Twin peaks in radio-frequency spectra of normal Fermi gases

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more on fermions from Henk Stoof at 13.30 today (F06)

Physics@FOM, Veldhoven, 23rd of January 2008

Pairing and superfluidity in Fermi systems

- Strongly-correlated fermions:
  - neutron stars and quark-gluon plasma
  - high-T_c superconductors
  - quantum gases

T [K]	T/T_F
10^{12}	10^{-6}
1~100	10^{-2}
10^{-9}	0.2

- In BCS theory pairs condense as they form, but when interactions are strong $T^{pairing} > T_{superfl.}$

- Rf measurements: a tool to probe interactions, presence of molecules and onset of pair correlations.

C. Regal et al. (Nature 2003), C. Chin et al., (Science 2004).

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Pairing Without Superfluidity: The Ground State of an Imbalanced Fermi Mixture

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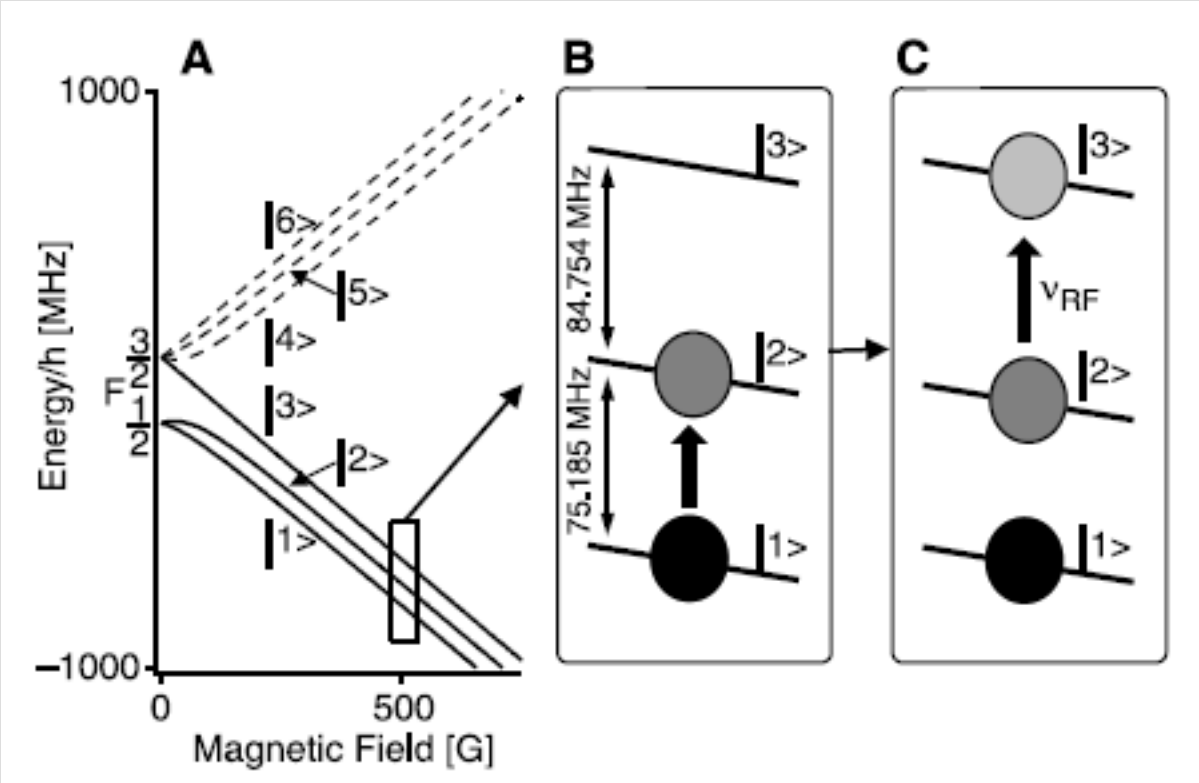

