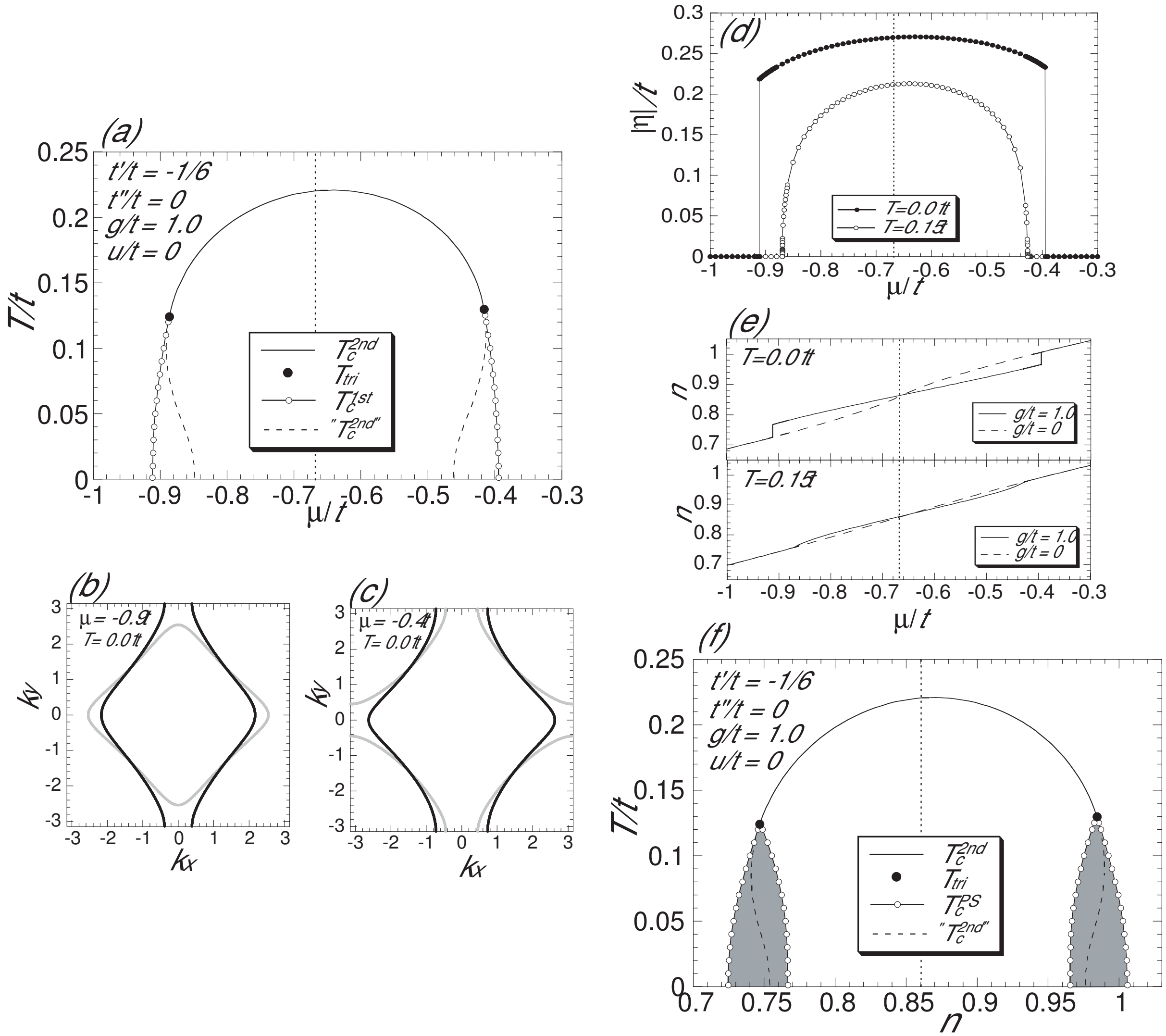
Khavkine et al. '04

Yamase et al. '05

First order transition

at low temperature

Tricritical points



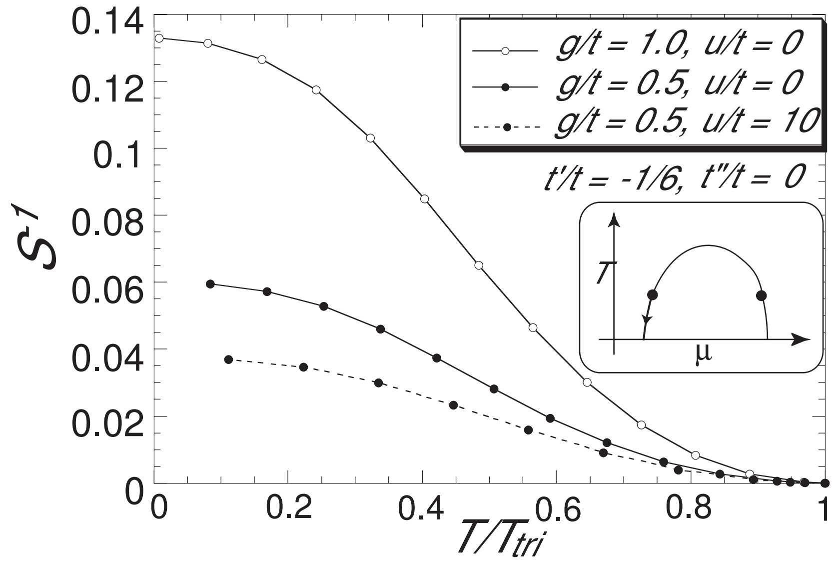
Linear response of $n_d = V^{-1} \sum_{\mathbf{k}} d_{\mathbf{k}} \langle n_{\mathbf{k}} \rangle$ to perturbation $H_d = -\mu_d \sum_{\mathbf{k}} d_{\mathbf{k}} n_{\mathbf{k}}$:

d-wave compressibility $\kappa_d = \frac{dn_d}{d\mu_d} = \frac{\kappa_d^0}{1 + g\kappa_d^0}$

