Pseudogap in ultracold Fermi gases:

comparison with experiments and Quantum Monte Carlo results and insights for the pseudogap phase of cuprates

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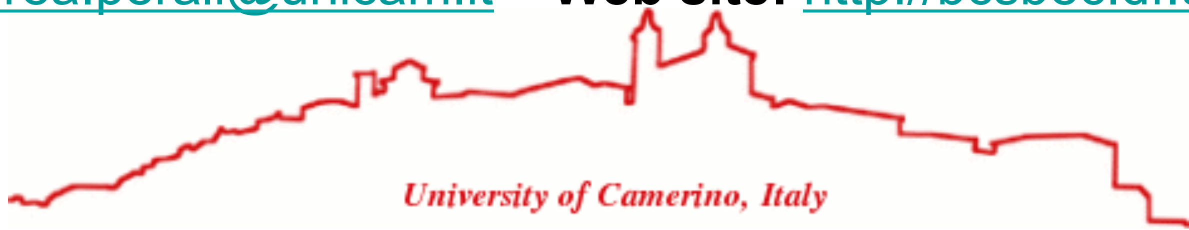


Outlines: Part I

- Physical system: interacting ultracold Fermi atoms.

- Pairing fluctuations as the origin of the pseudogap: results obtained by our pairing-fluctuations t-matrix theory for attractive fermions through the BCS-BEC crossover.

- Comparison between theory and QMC in the homogeneous case: evidences for pseudogap and remnant Fermi surface in the normal phase of a strongly interacting Fermi gas.

Outlines: Part II

- Experimental probe for pseudogap in ultracold Fermi gases: momentum resolved RF spectroscopy.

- Comparison between t-matrix results in the trap and JILA RF(k) experiments: evidences for pseudogap and remnant Fermi surface in the normal phase of a strongly interacting Fermi gas starting from unitarity to the onset of the molecular (BEC) regime.

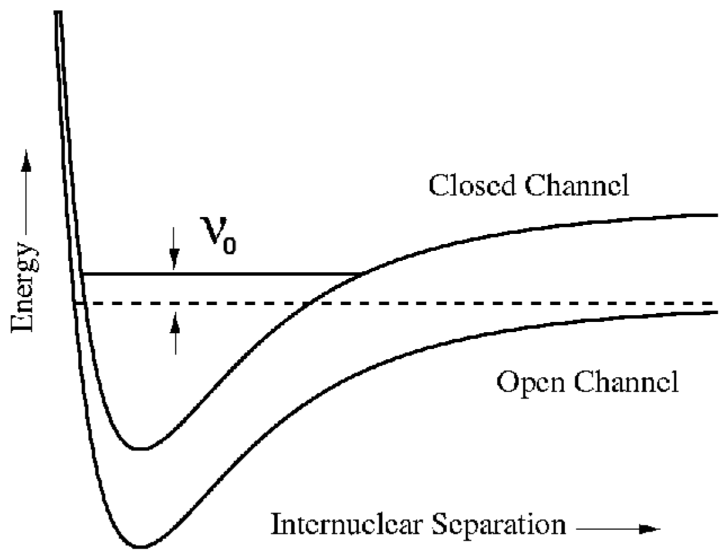
- The pseudogap in high-Tc superconductors and comparisons with the predictions of the pair fluctuations scenario.

Ultracold Fermi atoms in a trap

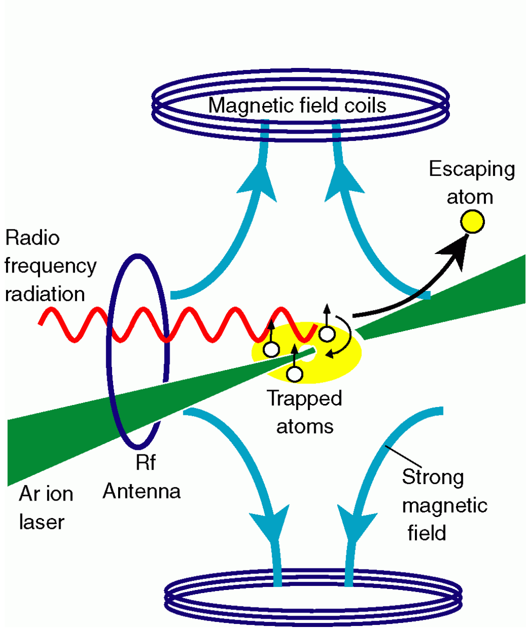
Fermionic atoms (Li, K) confined in a magneto-optical trap and cooled by evaporative cooling to the limit of quantum degeneracy.

Two (lowest) hyperfine levels are equally populated.

The fermionic atoms in the 2 levels interact via a point-contact attraction and the strength of the attraction can be tuned via a wide Fano-Feshbach resonance.



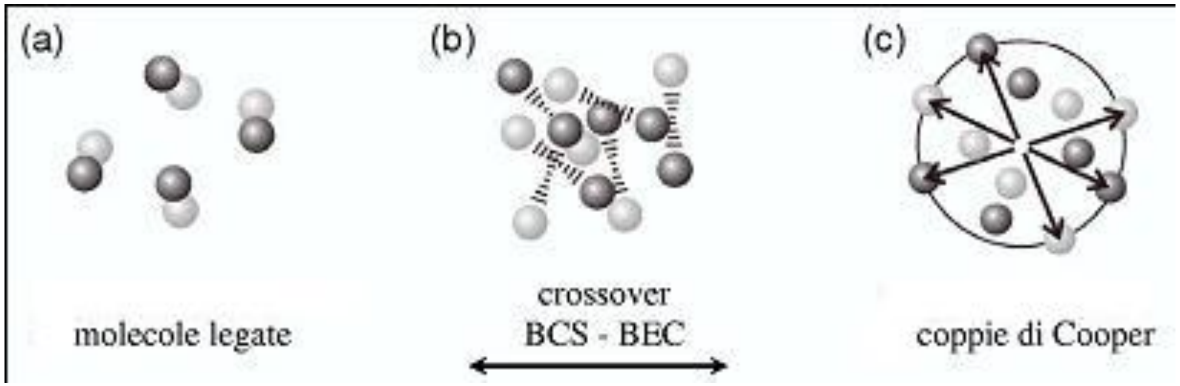
Magnetic trap with optical plug



Ultracold Fermi atoms in a trap

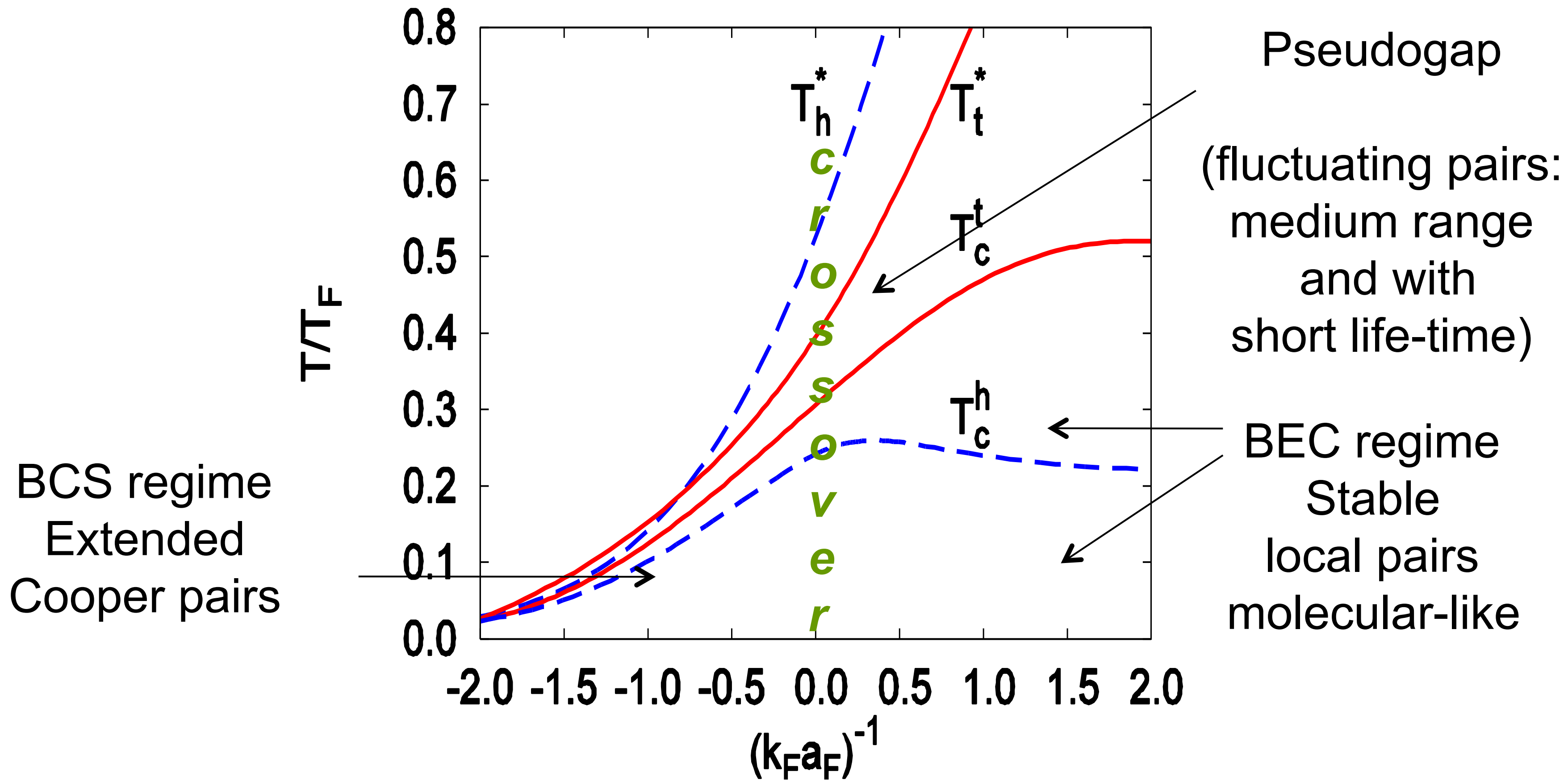
The interacting Fermi sea at low enough temperature can make a transition to a coherent (BCS-like) superfluid state.

The BCS-BEC crossover can be explored by tuning scattering length.



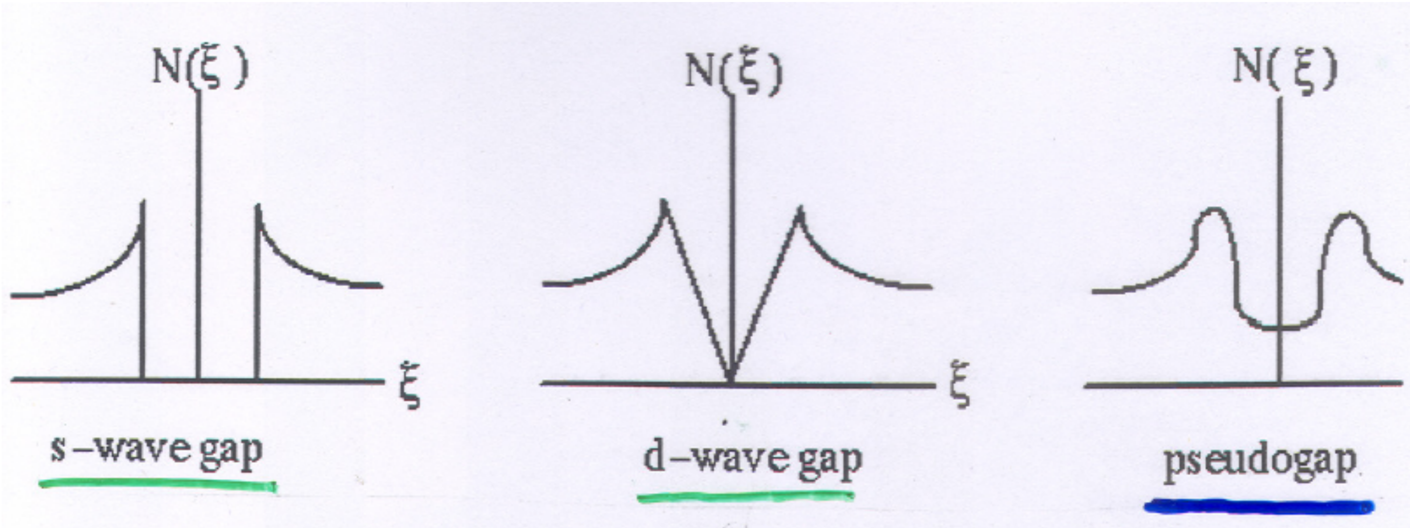
Nozières and Schmitt-Rink, J. Low. Temp. Phys. **59**, 195 (1985).
C. Sá de Melo *et al.* PRL **71**, 3202 (1993).
F. Pistolesi and G.C. Strinati, PRB **49**, 6356 (1994).

Phase diagram for the homogeneous and trapped Fermi gas as predicted by t-matrix

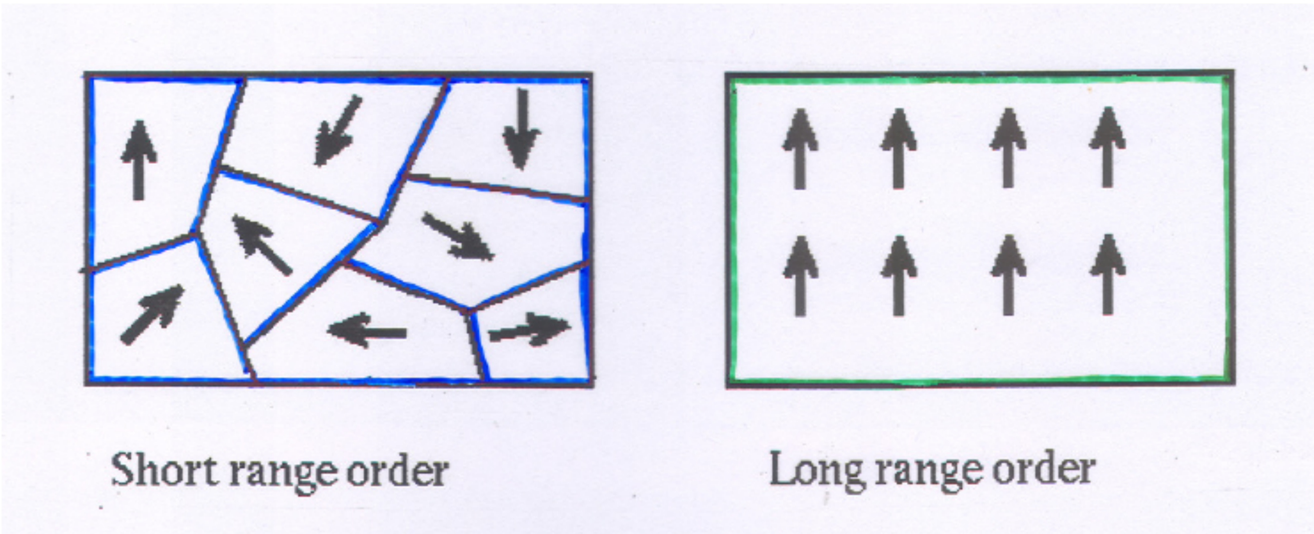


C. Sa de Melo, M. Randeria and J. Engelbrecht, PRL **71**, 3202 (1993) (homogeneous)
A. Perali, P. Pieri, L. Pisani, and G.C. Strinati, PRL **92**, 220404 (2004) (trap)

Pseudogap vs gap: density of states

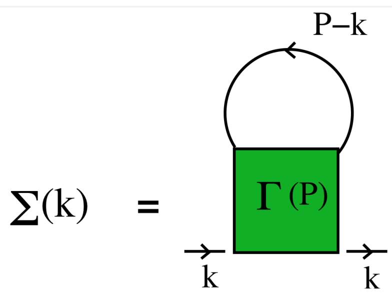


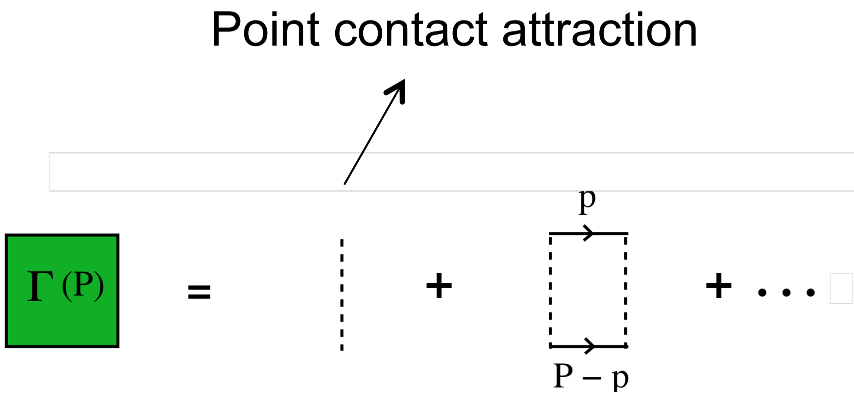
Precursor effect of the ordered state



The BCS to BEC crossover problem at finite temperature: inclusion of pairing fluctuations above Tc