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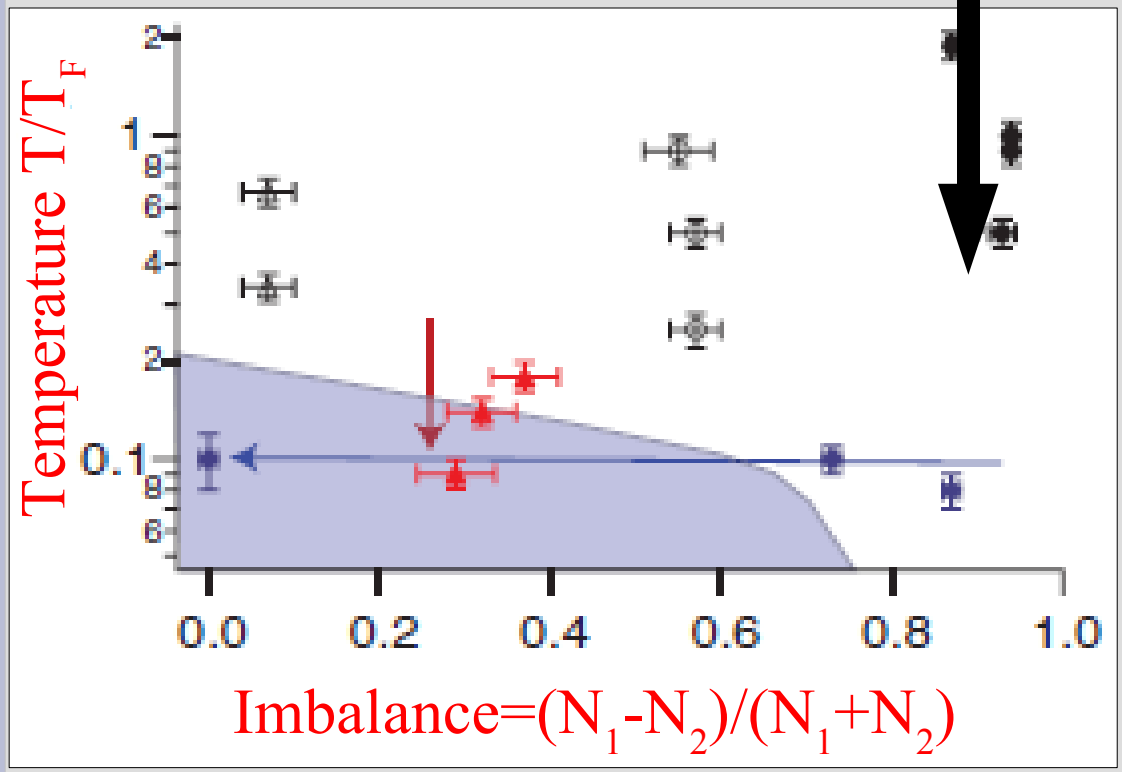