Stoner factor $S = (1 + g\kappa_d^0)^{-1}$

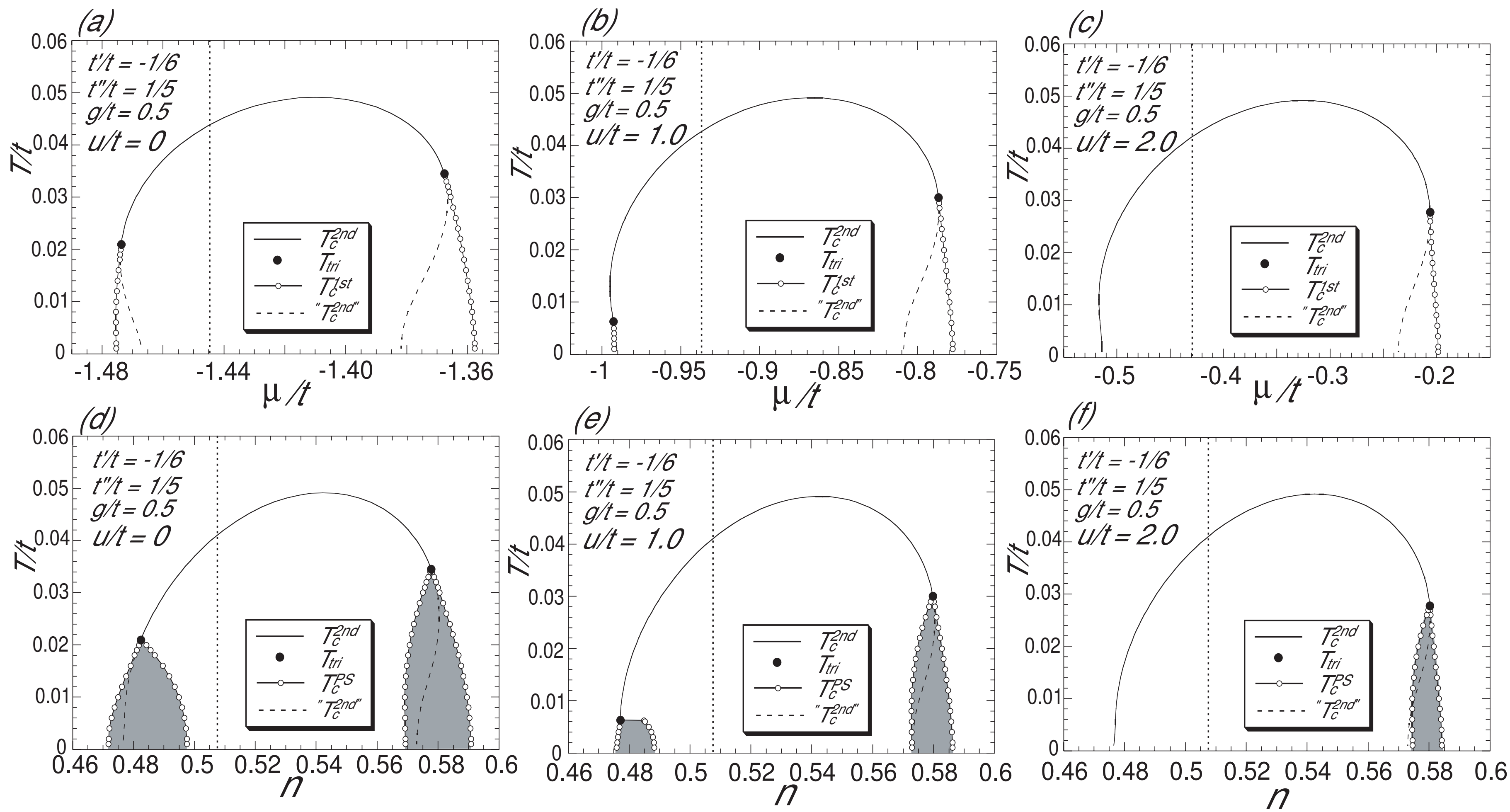
strongly enhanced even

at first order transition



$\Rightarrow$ Soft Fermi surface near transition

Phase diagrams for $t'/t = -1/6$, $t''/t = 1/5$, $g/t = 0.5$ and $u/t = 0, 1, 2$:



Quantum critical point for $u/t \geq 2$

2. Soft Fermi surface and non-FL behavior

Soft Fermi surface (near Pomeranchuk instability)

$\Rightarrow$ large response to anisotropic (d-wave) perturbations,
large Fermi surface fluctuations

Critical fluctuations near continuous Pomeranchuk transition,
quantum critical at $T = 0$, if transition remains continuous at low T

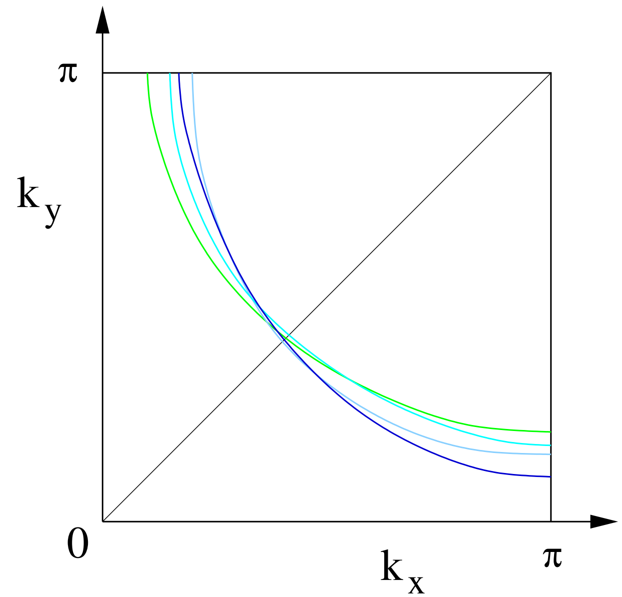
Non-Fermi liquid behavior in critical regime

wm, Rohe, Andergassen '03

Origin of non-FL behavior:

Electrons see fluctuating Fermi surface

$\Rightarrow$ enhanced and anisotropic decay rates

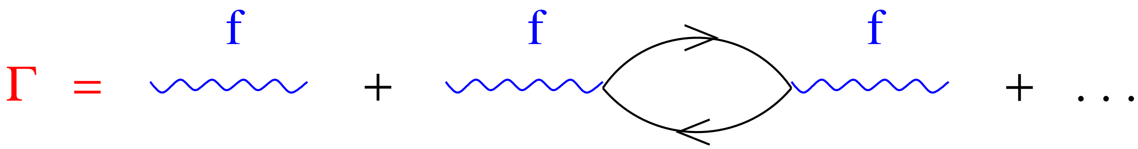


Fluctuations collective and overdamped;

not to be confused with:

- usual thermal smearing
- zero sound (propagating Fermi surface oscillation)

Dynamical effective interaction:



$$\Gamma_{\mathbf{k}\mathbf{k}'}(\mathbf{q},\omega) = \frac{u(\mathbf{q})}{1 - u(\mathbf{q})\,\Pi(\mathbf{q},\omega)} + \frac{g(\mathbf{q})}{1 - g(\mathbf{q})\,\Pi_d(\mathbf{q},\omega)}\, d_{\mathbf{k}}\, d_{\mathbf{k}'}$$

d-wave polarization function $\Pi_d^0(\mathbf{q},\omega) = -\int \frac{f(\xi_{\mathbf{p}+\mathbf{q}/2}) - f(\xi_{\mathbf{p}-\mathbf{q}/2})}{\omega - (\xi_{\mathbf{p}+\mathbf{q}/2} - \xi_{\mathbf{p}-\mathbf{q}/2})}\, d_{\mathbf{p}}^2$

Critical point for Fermi surface symmetry breaking:

$$\lim_{\mathbf{q}\to 0} g(\mathbf{q})\,\Pi_d(\mathbf{q},0) = 1$$

(while $g(\mathbf{q})\,\Pi_d(\mathbf{q},0) < 1$ for $\mathbf{q} \neq 0$)

Singular part near Pomeranchuk instability for small $\mathbf{q}$ and small $\omega/|\mathbf{q}|$

$$\Gamma_{kk'}(\mathbf{q},\omega) \sim \frac{g(\mathbf{0})\, d_{\mathbf{k}}\, d_{\mathbf{k}'}}{(\xi_0/\xi)^2 + \xi_0{}^2\,|\mathbf{q}|^2 - i\frac{\omega}{u|\mathbf{q}|}}$$

Parameters:

Velocity $u > 0$ (related to $\mathrm{Im}\Pi_d$)
microscopic length scale ξ_0
correlation length ξ, related to Stoner factor by $S = (\xi/\xi_0)^2$

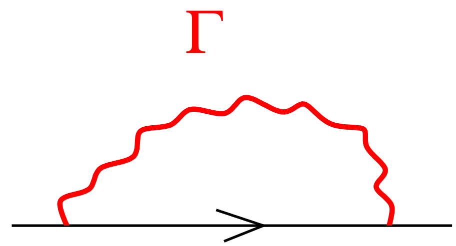
No generic "non-analytic" corrections in charge channel (Chubukov + Maslov '03)

Temperature dependence of ξ determined by dangerously irrelevant interaction of critical fluctuations (Millis '93);
in quantum critical regime:

$$\xi(T) \propto \frac{1}{\sqrt{T}} \times \text{logarithmic corrections}$$

Electron self-energy:

Leading order (Fock approximation)

$\Sigma =$ 

At quantum critical point ($T = 0$, $\xi = \infty$):

$$\mathrm{Im}\Sigma(\mathbf{k}_F, \omega) \; = \; \frac{g \, d_{\mathbf{k}_F}^2}{4\sqrt{3}\pi v_{\mathbf{k}_F}} \frac{u^{1/3}}{\xi_0^{4/3}} |\omega|^{2/3} \quad \text{for} \;\; \omega \to 0$$

- large anisotropic imaginary part
- maximal near van Hove points,
  minimal near diagonal in Brillouin zone