T-matrix self-energy:





Ladder resummation

$$\Sigma\,(k) = -\int \frac{d\mathbf{P}}{(2\pi)^3}\frac{1}{\beta}\sum_{\Omega_\nu}\Gamma_0(P)\,G^0(P-k)$$

where

$$\Gamma_0(P)^{-1} = -\frac{1}{v_0} - \int \frac{d\mathbf{p}}{(2\pi)^3}\frac{1}{\beta}\sum_{\omega_l} G^0(p+P)\,G^0(-P)$$

$$= -\frac{m}{4\pi a} - \int \frac{d\mathbf{p}}{(2\pi)^3}\left[\frac{1}{\beta}\sum_{\omega_l} G^0(p+P)\,G^0(-P) - \frac{m}{p^2}\right]$$

$k = (\mathbf{k},\omega_n)\ ;\ P = (\mathbf{P},\Omega_\nu)$

$p = (\mathbf{p},\omega_l)$

A. Perali, P. Pieri, G.C. Strinati, and C. Castellani, Phys. Rev. B **66**, 024510 (2002).

P. Pieri, L. Pisani, and G. Strinati, Phys. Rev. B **70**, 094508 (2004).

Single particle spectral function and density of states

Spectral function determined by analytic continuation to the real axis of the interacting Green's function

$$A(k,\omega) = -\frac{1}{\pi}\mathrm{Im}G^R(k,\omega) = \frac{(-1/\pi)\mathrm{Im}\sum(k,\omega)}{(\omega - \xi(k) - \mathrm{Re}\sum(k,\omega))^2 + \mathrm{Im}\sum(k,\omega)^2}$$

$$\xi(k) = \frac{\hbar^2 k^2}{2m} - \mu$$

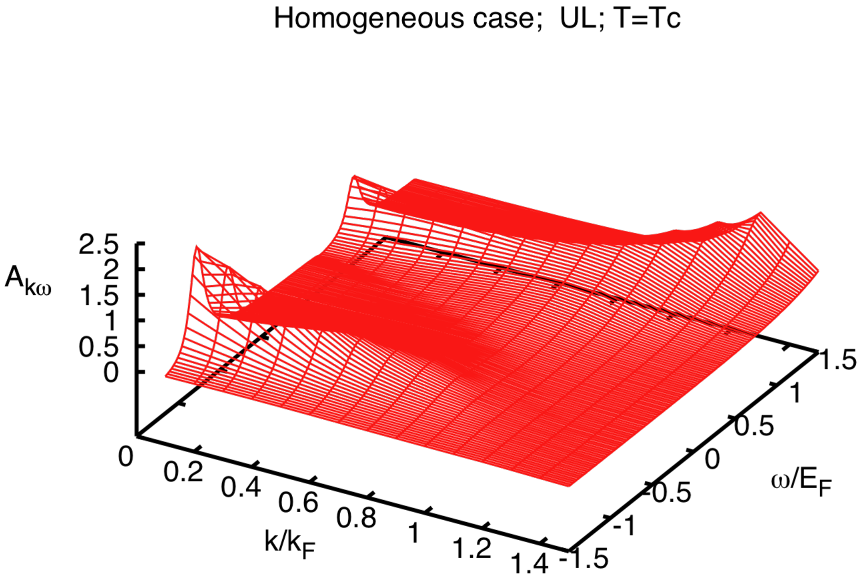
Sum rule $\int_{-\infty}^{+\infty} A(k,\omega)d\omega = 1$

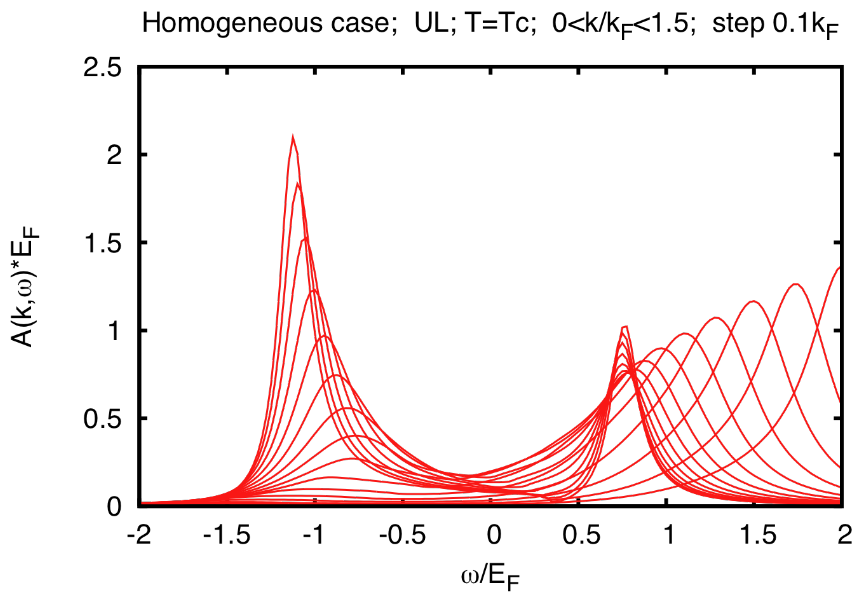
Momentum distribution $\int_{-\infty}^{+\infty} A(k,\omega)f(\omega)d\omega = n_k$

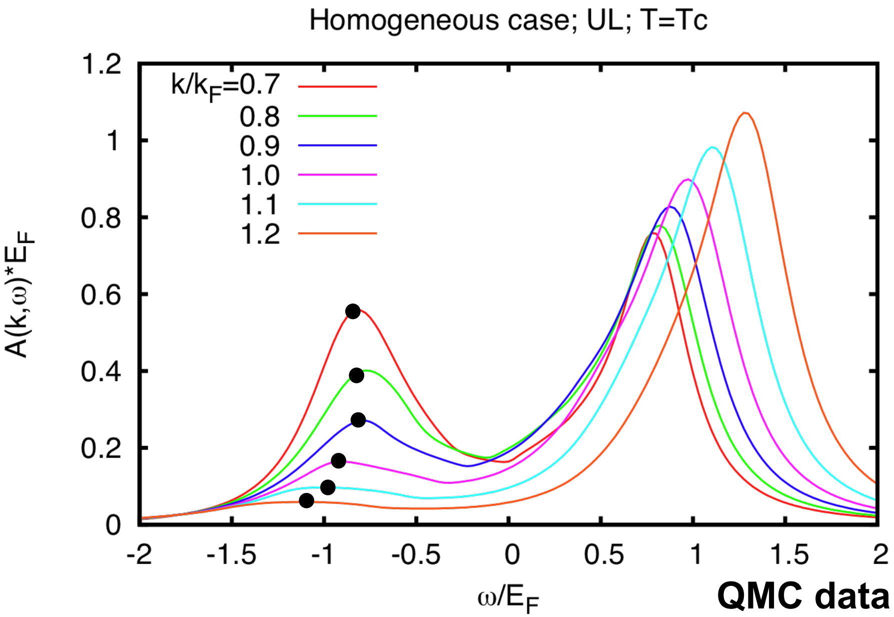
Density of states $N(\omega) = \int \frac{d\mathbf{k}}{(2\pi)^3} A(k,\omega)$

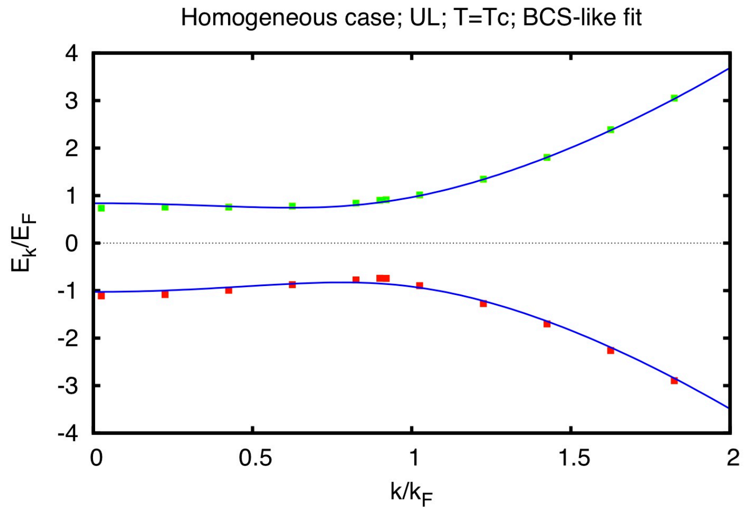
Total density of fermions $n_\uparrow = n_\downarrow = \int_{-\infty}^{\infty} d\omega A(k,\omega) f(\omega)$ $\longrightarrow$ Chemical potential

Spectral function at T=Tc, unitary limit



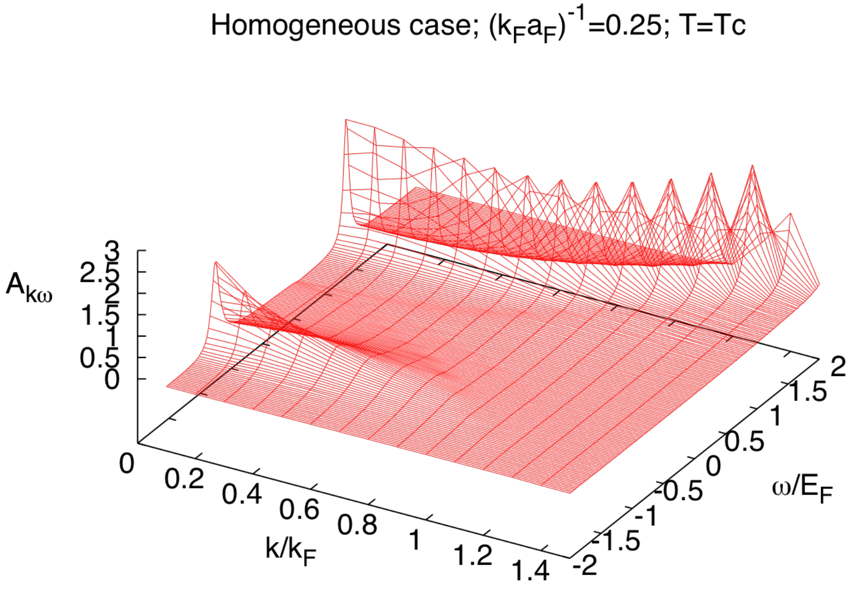


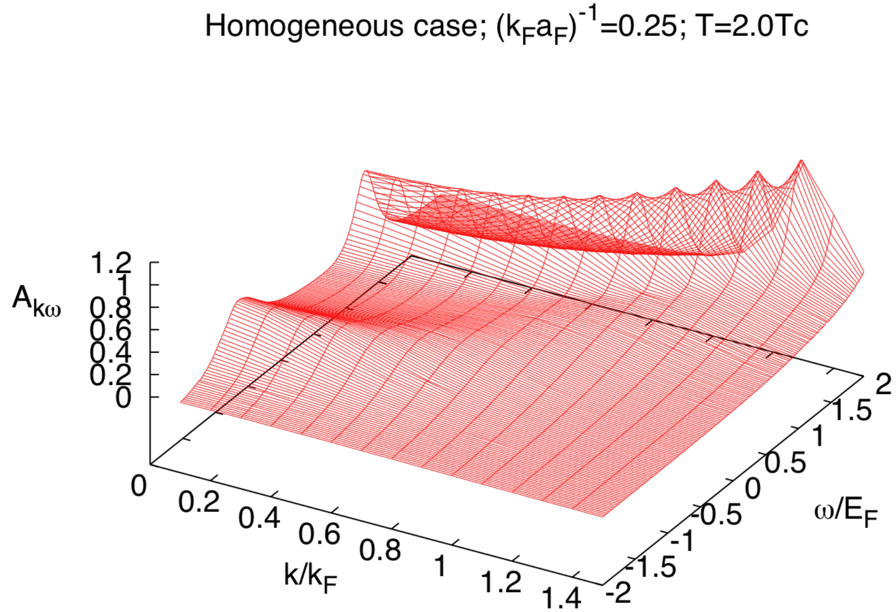


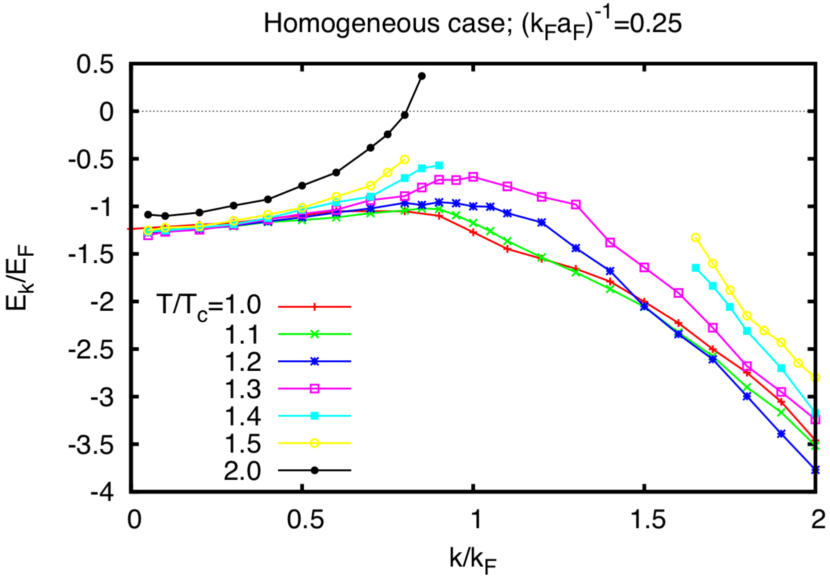


QMC data by Bulgac group (PRL **107**, 145304 (2011))
confirm a sizeable pseudogap at unitarity at T=Tc (**QMC**: **0.42EF** *vs* **t-matrix**: **0.8EF**)