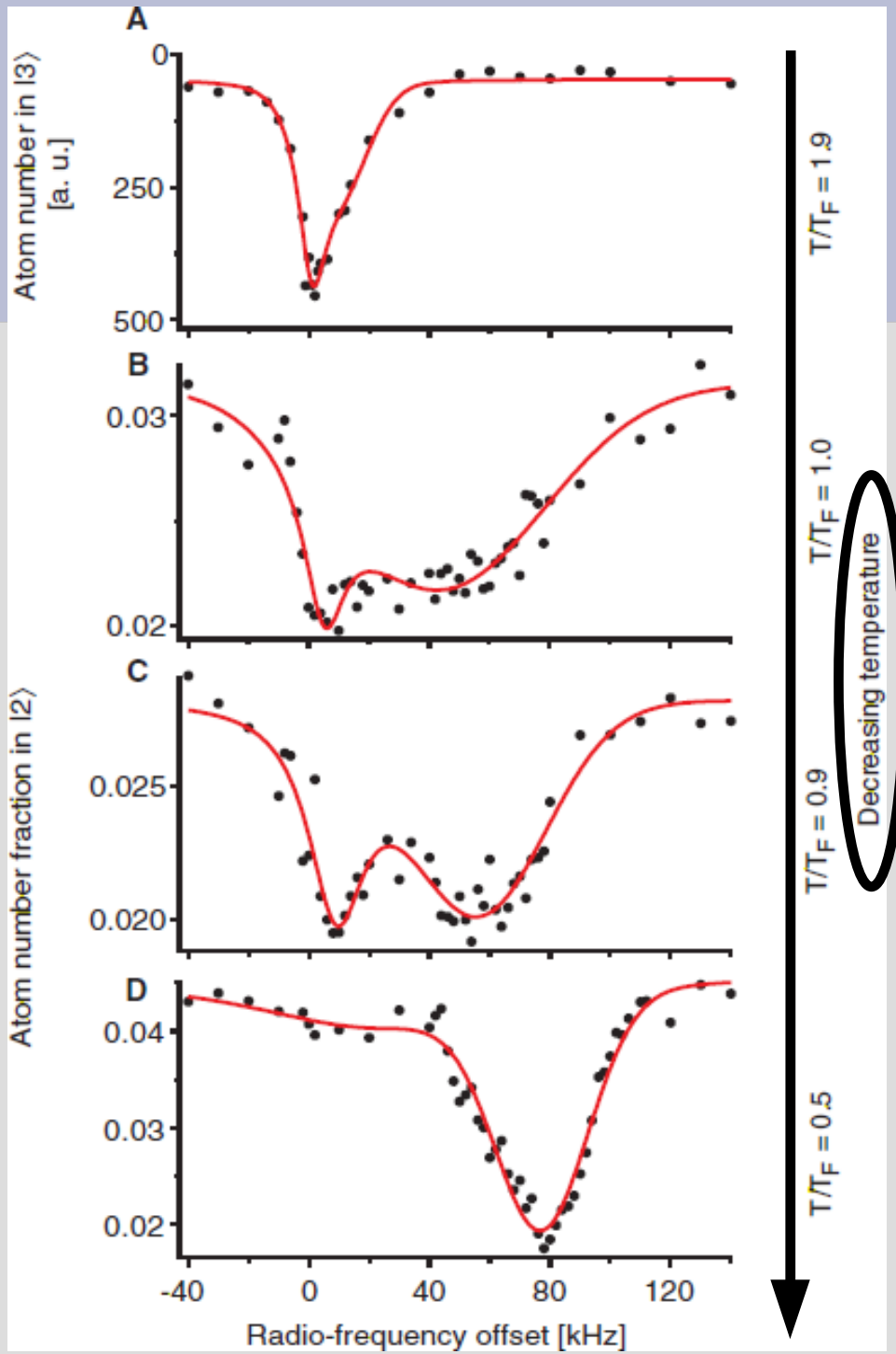
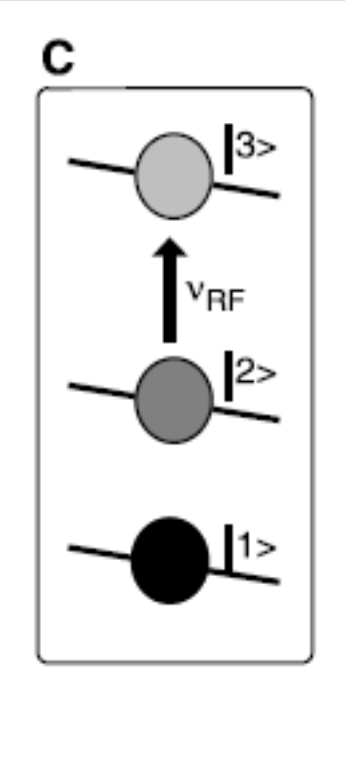
$N_2/N_1=5\%$