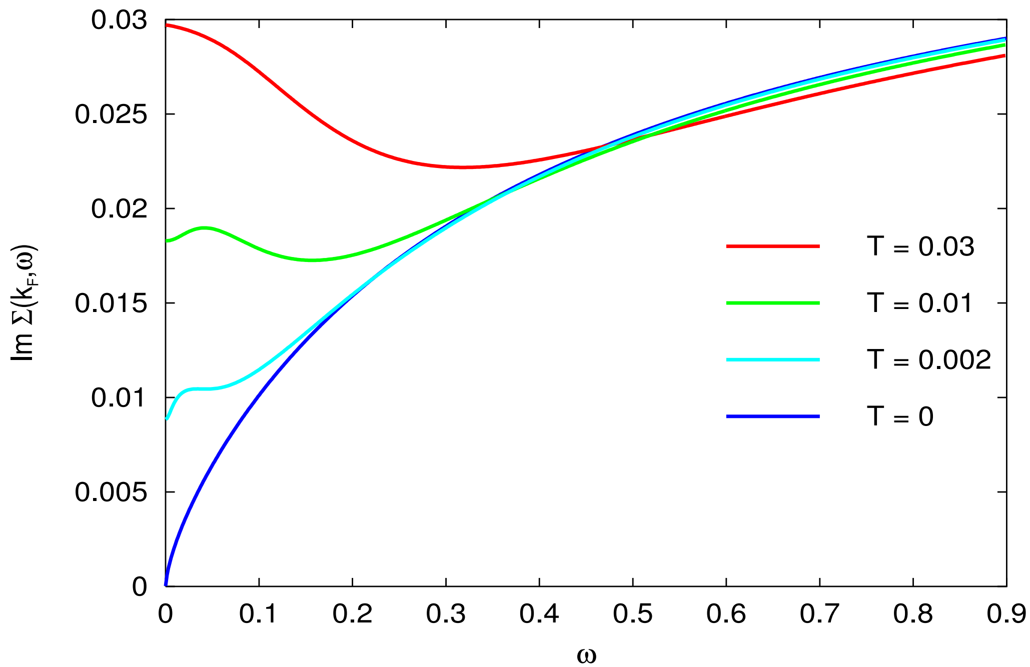
$\Rightarrow$ no quasi-particles away from Brillouin zone diagonal