Temperature evolution at $(k_F a)^{-1}$=0.25

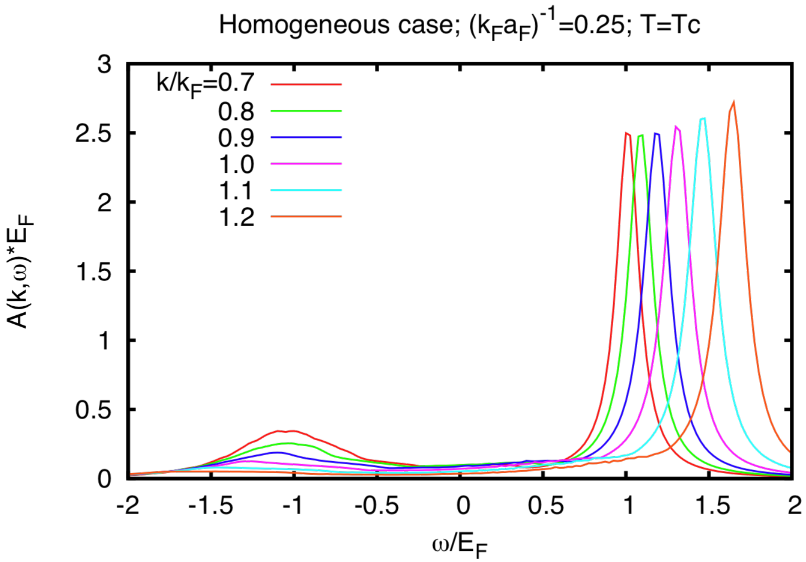


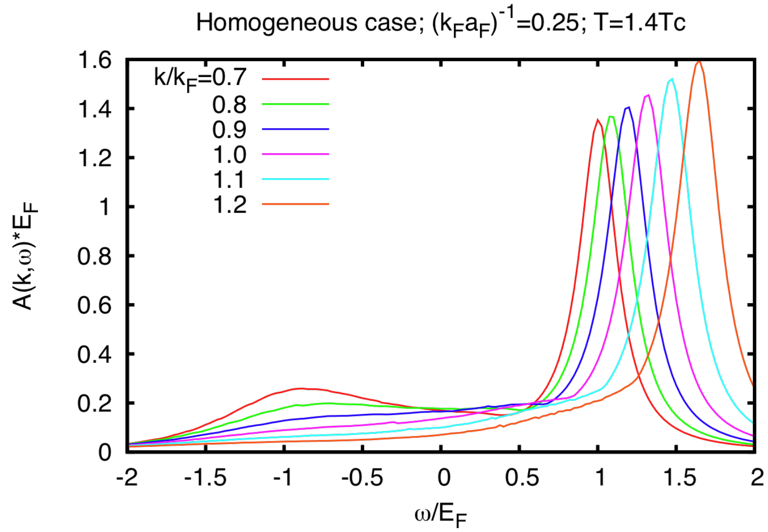


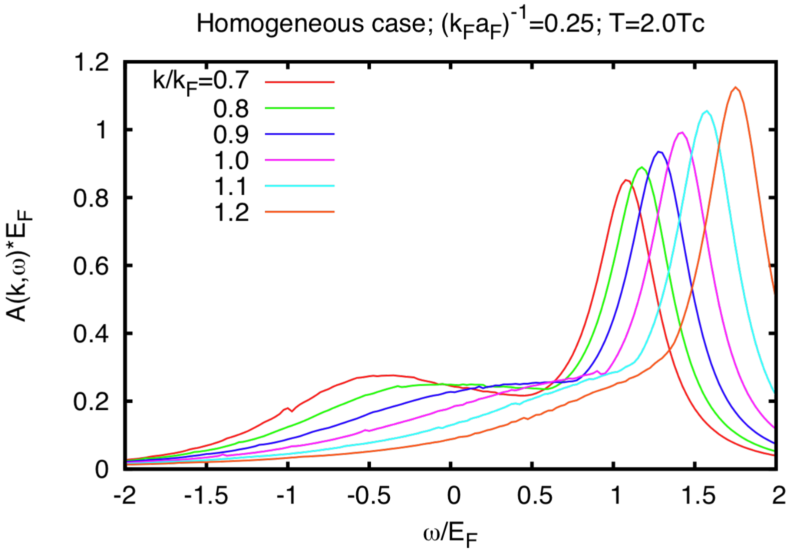


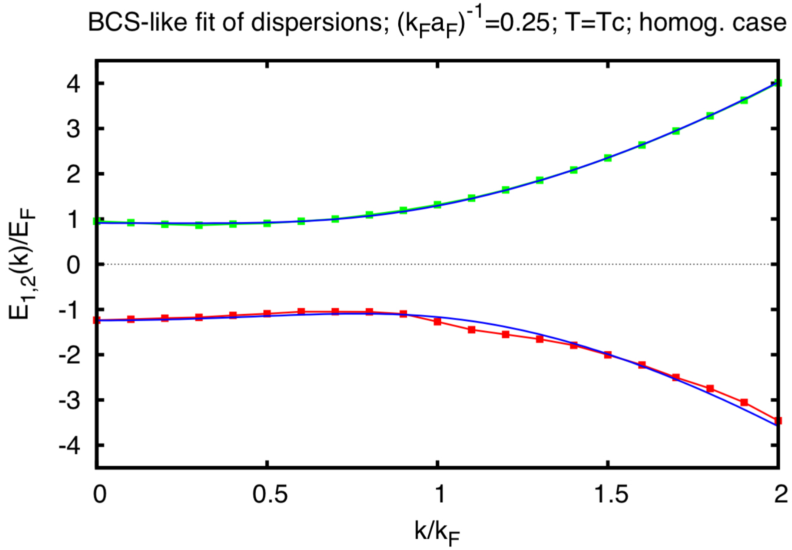
F. Palestini, A. Perali, P. Pieri, G.C. Strinati, Phys. Rev. B **85**, 024517 (2012).

Temperature evolution at $(k_F a)^{-1}$=0.25

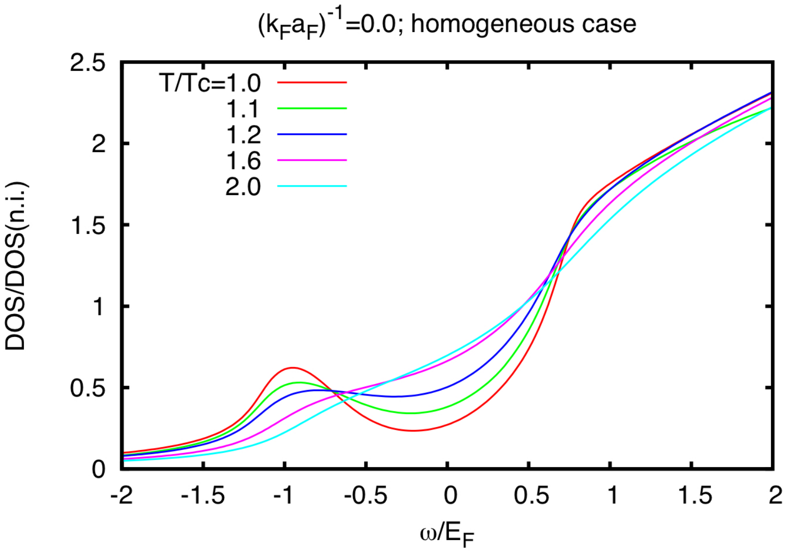


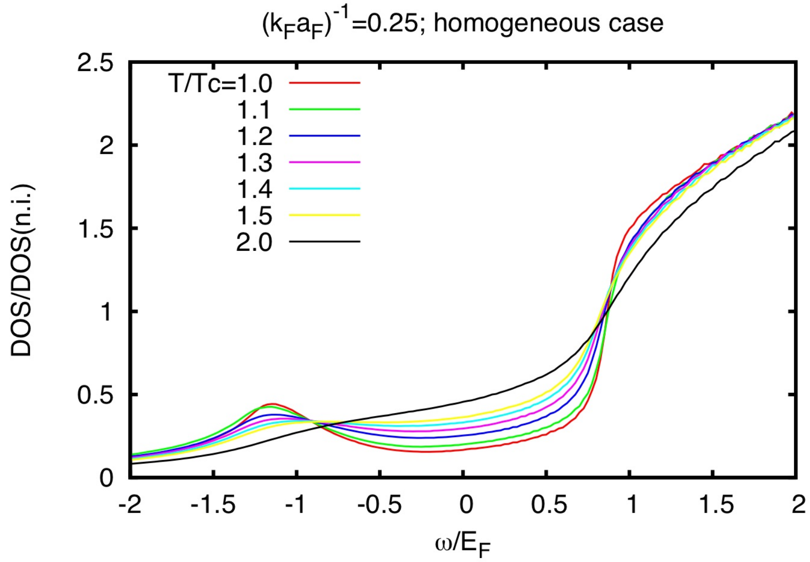


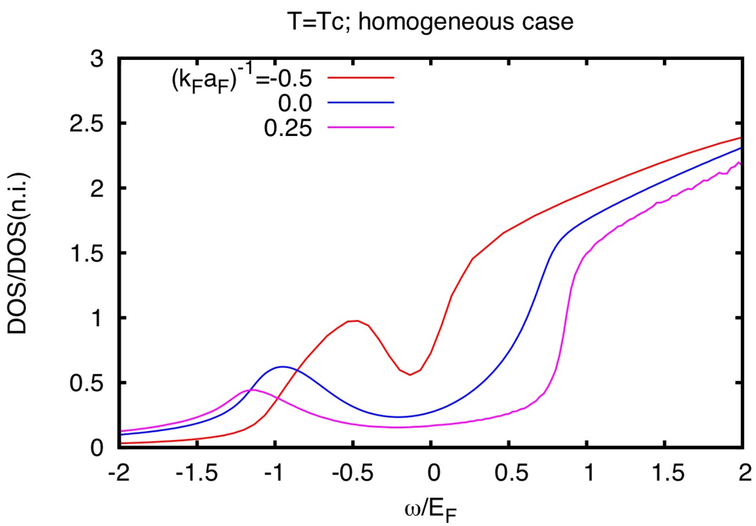




Density of states







QMC (squares)

T-matrix (circles)

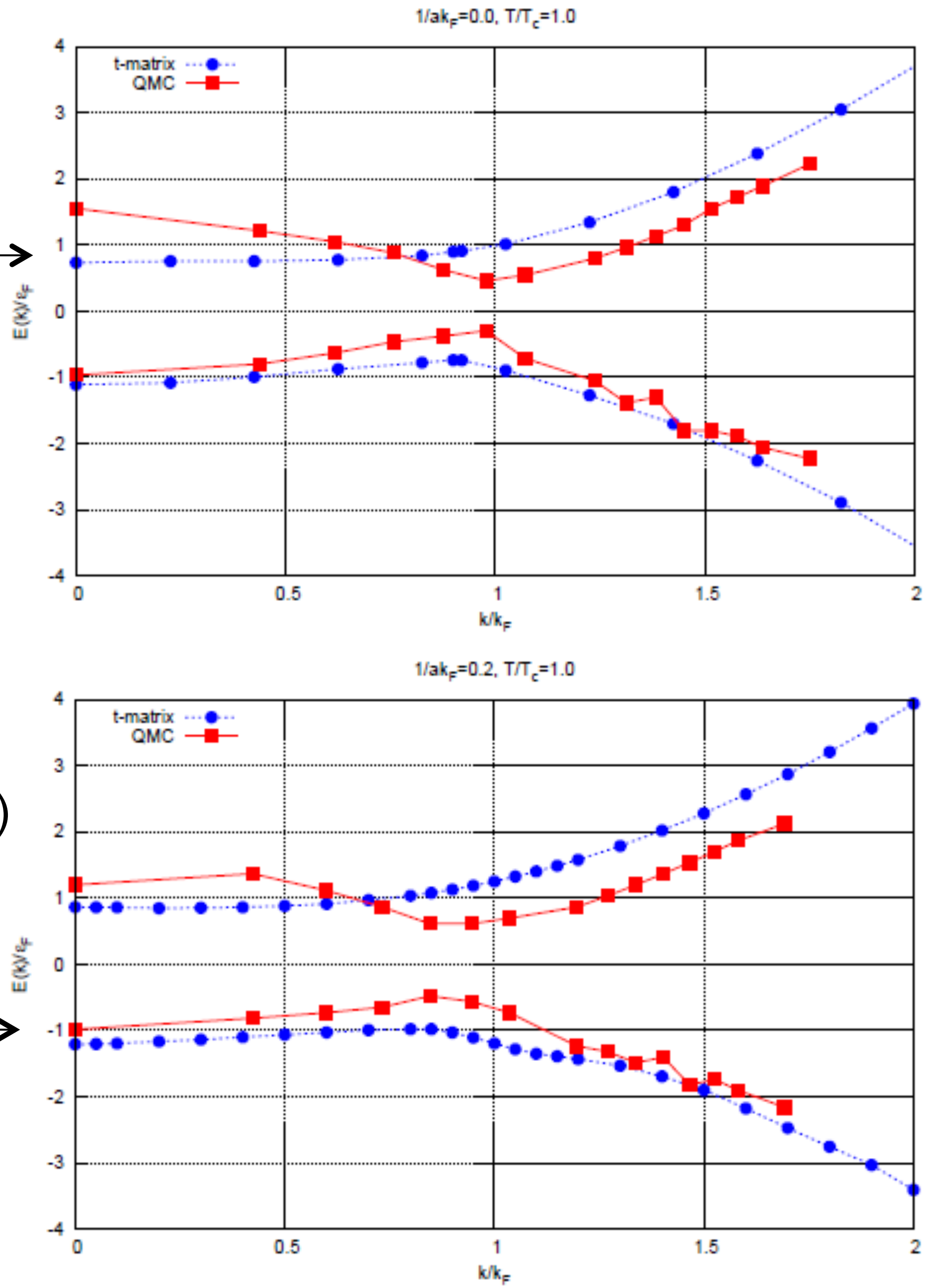
Unitarity limit and T=Tc

A(k,w) peaks dispersions

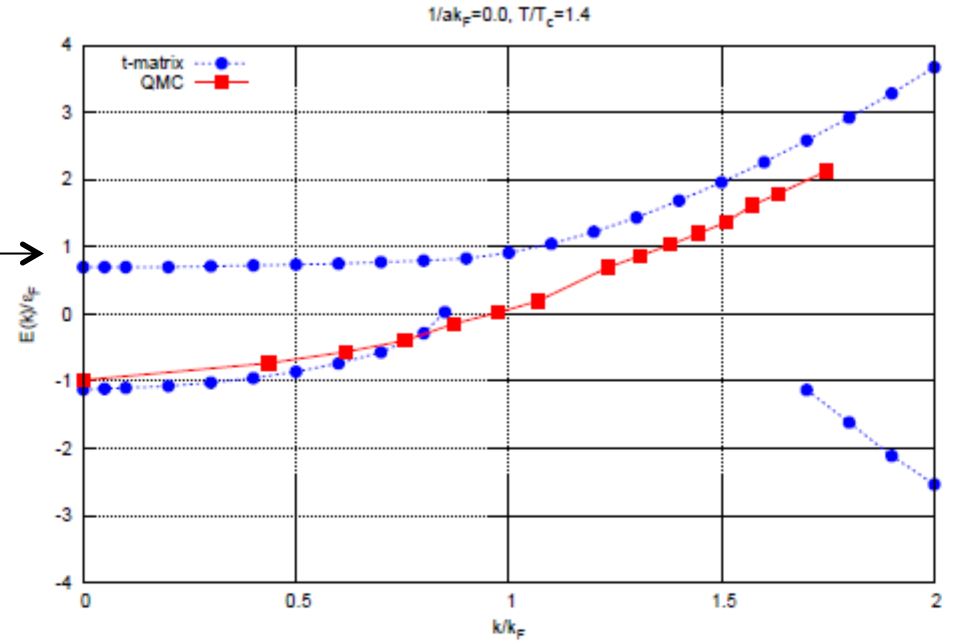
Comparison with QMC

P. Magierski, G. Wlazlowski and A. Bulgac, Phys. Rev. Lett. **107**, 145304 (2011)

$(k_F a)^{-1}$=0.20 and T=Tc



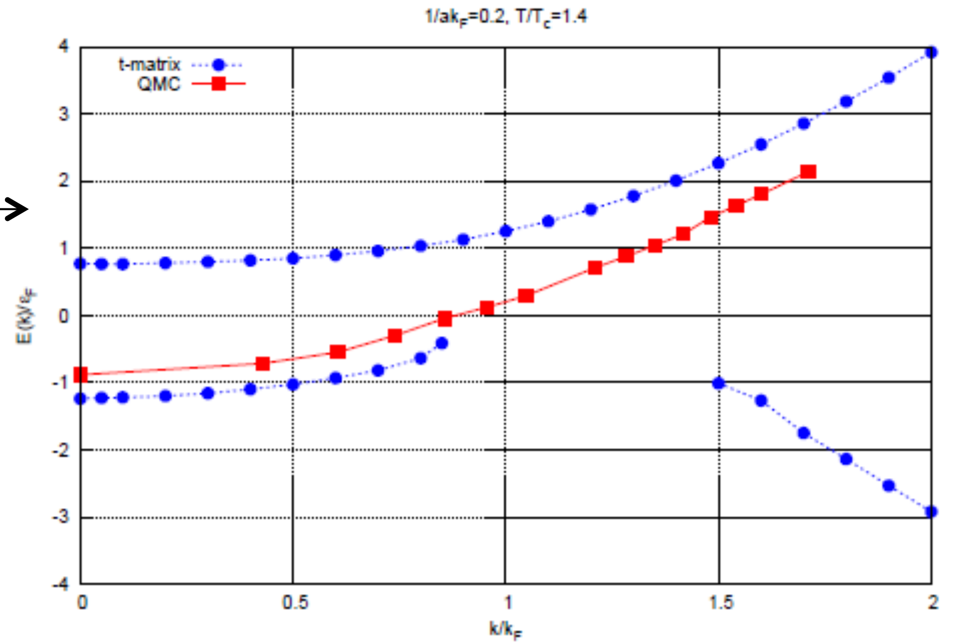
Unitarity limit and T=1.4Tc



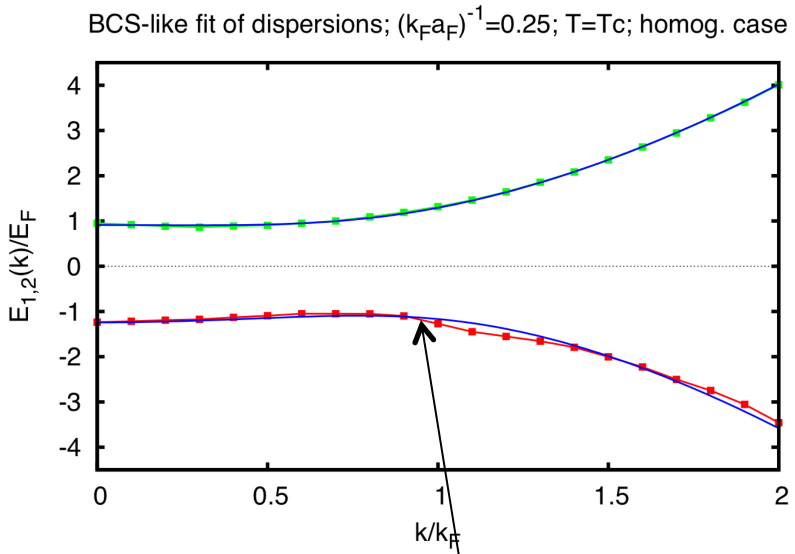
QMC (squares)