Linear response theory



$$H_{\rm rf} = \frac{\Omega}{2}\int d\mathbf{r}\left[e^{-i\omega t}\psi_3^\dagger(\mathbf{r},t)\psi_2(\mathbf{r},t) + \text{h.c.}\right]$$

$$\text{Transition rate: } R(\omega) \propto -\int d\mathbf{r}d\mathbf{r}'\,\text{Im}\mathcal{D}(\mathbf{r},\mathbf{r}',\omega)$$

$$\mathcal{D}(\mathbf{r},\mathbf{r}',\omega) = \text{F.T.}\Big\{-i\theta(t-t')\langle[\psi_3^\dagger(\mathbf{r},t)\psi_2(\mathbf{r},t),\psi_2^\dagger(\mathbf{r}',t')\psi_3(\mathbf{r}',t')]\rangle\Big\}.$$

Working Assumptions:
use ladder approx. to evaluate T-matrix and self-energy
include the resonant 1-2 interaction
neglect the weaker 1-3 interaction

Spectral function A_2 and spectrum

(no trap, unitarity, $T>T_c$)

Inset: $A_2(\omega)=-2\mathrm{Im}G_2(k=0,\omega)$

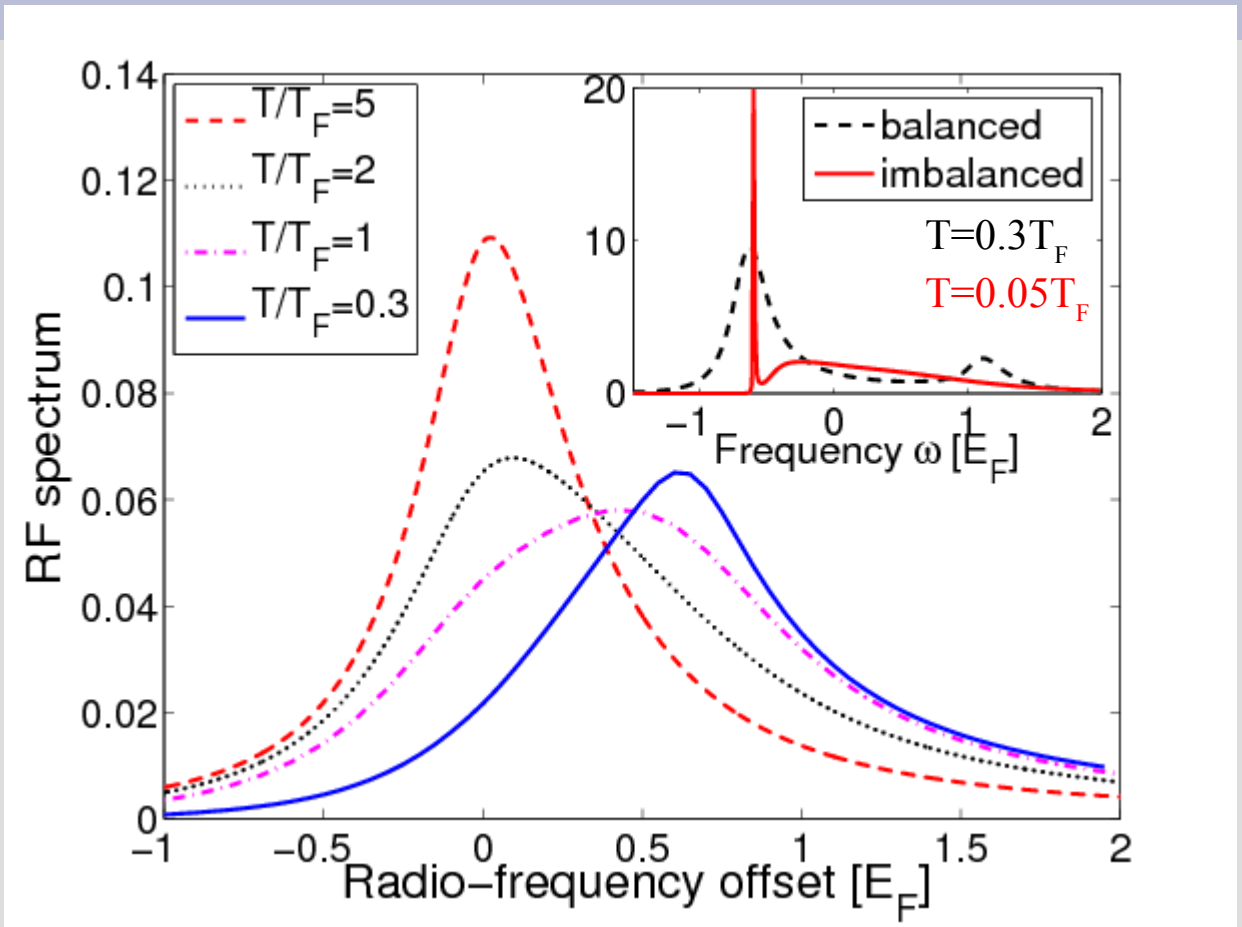
(*pseudogap* regime)