Above quantum critical point: Dell'Anna + wm '05

$\mathrm{Im}\Sigma(\mathbf{k}_F, \omega)$ for

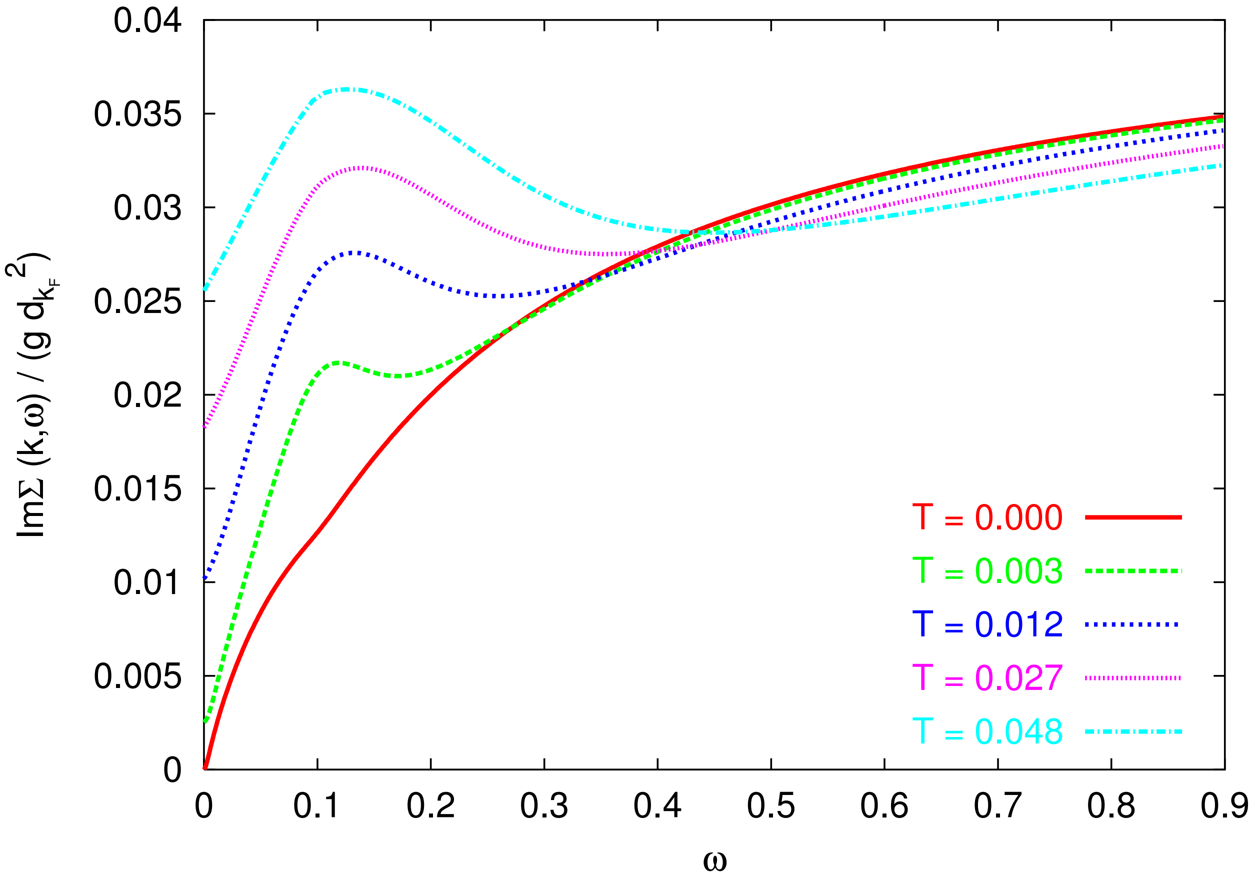
$T \geq 0$,

$\xi(T) \propto T^{-1/2}$



$$\mathrm{Im}\Sigma(\mathbf{k}_F, 0) \;\to\; \frac{g\, d_{\mathbf{k}_F}^2}{4 v_{\mathbf{k}_F} \xi_0^2}\, T\, \xi(T) \;\propto\; T^{1/2} \times \text{log. corr.} \quad \text{for} \;\; T \to 0$$

For $\mathbf{k}$ outside Fermi surface:



Selfconsistency (G instead of G_0 in Fock term) yields no qualitative changes.

At least at $T = 0$ results for Σ also stable against vertex corrections (cf. fermions coupled to gauge field, in particular Altshuler et al. '94)

3. Experimental signatures – cuprates

• Response to lattice distortions:

Strong reaction of electronic properties to slight LTT lattice distortions observed in

$\mathrm{La_{2-x}Ba_xCuO_4}$ (Axe et al. '89)
Nd-doped LSCO (Büchner et al. '94)

Increasing evidence for strong ab-anisotropy of electronic properties of $\mathrm{CuO_2}$-planes in

YBCO (Lu et al. '01, Hinkov et al. '04)

• Linewidth in photoemission:

Large anisotropic decay rates for single-particle excitations observed in optimally doped cuprates

• Anisotropy in transport:

c-axis vs. ab-plane anisotropy in transport
follows naturally from anisotropic decay rate
with minima on the Brillouin zone diagonals

$\leftrightarrow$ "cold spot" scenario (Ioffe + Millis '98)

• Relation to (dynamical) stripes ?

Stripes break orientation and translation symmetry

• Raman scattering:

Signatures in B_{1g}-channel ?

Spin-dependent d-wave Pomeranchuk instability proposed recently
for $\mathrm{Sr_3Ru_2O_7}$ (Grigera et al. '04)

Conclusions:

- Interactions can induce symmetry-breaking Fermi surface deformations:
  Pomeranchuk instability

- Near Pomeranchuk instability soft Fermi surface
  reacting strongly to anisotropic perturbations.

- Fluctuations of soft Fermi surface lead to
  large anisotropic quasi-particle decay rates.