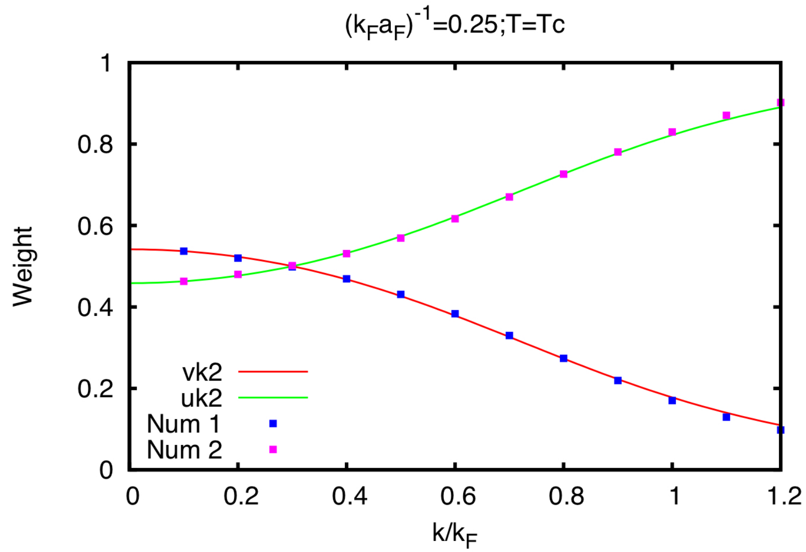
T-matrix (circles)

$(k_F a)^{-1}$=0.20 and T=1.4Tc



BCS-like equations for dispersions and weights





$$E(k) = -\sqrt{\left[(k^2 - k_L^2)/2m\right]^2 + \Delta_{pg}^2}$$

"pseudo-Luttinger" wave-vector

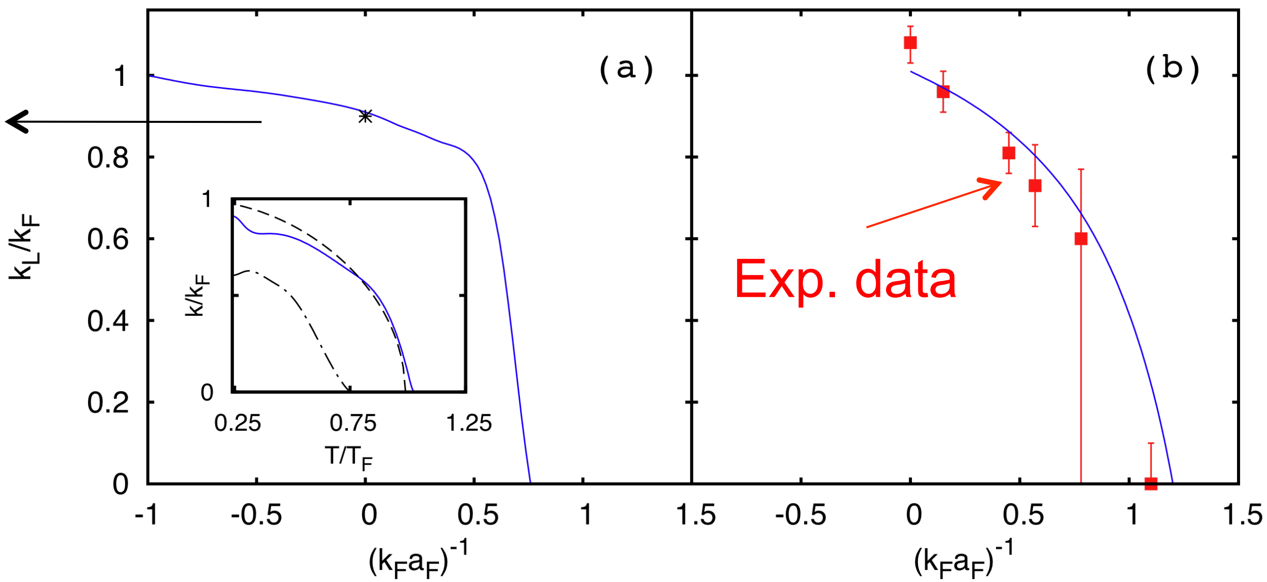
$$v_k^2 = \frac{1}{2}\left(1 - \frac{k^2/2m - \mu}{|E_k|}\right)$$

$$u_k^2 = 1 - v_k^2$$

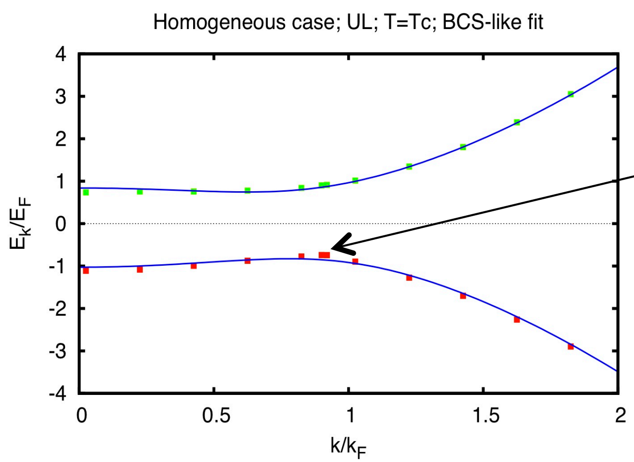
“Remnant Fermi surface”in the pseudogap phase

QMC prediction:
J. Carlson and
S. Reddy
PRL **95**, 060401
(2005).

Homogeneous case   Trap case



UNICAM + JILA collaboration
A. Perali et al.
PRL **106**, 060402 (2011).



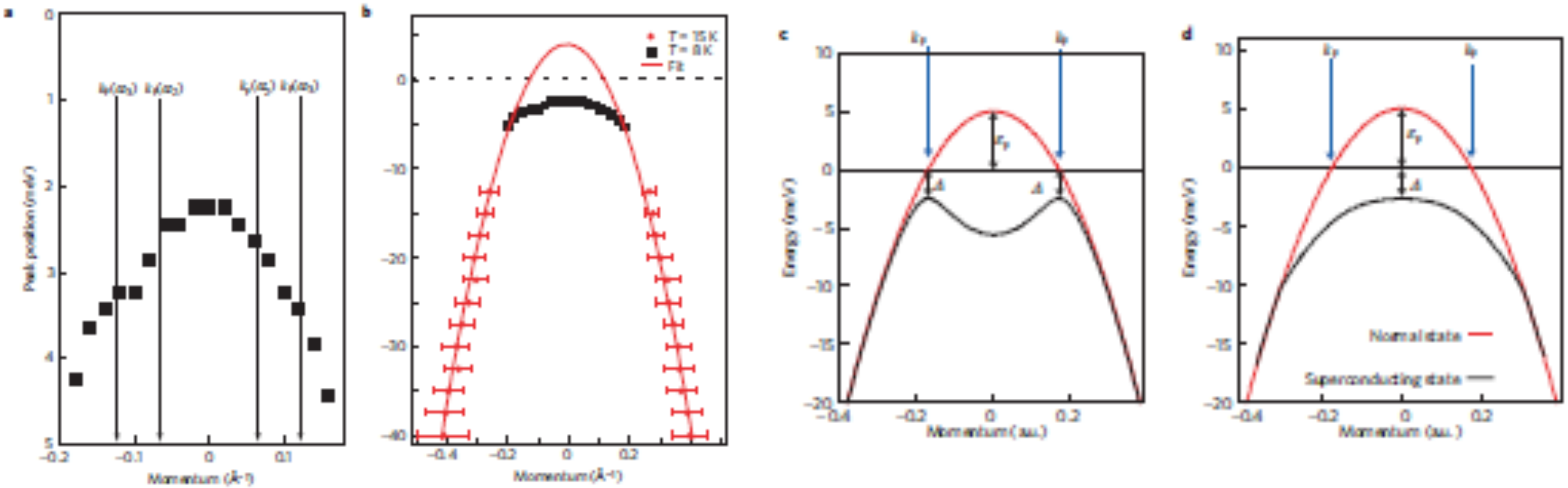
“pseudo-Luttinger”
wave-vector
k_L

First ARPES evidence of the BCS-BEC crossover in solid state superconductors: the case of iron-chalcogenides

Y. Lubashevsky et al. (*Kanigel group*) Nature Physics **8**, 309 (2012).

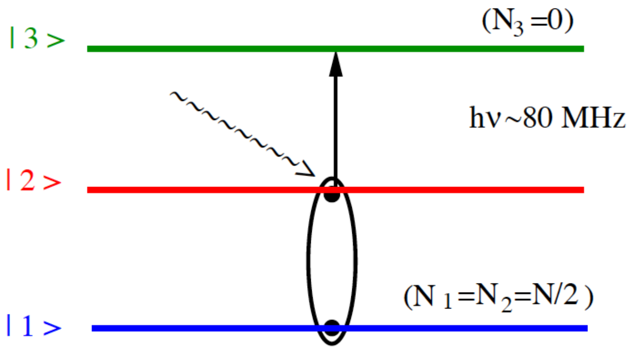
Evidence of a Fermi surface collapses in the superconducting state with a possible sign changes in the chemical potential.

The dispersion of the lower branch becomes an inverted parabola. (**kL->0**)



Evidences of BCS-BEC crossover also in doped MgB2 superconductors:
D. Innocenti, A. Ricci, N. Poccia, A. Valletta, S. Caprara, A. Perali,
A. Bianconi, Phys. Rev. B **82**, 184528 (2010).

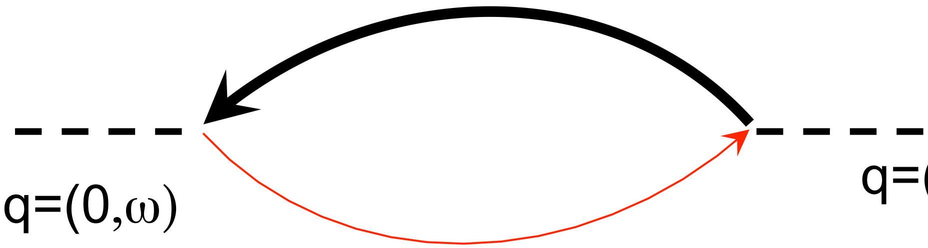
How does the pseudogap enters RF spectroscopy?



Dressed (interacting) Green's function propagating fermions of the initial level 2

$G_2(k,\Omega-\omega)$

External perturbation (RF pulse)



q=(0,ω)

q=(0,ω)

$G_3^0(k,\Omega)$

Bare (non-interacting) Green's function propagating fermions of the final level 3

$$RF(\omega) = (-1/\pi)\,\mathrm{Im}\,\Pi_{23}^R(\omega)$$

$$\Pi_{23}(\omega_l) = T\sum_n \int d^3k\, G_2(k,\omega_n-\omega_l)\,G_3^0(k,\omega_n)$$

$$i\omega_l \rightarrow \omega + i0^+$$

RF spectrum (*without* final state effects)

In the absence of final state effects, linear response theory yields for the the **RF** experimental signal the expression:

$$RF(\omega_\delta) = \int d^3 r \int \frac{d^3 k}{(2\pi)^3} A(k, k^2/(2m) - \omega_\delta - \mu_2(r); r) f[k^2/(2m) - \omega_\delta - \mu_2(r)]$$

where ω_δ is the detuning of the RF probe with respect to the frequency of the atomic transition $|2\rangle \to |3\rangle$
The third state is initially empty.

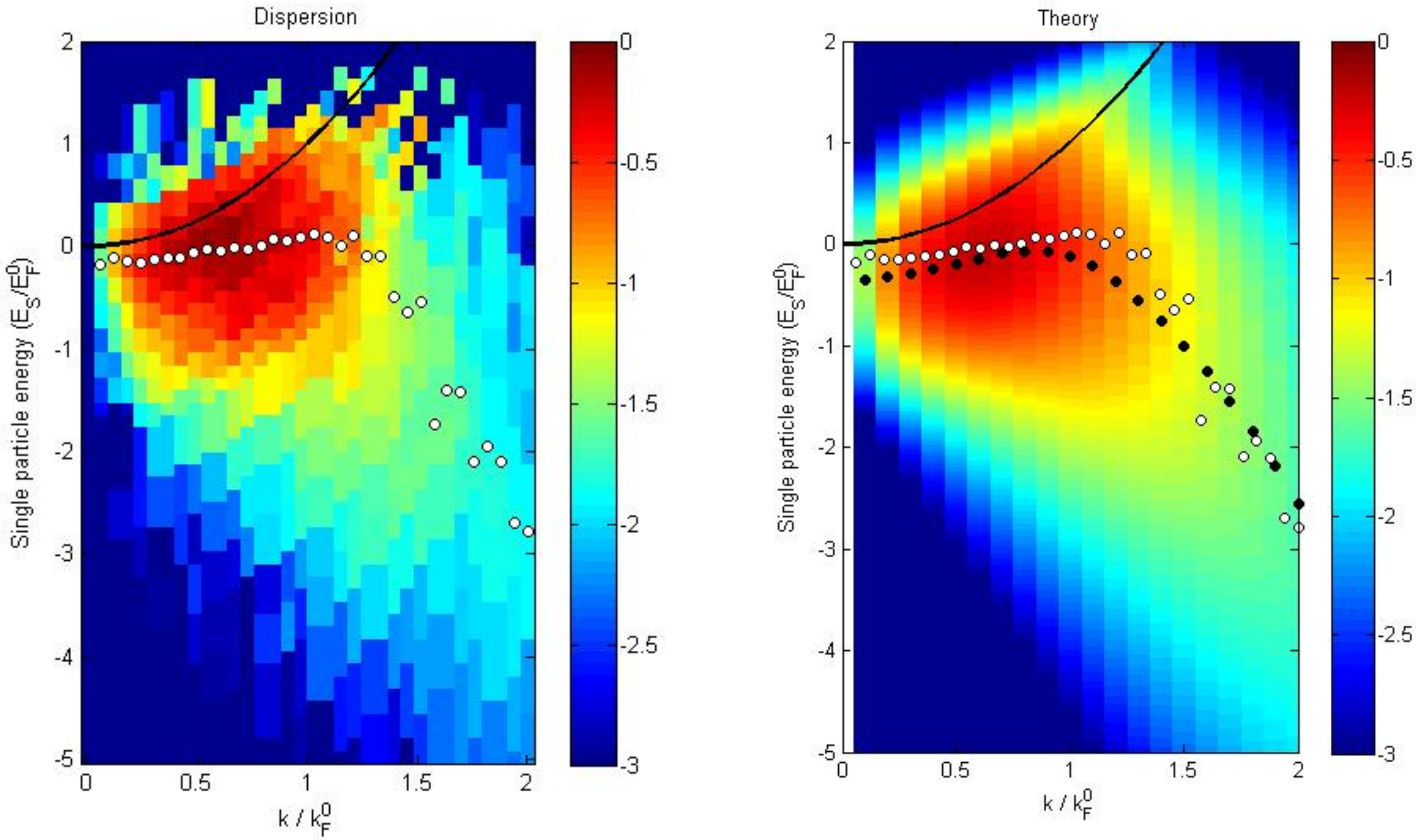
In the JILA experiment with ^{40}K fermions the final state effects are negligible [*J.T. Stewart, J.P. Gaebler and D.S. Jin,* Nature **454**, 744 (2008).]