Energy of an impurity in a Fermi sea,
MC result by Lobo et al., PRL 2006.

Main:
spectrum ($T=0.3T_F$, $n_1=n_2$)

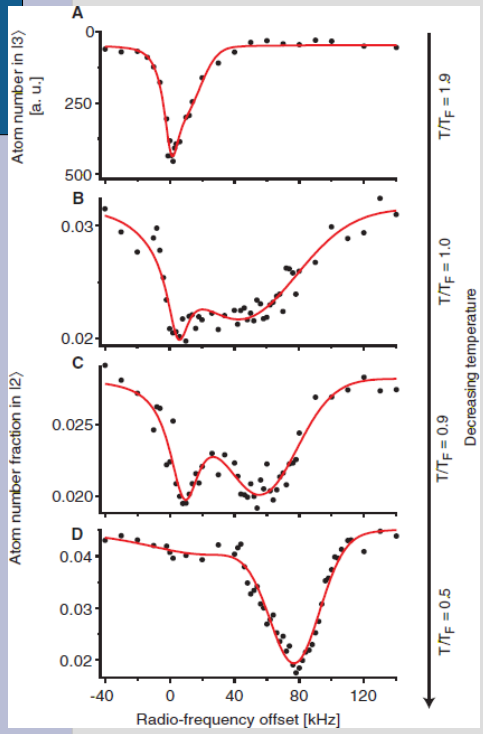
$$\mathrm{Im}\mathcal{D}(\omega) = -\mathcal{V}\int \frac{d\mathbf{k}}{(2\pi)^3} A_2(k,\xi_{2k}-\omega) f(\xi_{2k}-\omega)$$

$$\xi_{2k} = k^2/2m - \mu_2$$



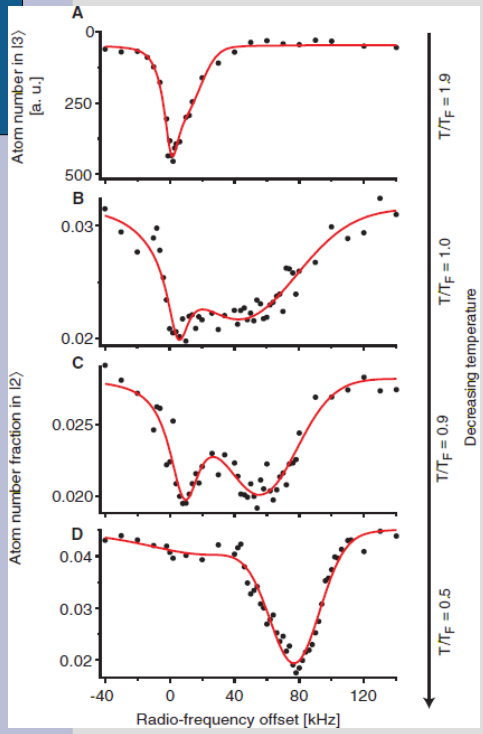
No double peaks,
even in the pseudogap regime!

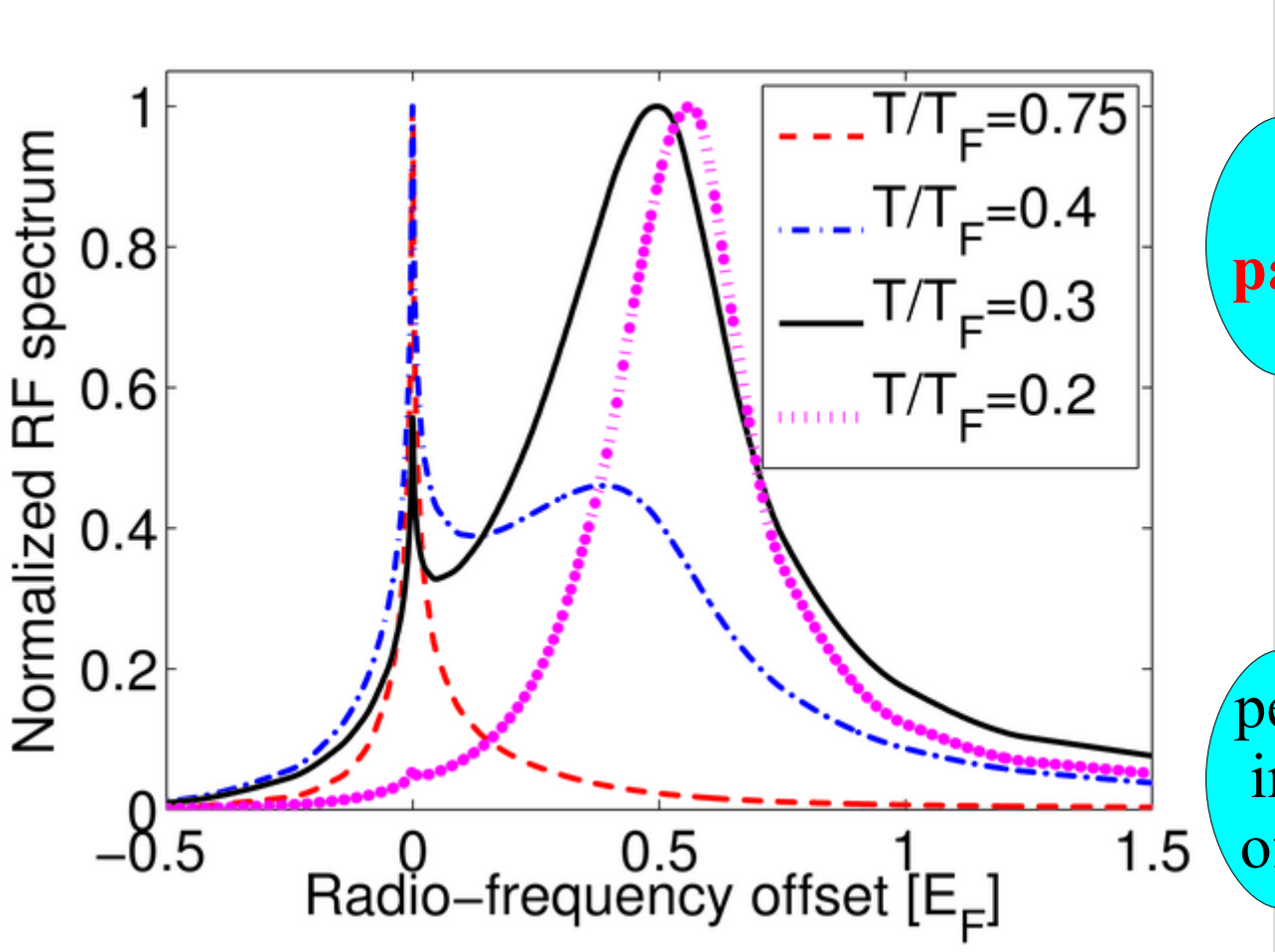
Spectrum of a trapped sample at unitarity