The **momentum resolved** RF spectrum measured at JILA is directly proportional to

$$RF(k; E_s) = k^2 \int d^3 r A(k, E_s - \mu_2(r); r) f[E_s - \mu_2(r)]$$

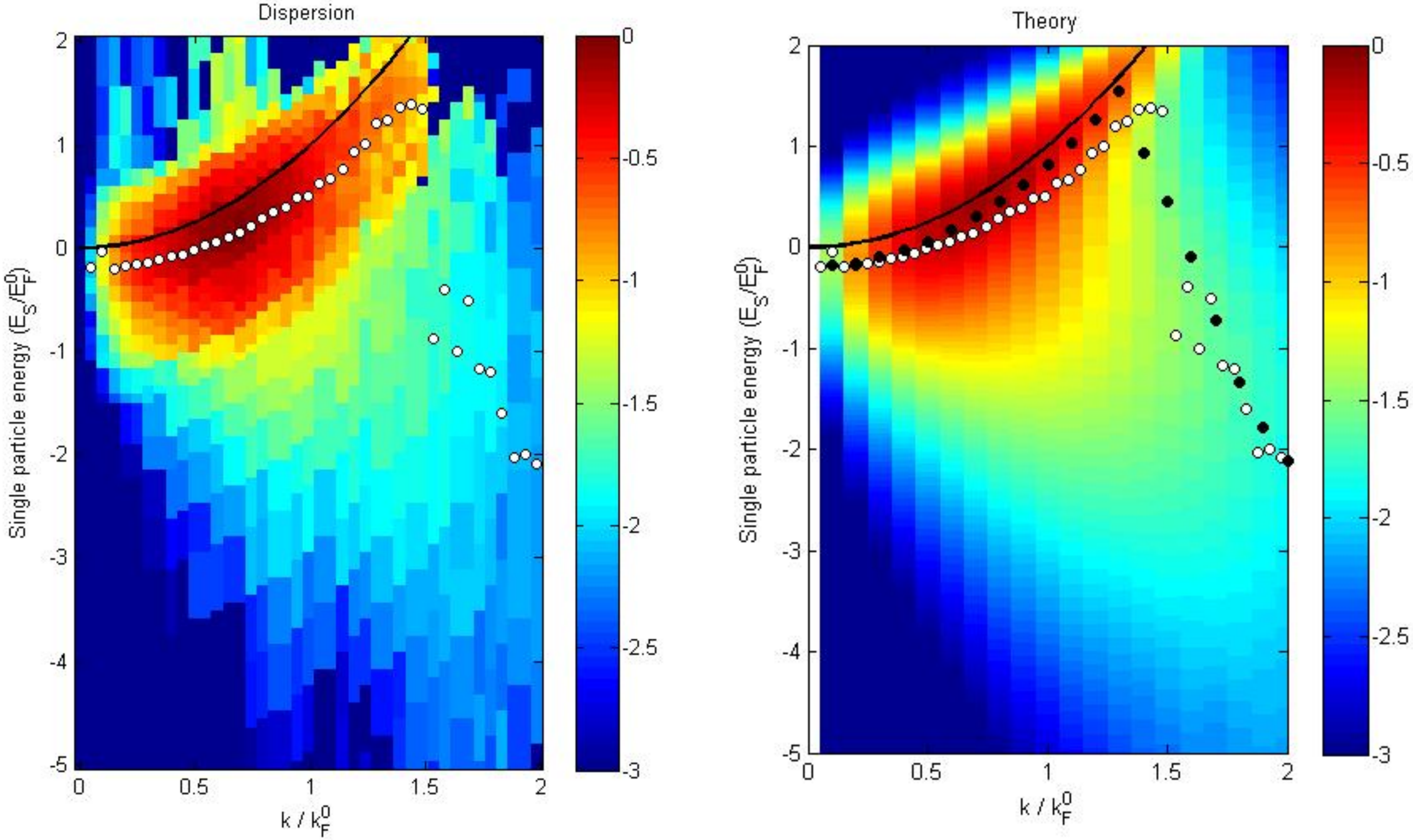
where the single-particle energy is $E_s = k^2/(2m) - \omega_\delta$

Above Tc, close to unitarity: intensity plot

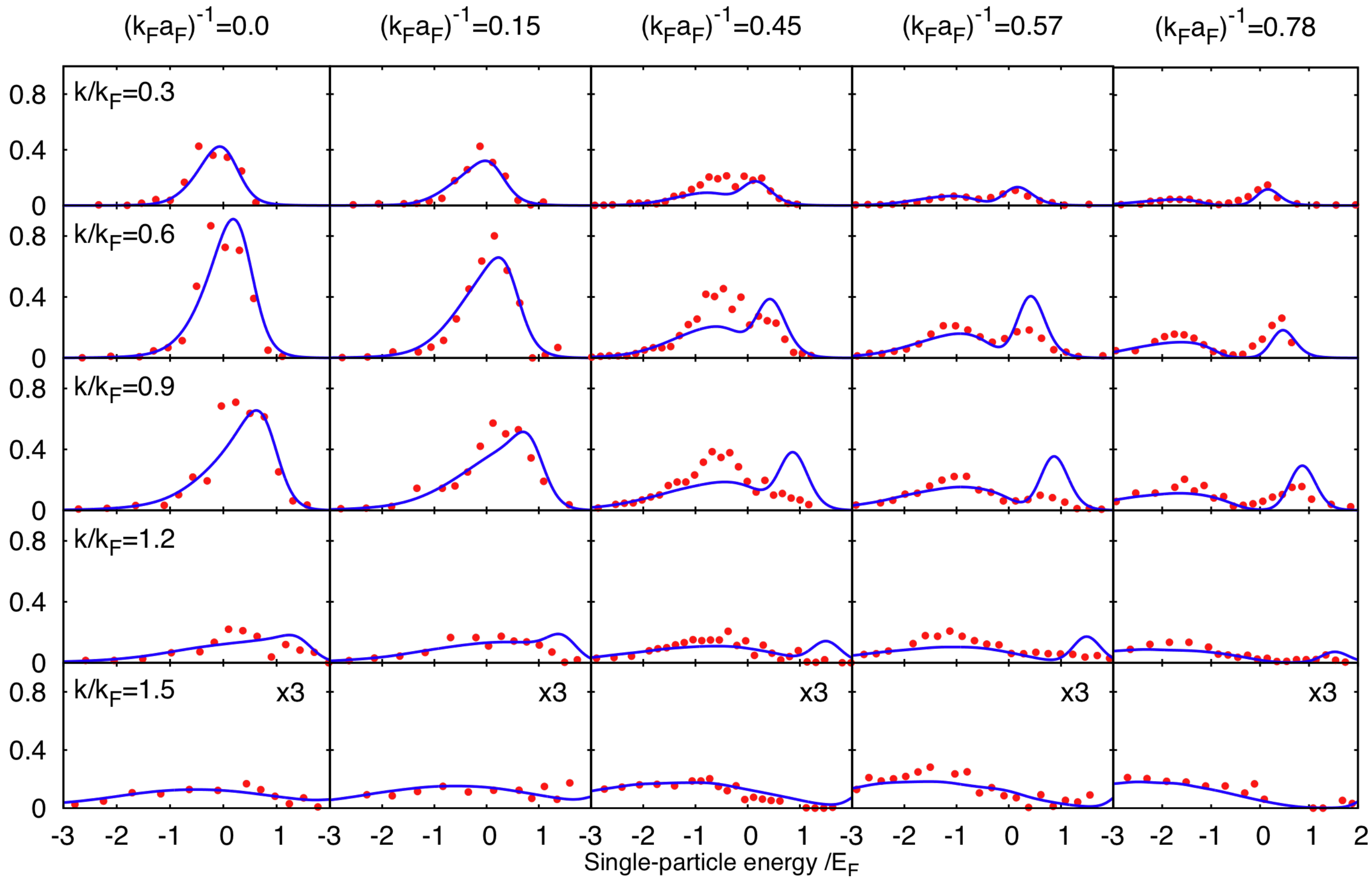


JILA + UNICAM collaboration:
J. P. Gaebler et al., Nature Phys. **6**, 569 (2010).

Closing of the pseudogap at 2.0Tc



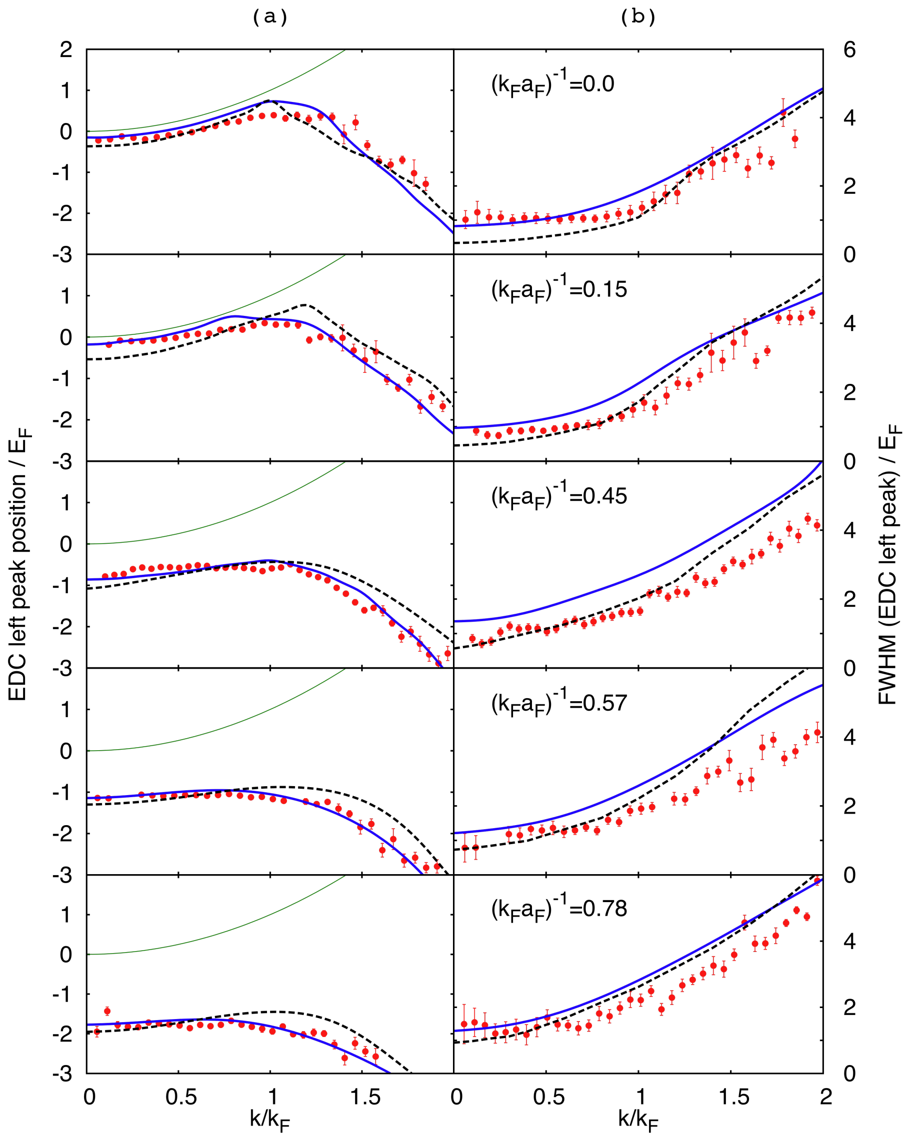
Comparison with momentum resolved RF spectra from JILA experiment



No fitting parameters

UNICAM + JILA collaboration
A. Perali et al., PRL **106**, 060402 (2011).

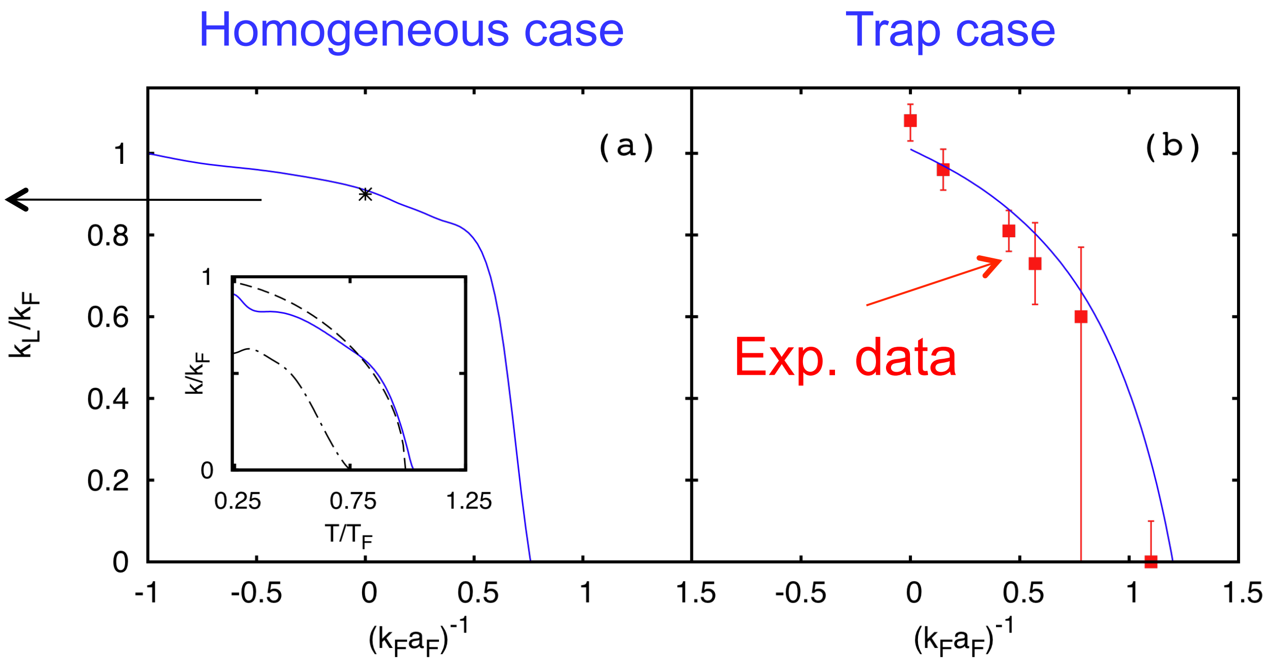
“Quasi-particle” dispersions and widths



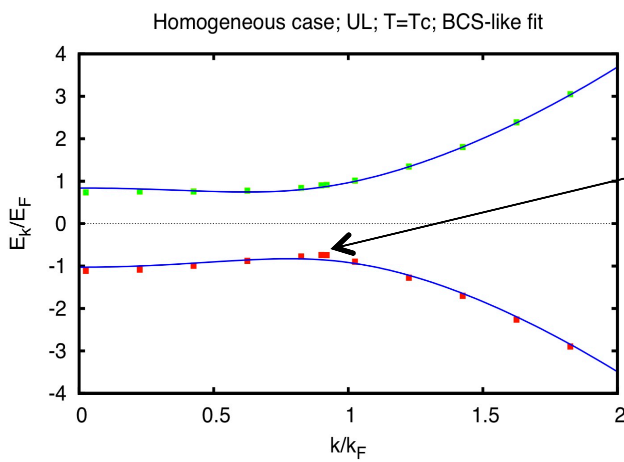
Strong deviations from a Fermi liquid picture of the single particle excitations

"Remnant Fermi surface"in the pseudogap phase

QMC prediction:
J. Carlson and
S. Reddy
PRL **95**, 060401
(2005).

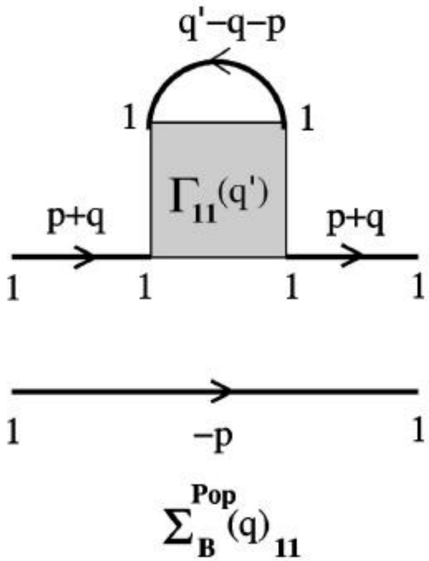


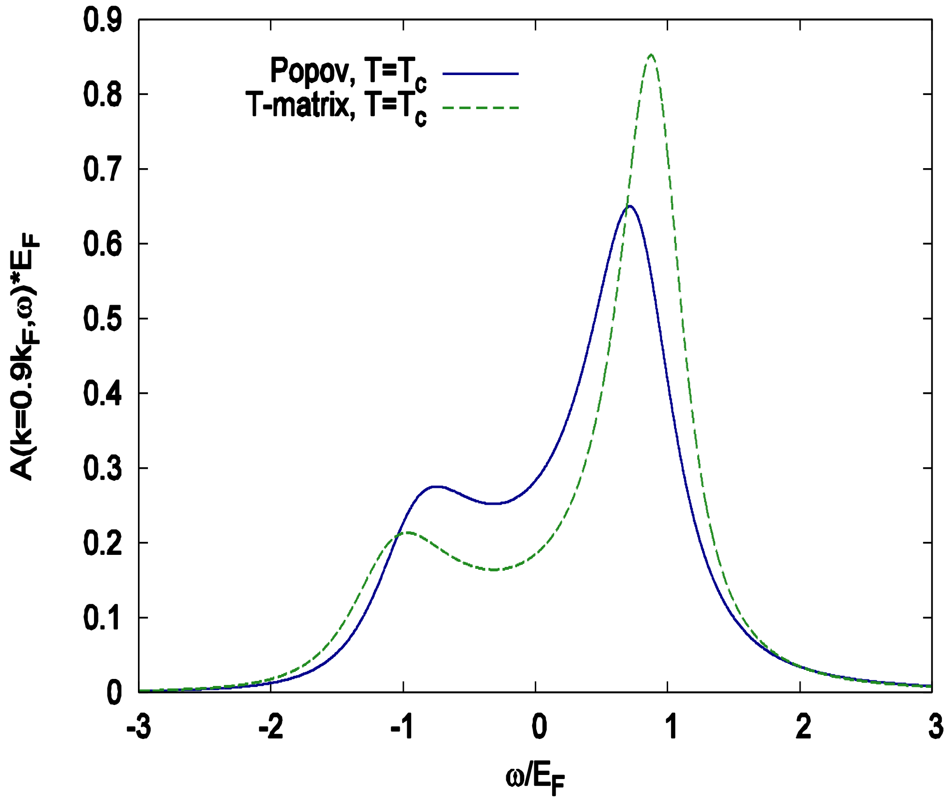
UNICAM + JILA collaboration
A. Perali et al.
PRL **106**, 060402 (2011).

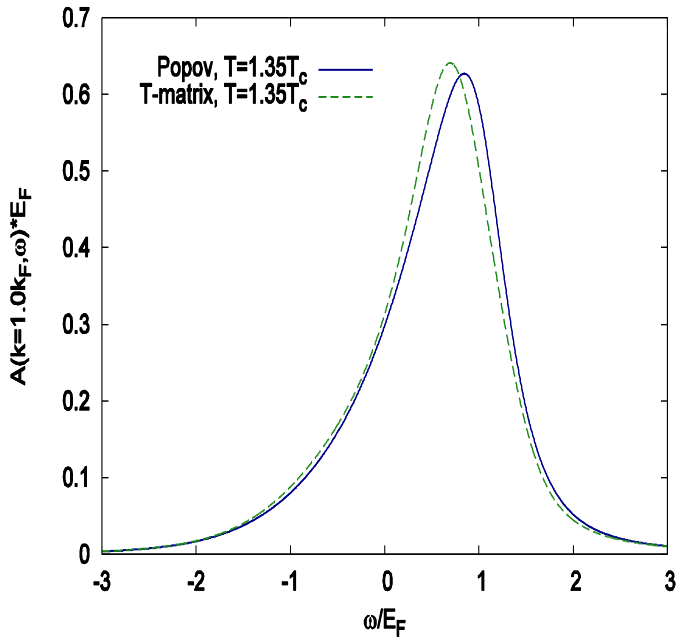


"pseudo-Luttinger"
wave-vector
k_L

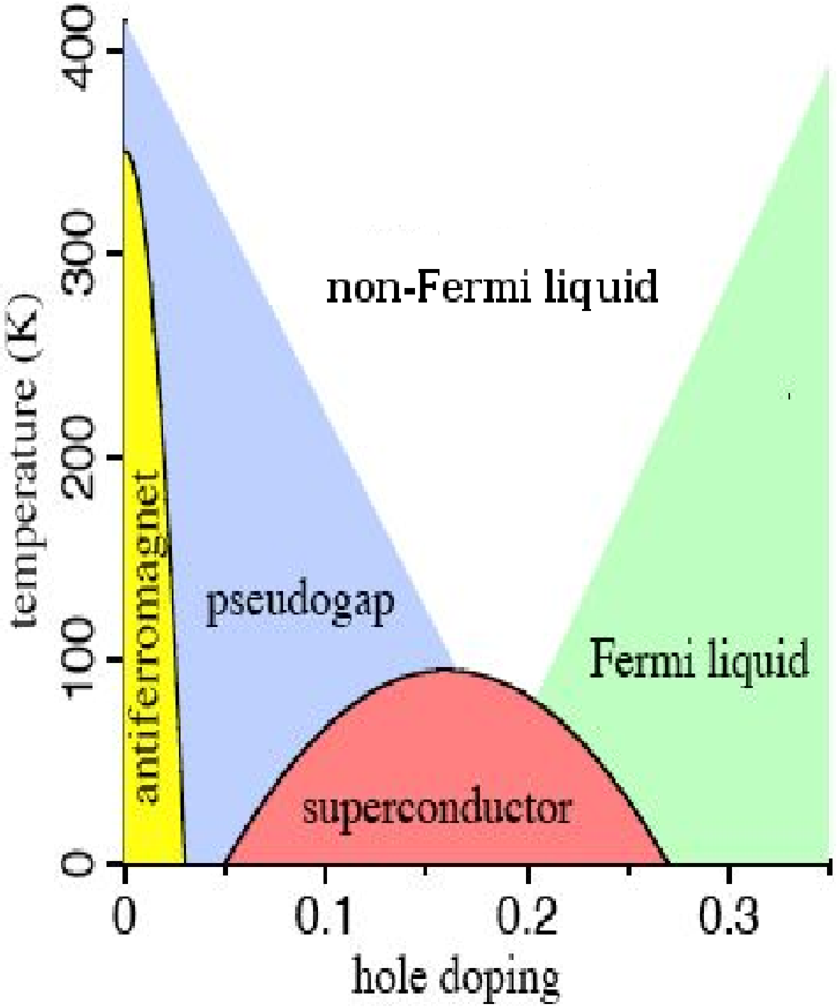
Popov corrections to the t-matrix approach

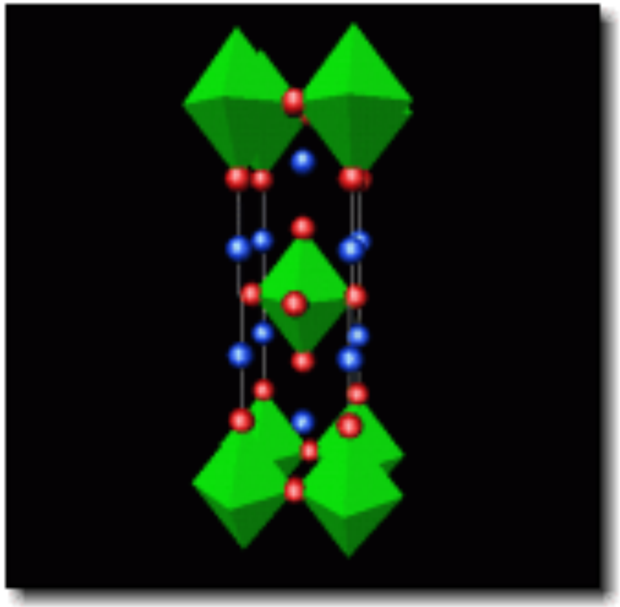






High-Tc superconductors: phase diagram





$La_{2-x}Sr_xCuO_4$

Gap and pseudogap in high-Tc superconductors

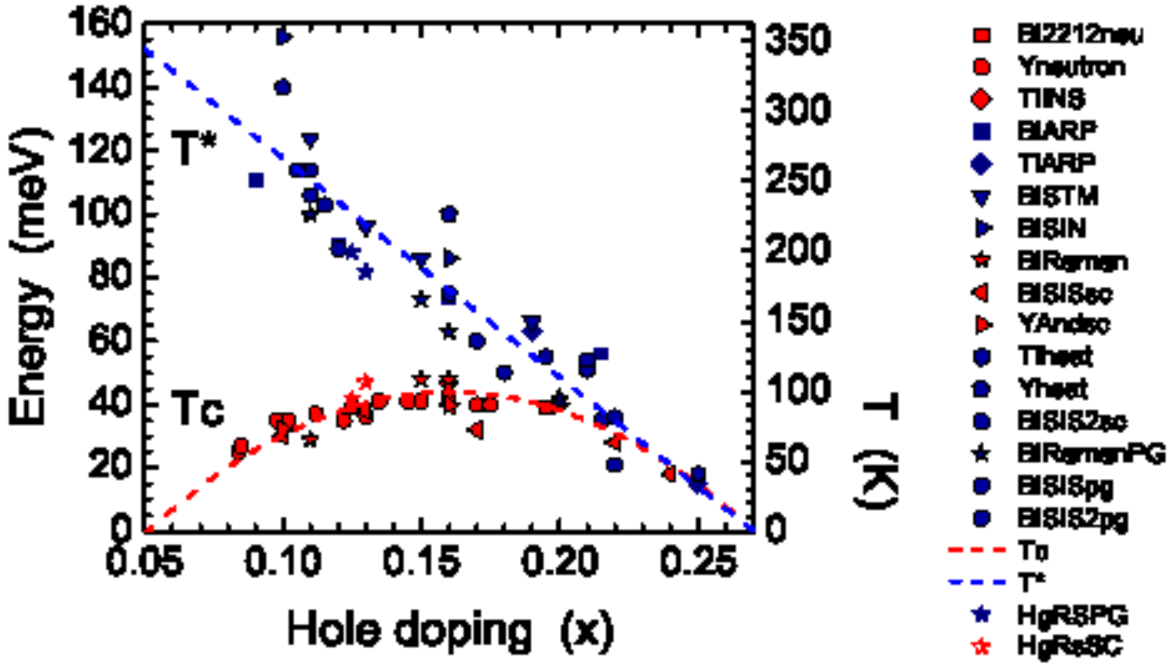


FIG. 2: Energy of pseudogap (blue points) and superconducting gap (red points) for a number of HTSCs as measured as a function of hole doping x (obtained from Ref. [11]). Lines are

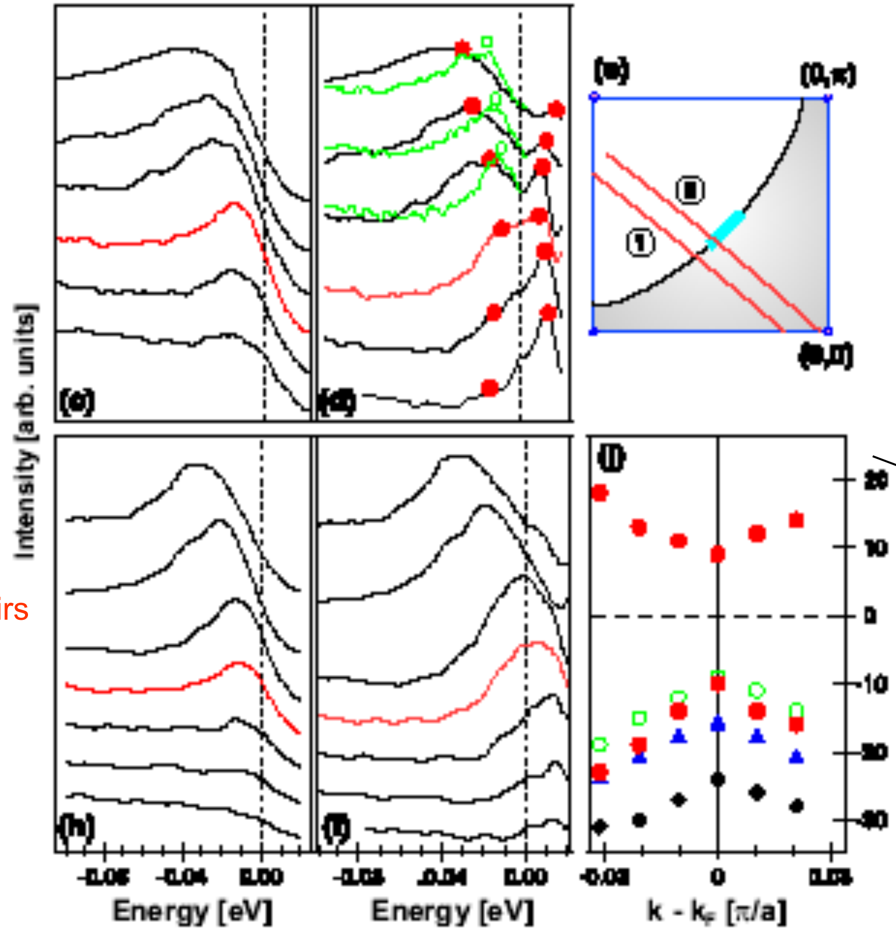
Two Gaps Make a High Temperature Superconductor?
S. Huefner, M. A. Hossain, A. Damascelli, and G. Sawatzky,
Rep. Prog. Phys. 71, 062501 (2008).

Pseudogap in underpoded superconducting cuprates: pairing above Tc *and/or* other mechanisms ?

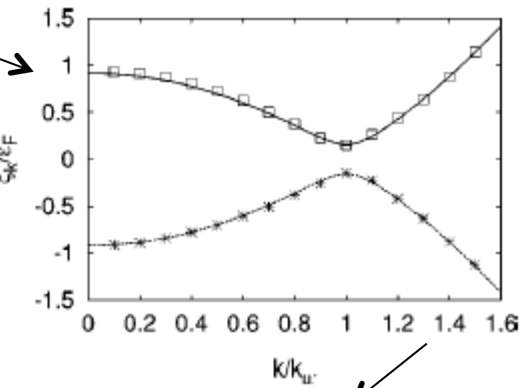
M. Shi, …
Campuzano..
Mesot

EPL **88**, 27008 (2009)

"Spectroscopic evidence for preformed Cooper pairs in the pseudogap phase of cuprates"



ARPES spectra for underdoped $La_{1.895}Sr_{0.105}CuO_4$ at T=49K > *Tc=30 K*

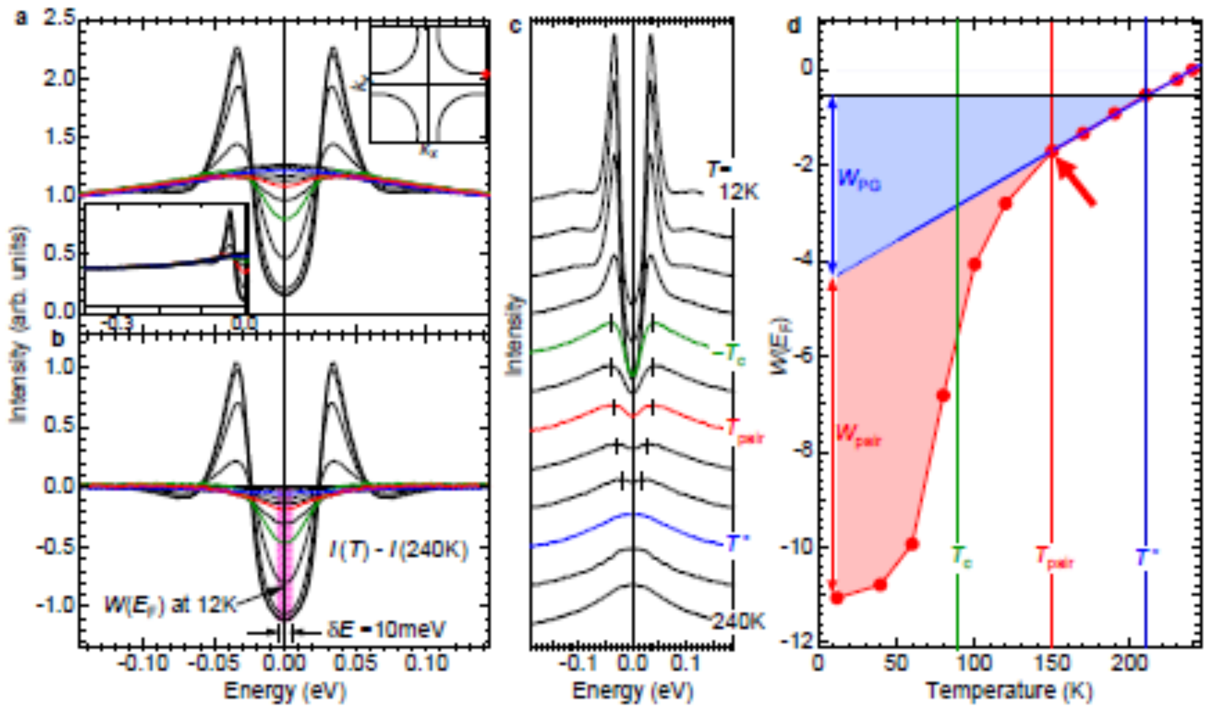


A. Perali, P. Pieri,
B. G.C. Strinati, C. Castellani,
PRB **66**, 024510 (2002).

The dispersions in the gapped region of the zone obtained from the **Fermi function divided spectra**. The pair of **closed circles** are the two branches of the dispersion derived from (d) at **49K**, the dispersion indicated with **open circles** is along the same cut (cut 1 in (e)) but at **12K**. The curves indicated by triangles and diamonds are the dispersions at 49K in the vicinity of the lower underlying Fermi surface along cut 2 and 3 in Fig. 1(j), respectively.

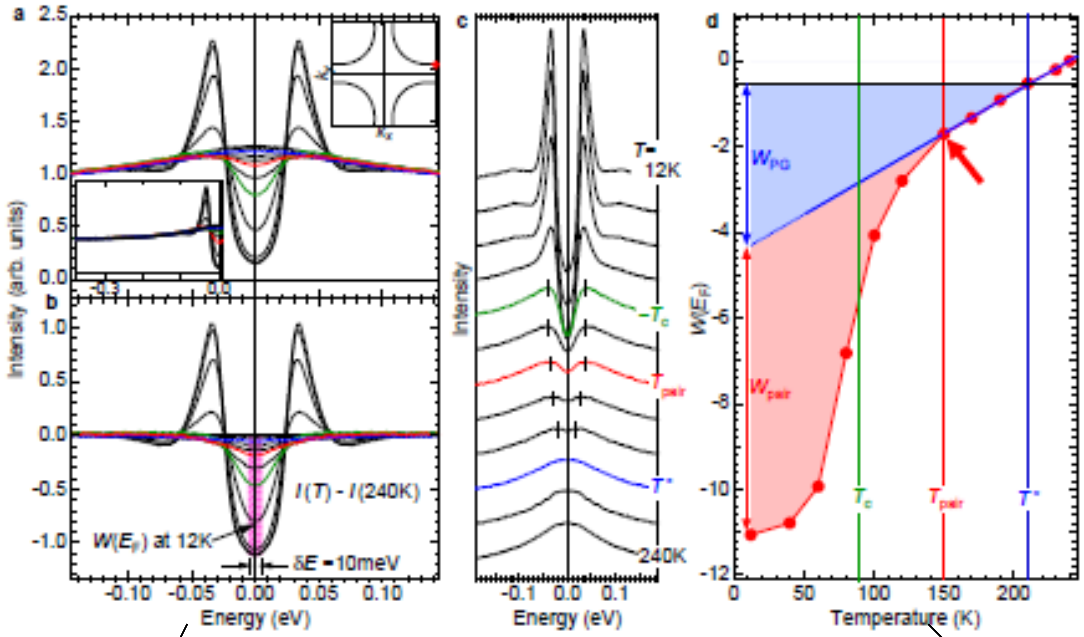
Suppression of spectral weight at the antinode in Bi2212: temperature dependence

ARPES (helium ultraviolet lamp): Energy resolution of 10 meV

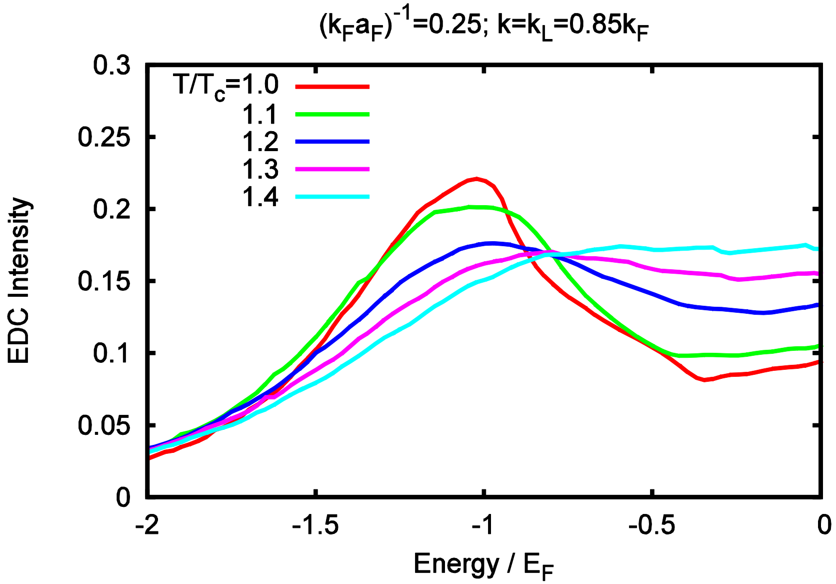


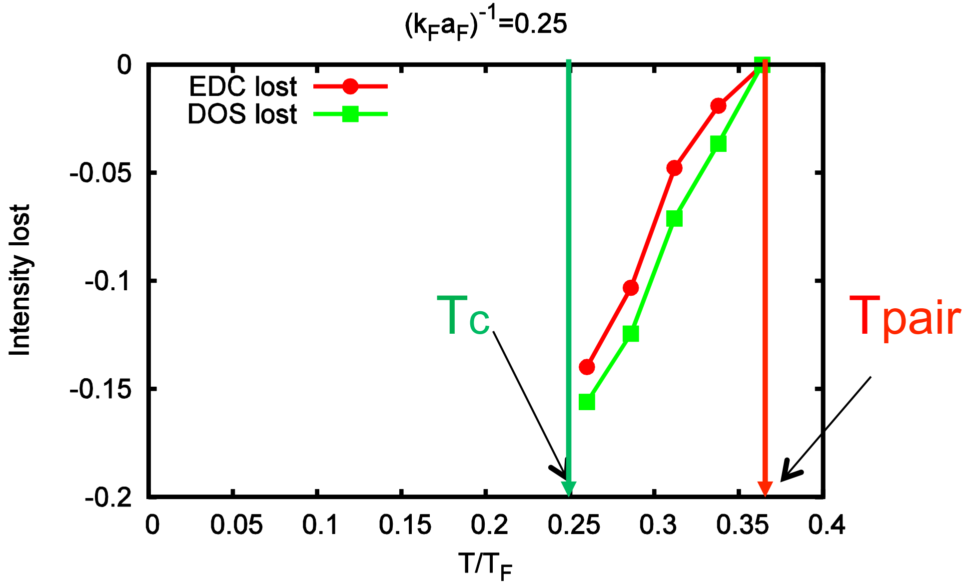
“Disentangling Cooper-pair formation above the transition temperature from the pseudogap state in the cuprates”
T. Kondo et al., Nature Physics **7**, 21 (2011).

Comparison with pseudogap from t-matrix



Rapid intensity
drop with
similar curvature
and slope





Concluding remarks

- A **pairing gap** at T=Tc (**pseudogap**), from close to unitarity to the BEC regime, is present in the single-particle spectral function A(k,w). The peaks dispersion of A(k,w) can be fitted by a BCS-like dispersion, as also obtained in QMC simulations.

- **Momentum resolved RF spectroscopy**: comparison between experiments, QMC for the homogeneous system and t-matrix calculations for EDCs, peaks and widths demonstrate the presence of a pseudogap close to Tc, in the normal phase of strongly-interacting ultracold fermions.

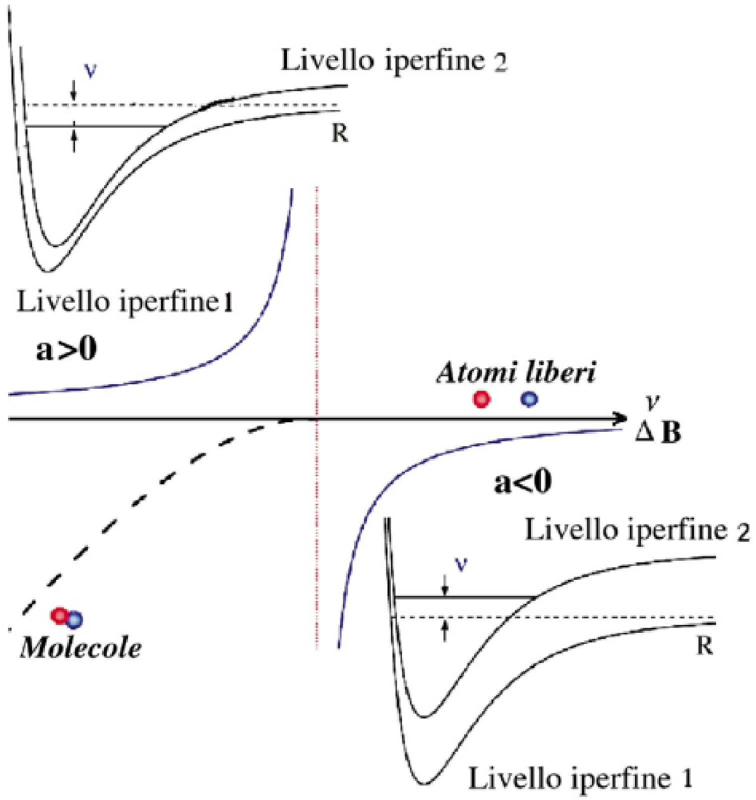
- The pseudogap coexists with a "remnant Fermi surface" which approx. satisfies the Luttinger theorem in an extended coupling range.

- The pseudogap phase of an ultracold Fermi gas in the crossover regime of the BCS-BEC crossover has important similarities with the (strong) pseudogap phase of underdoped cuprates characterized by ARPES.

- Extension of the t-matrix approach to multiband superconductors and superfluids is in progress.

Supplementary material

Fano-Feshbach resonance



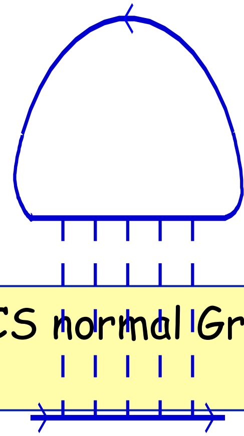
- FF resonance: When the energy of collision between 2 free atoms in the hyperfine level 1 becomes resonant with the energy of the first bound state of the interatomic potential of a second hyperfine level.

The BCS to BEC crossover problem at finite temperature:
inclusion of pairing-fluctuations below and above Tc

T-matrix self-energy in the superfluid phase:

$$\Sigma_{11}(k) = -\int \frac{d\mathbf{q}}{(2\pi)^3} \frac{1}{\beta} \sum_{\Omega_\nu} \Gamma_{11}(q) G_{11}^0(q-k)$$

$$\Sigma_{12}(k) = -\Delta$$



"bare" BCS normal Green's function

Composite boson propagator

$k = (\mathbf{k}, \omega_n)\,;\, p = (\mathbf{p}, \omega_l)\,;\; q = (\mathbf{q}, \Omega_\nu)$

1, 2 : Nambu indices

where

$$\Gamma_{11}(q) = \frac{\chi_{11}(-q)}{\chi_{11}(q)\chi_{11}(-q) - \chi_{12}(q)^2}$$

and

$$\chi_{11}(q) = -\frac{1}{v_0} - \int \frac{d\mathbf{p}}{(2\pi)^3} \frac{1}{\beta} \sum_{\omega_l} G_{11}^0(p+q)\, G_{11}^0(-p)$$

$$\chi_{12}(q) = \int \frac{d\mathbf{p}}{(2\pi)^3} \frac{1}{\beta} \sum_{\omega_l} G_{12}^0(p+q)\, G_{21}^0(-p)$$

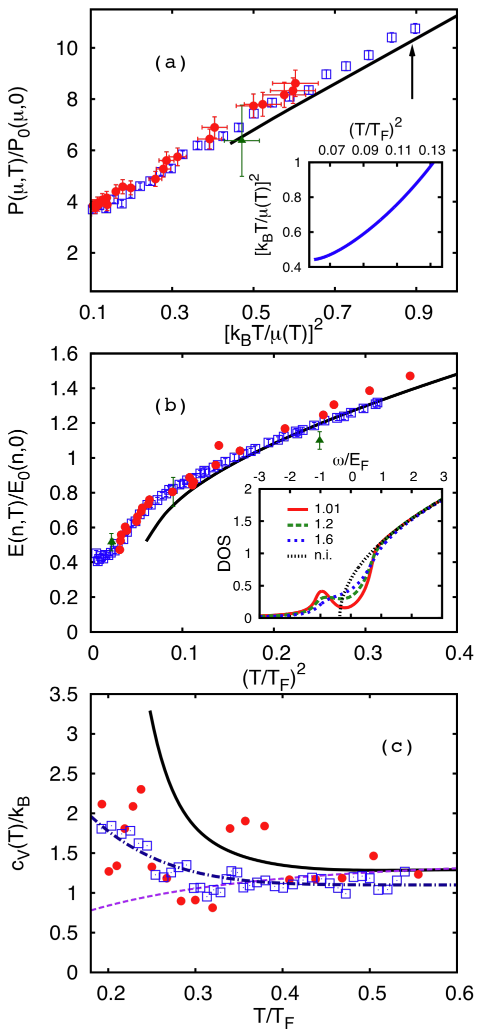
"bare" BCS anomalous Green's function

A. Perali *et al*, Phys. Rev. B **66**, 024510 (2002).

P. Pieri, L. Pisani, and G. Strinati, Phys. Rev. B **70**, 094508 (2004).

Is the unitary Fermi gas in the normal phase a Fermi liquid?

For the normal unitary Fermi gas $T/T_F > 0.15$



S. Nascimbene et al., Nature **463**, 1057 (2010) and arXiv:1006.4052

A. Bulgac et al., PRL **96**, 90 404 (2006)

Gap and pseudogap in underdoped LaSrCuO

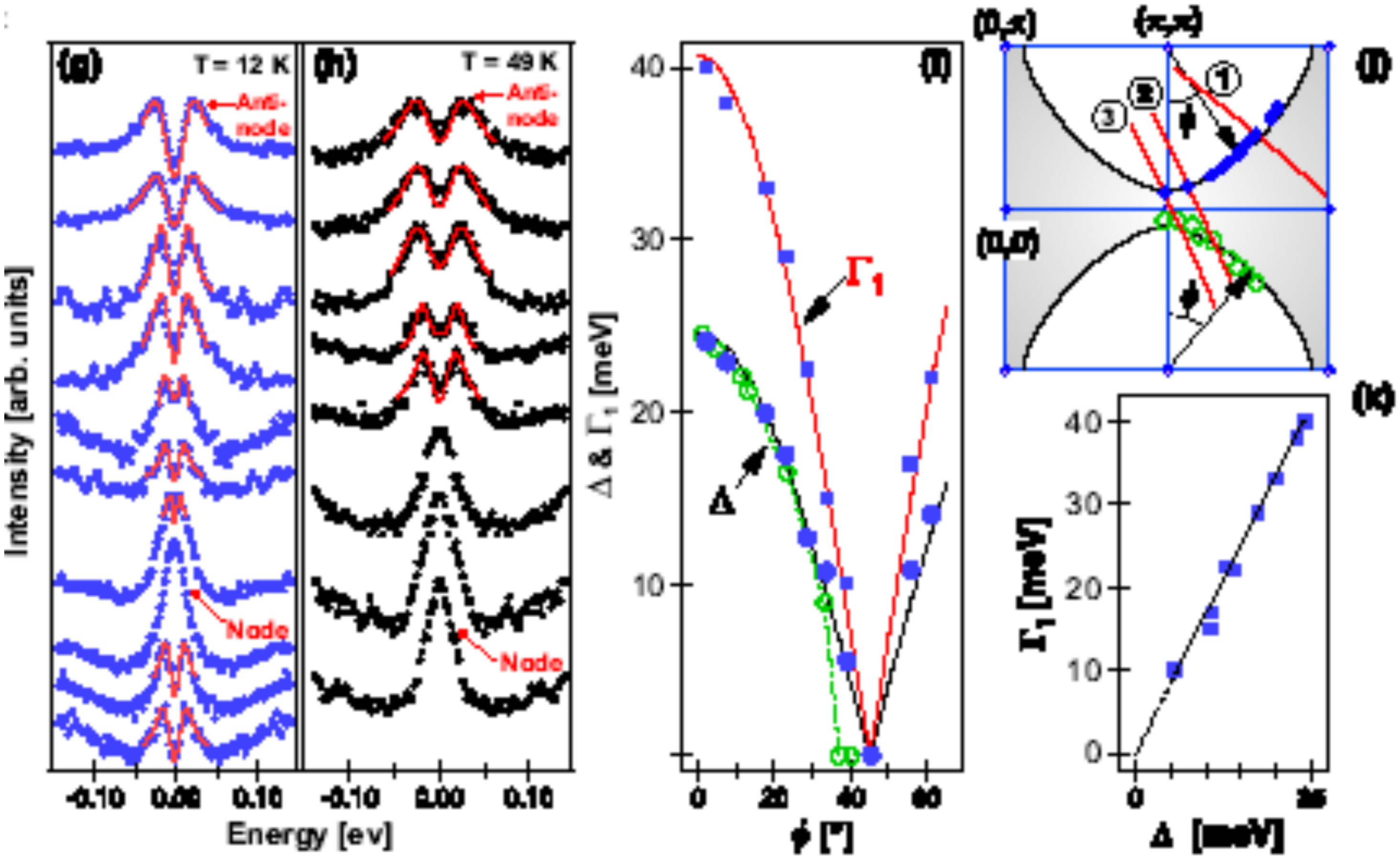
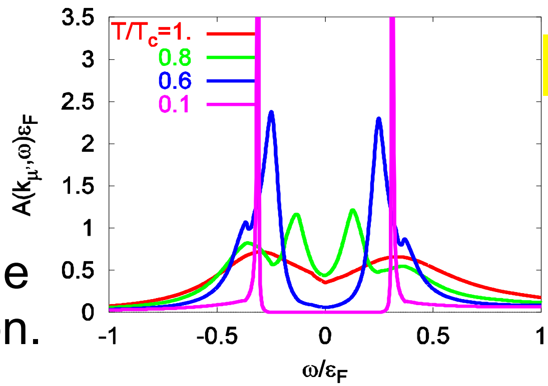


FIG. 1: (Color online) ARPES spectra for underdoped $La_{1.895}Sr_{0.105}CuO_4$ ($T_c = 30K$). (a)-(c): ARPES intensities at $T = 12K$ along momentum cuts that cross the Fermi surface at the node, between the node and the anti-node, and at the anti-node. The corresponding cuts are indicated in (j). (d)-(f): the same as (a)-(c), but the spectra are acquired at 49K. (g)-(h): the symmetrized spectra for various k_F from the anti-node (top) to the node (bottom) at 12K and 49K, respectively. The solid

Spectral weight function below Tc

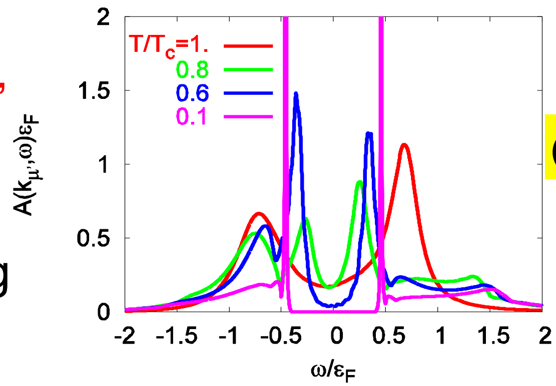
$$A(\mathbf{k},\omega) = -\frac{1}{\pi}\,\mathrm{Im}\,G_{11}^{R}(\mathbf{k},\omega)$$

Wave vector **k** chosen for each coupling at a value $\mathbf{k}_{\mu'}$ which minimizes the gap in the spectral function.



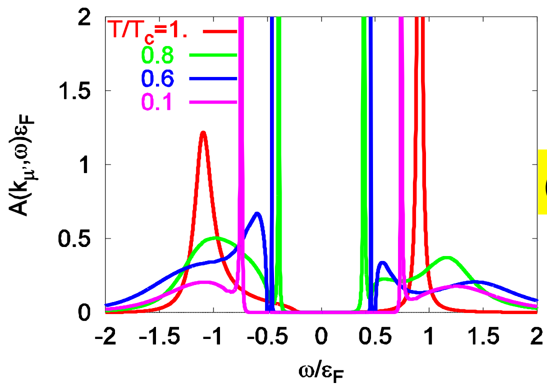
$(k_F a_F)^{-1} = -0.5$

•In the superfluid phase: narrow “coherent peak” over a broad “pseudogap” feature.



$(k_F a_F)^{-1} = 0.1$

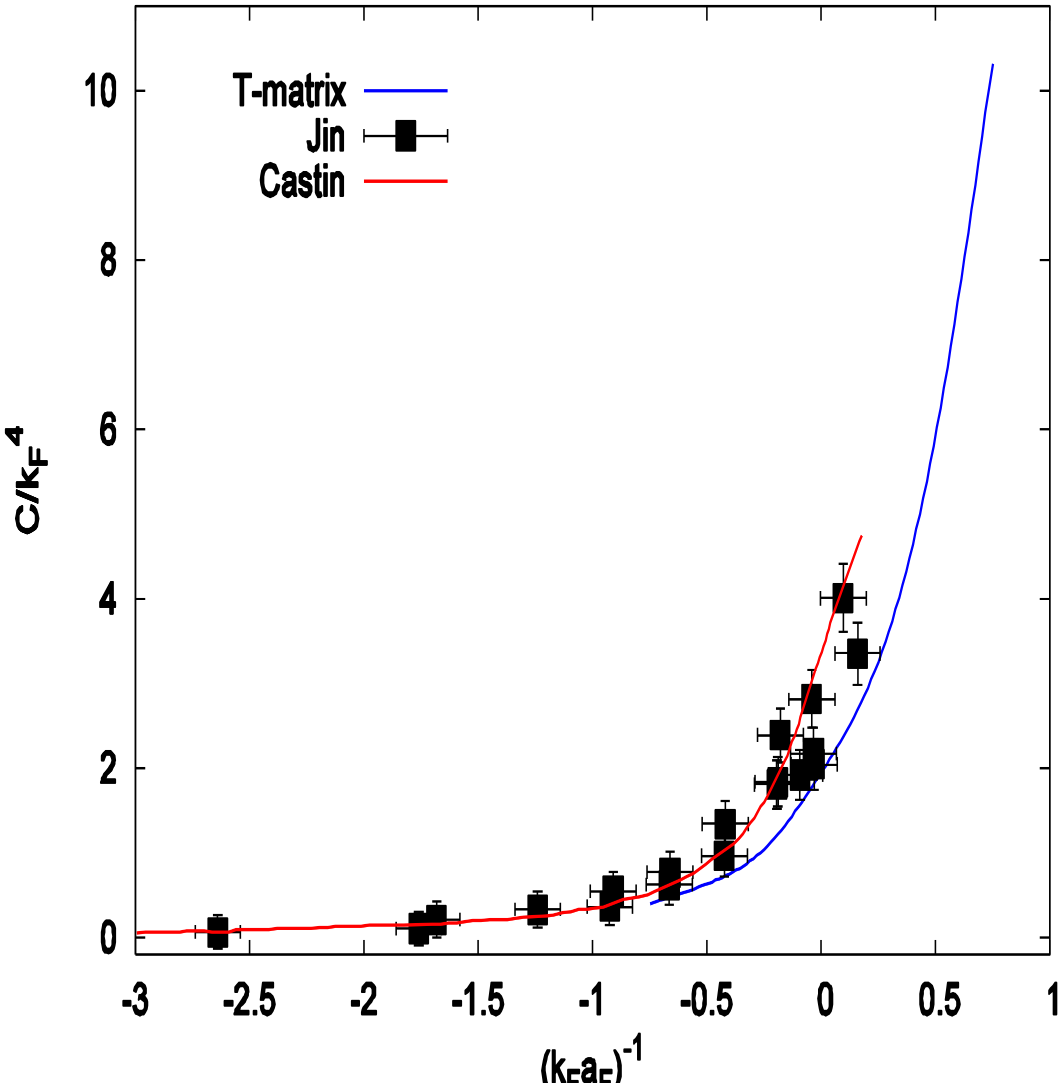
• Pseudogap evolves into real gap when lowering temperature from $T=T_c$ to T=0.



$(k_F a_F)^{-1} = 0.5$

P. Pieri, L. Pisani, G.C. Strinati, PRL **92,** 110401 (2004).

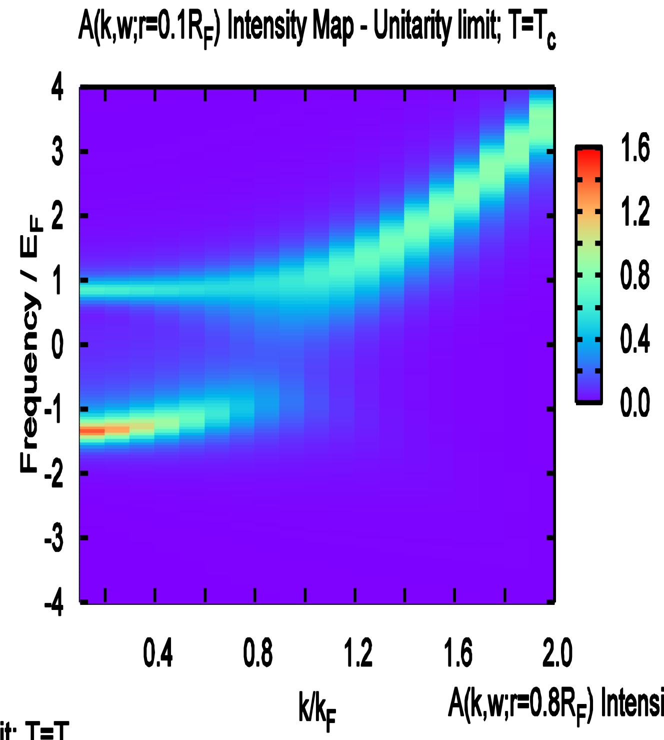
Contact intensity



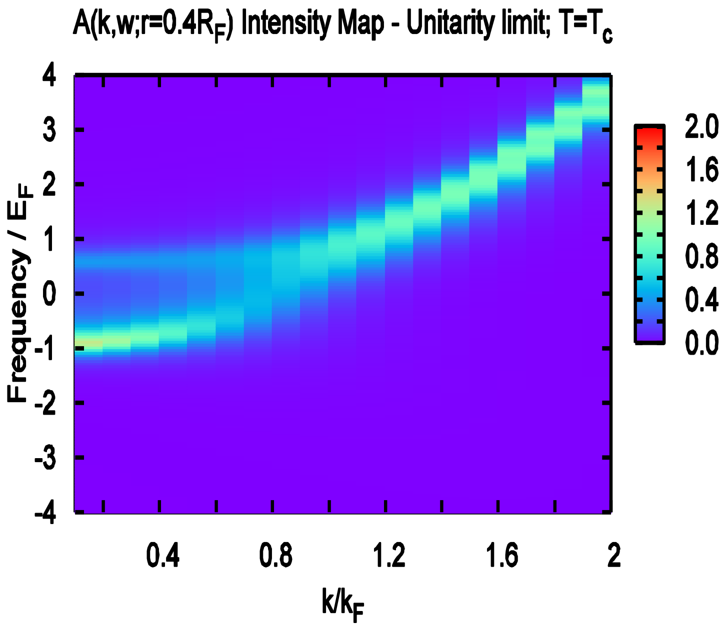
Single-particle spectral function

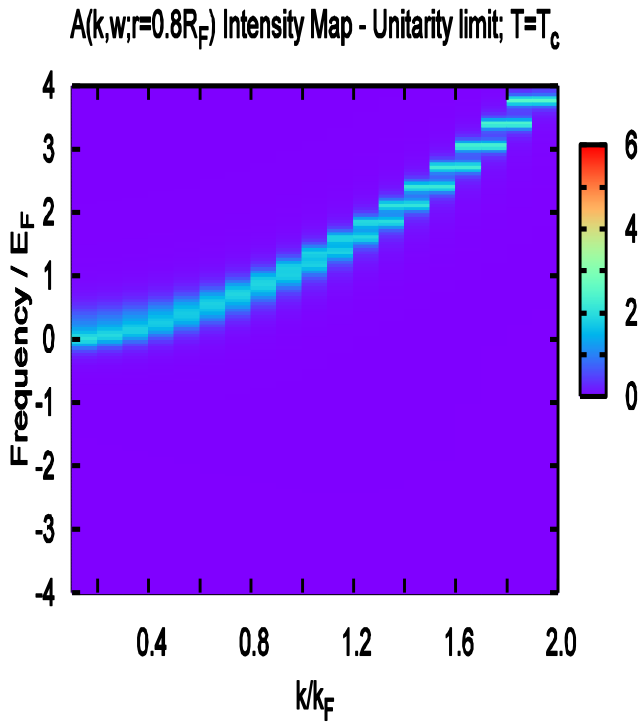
within t-matrix

(trapped case)



Radial dependent
Pseudogap opening



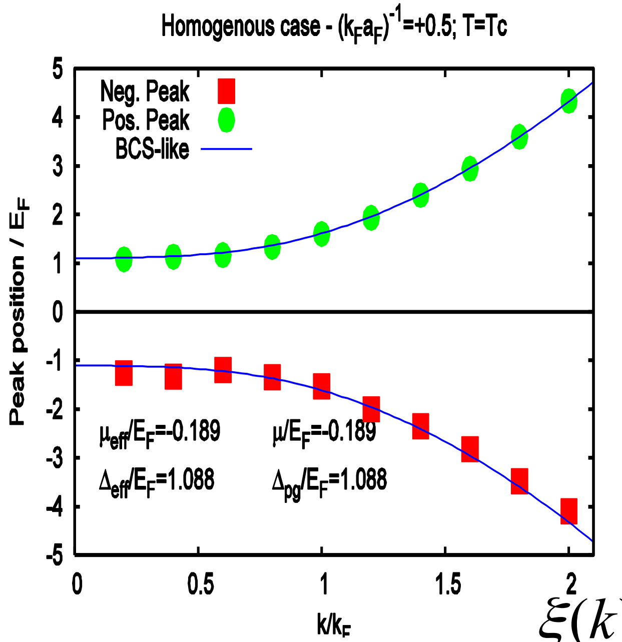


Single-particle spectral function

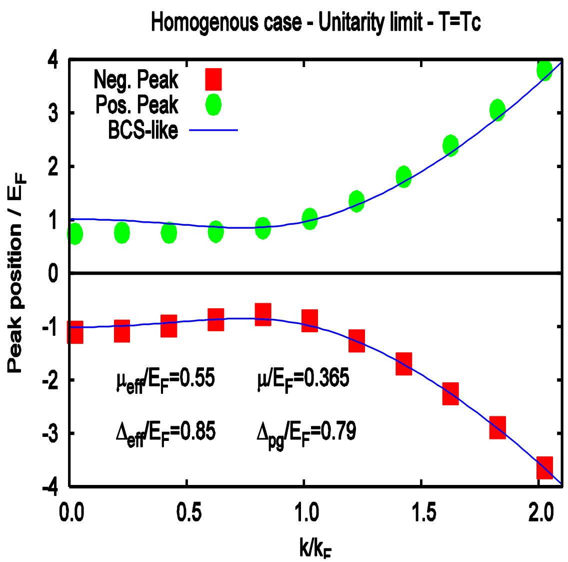
within t-matrix

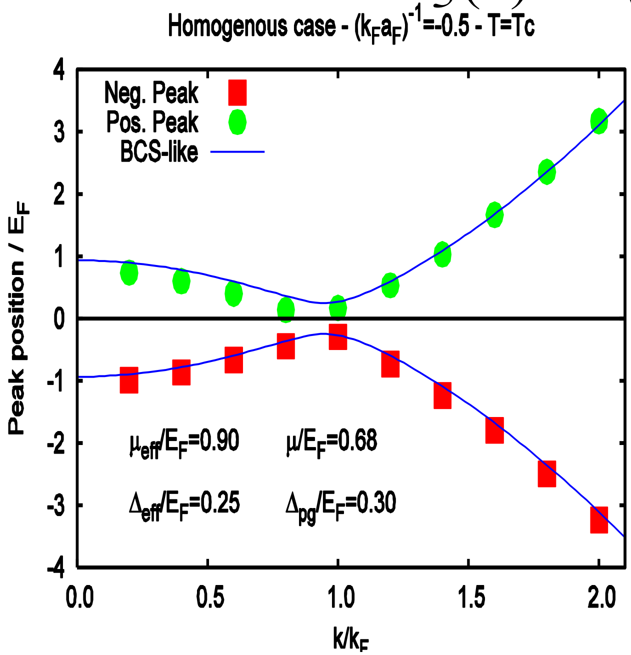
(homogenous case)

Left and Right peaks position as evidence for pseudogap opening

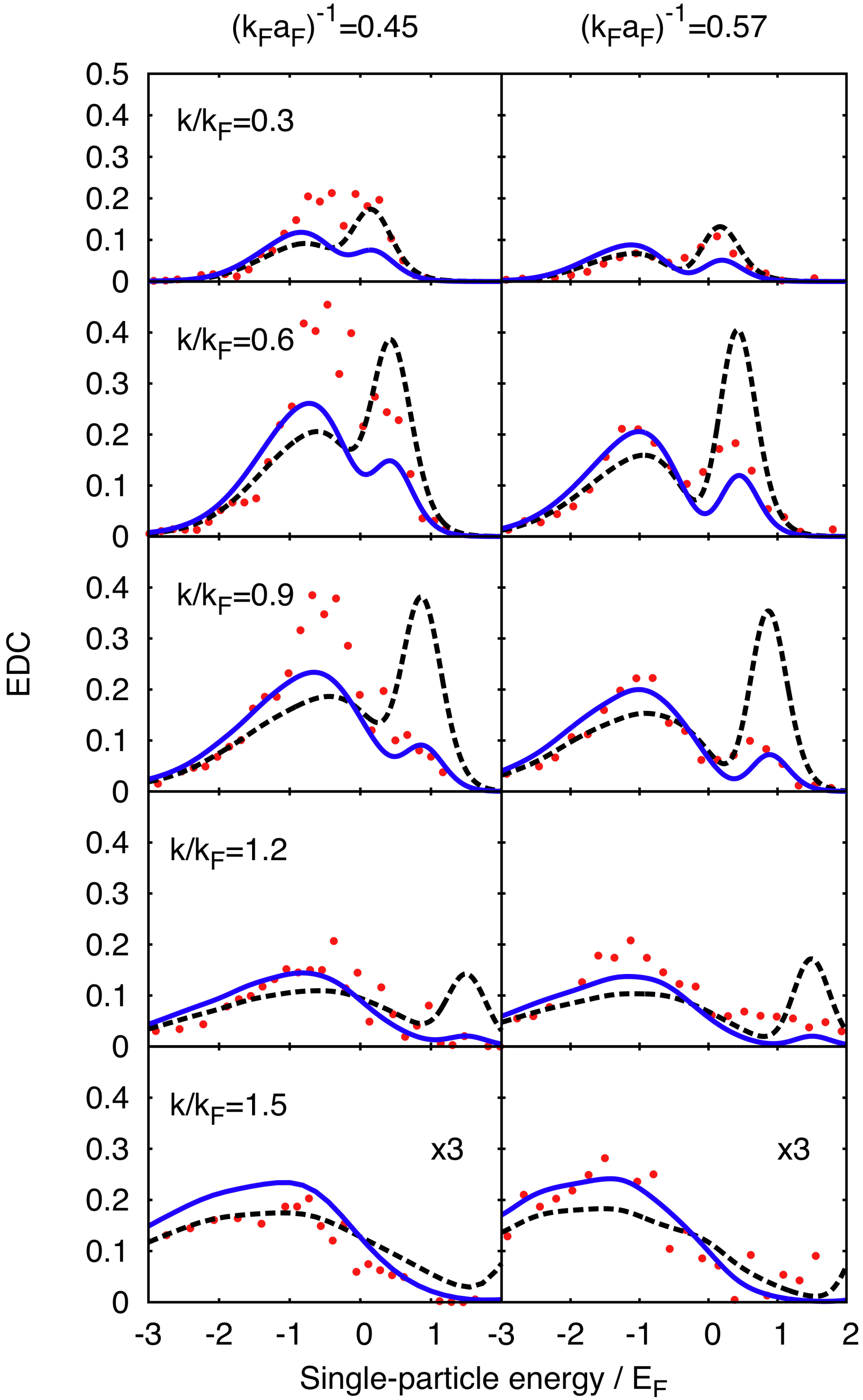


$$\xi(k) = \pm\sqrt{(k^2 - \mu)^2 + \Delta^2}$$





A. Perali *et al*, Phys. Rev. B **66**, 024510 (2002).



$(k_Fa_F)^{-1}$=0.45
$(k_Fa_F)^{-1}$=0.57
k/k_F=0.3
k/k_F=0.6
k/k_F=0.9
k/k_F=1.2
k/k_F=1.5
x3
x3
EDC
Single-particle energy / E_F