$N_2/N_1=5\%$

Spectrum of a trapped sample at unitarity



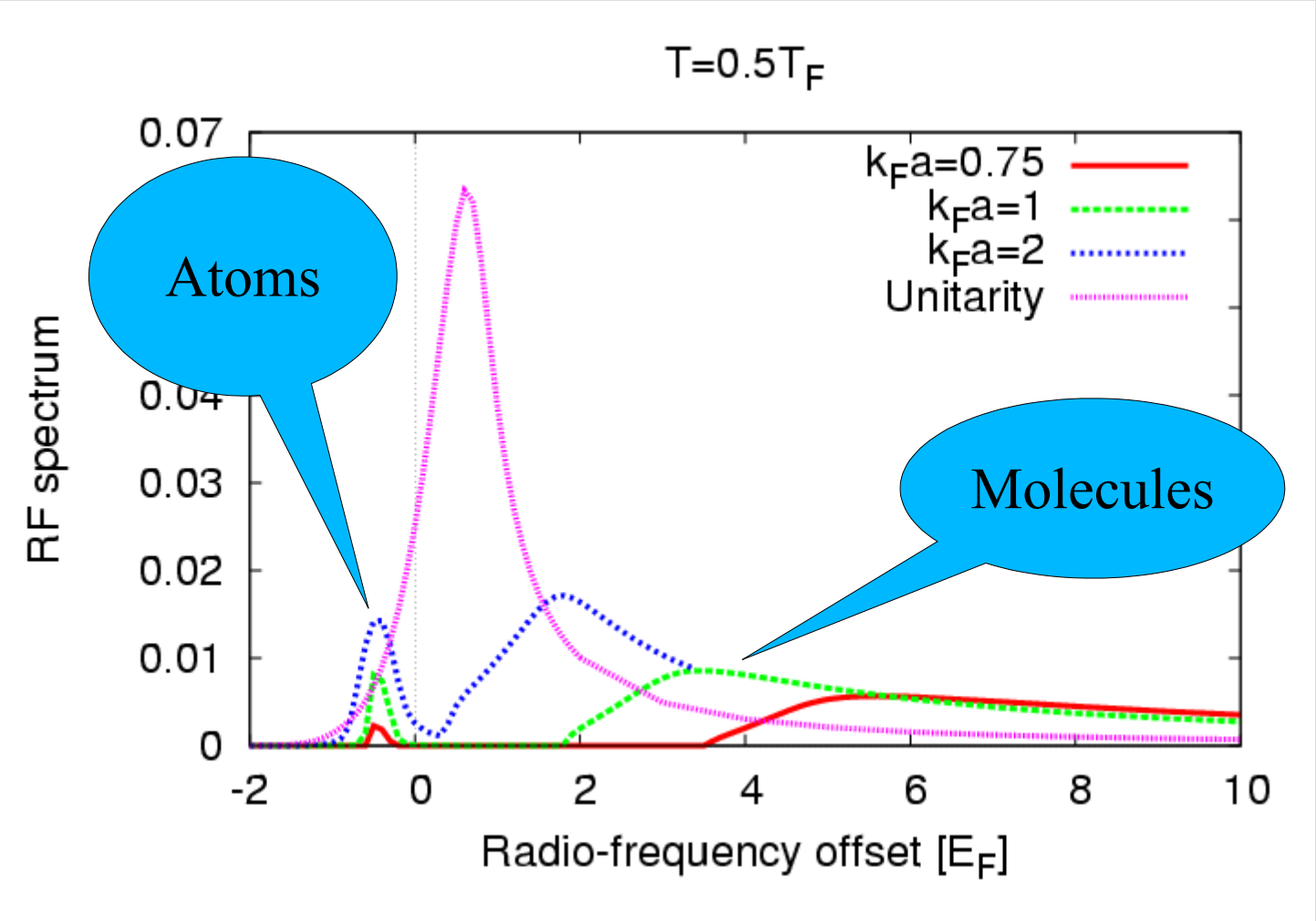


no fitting parameters!

peak position independent of imbalance

$N_2/N_1=5\%$

Double peaks on the BEC side
(no trap, $n_1=n_2$)



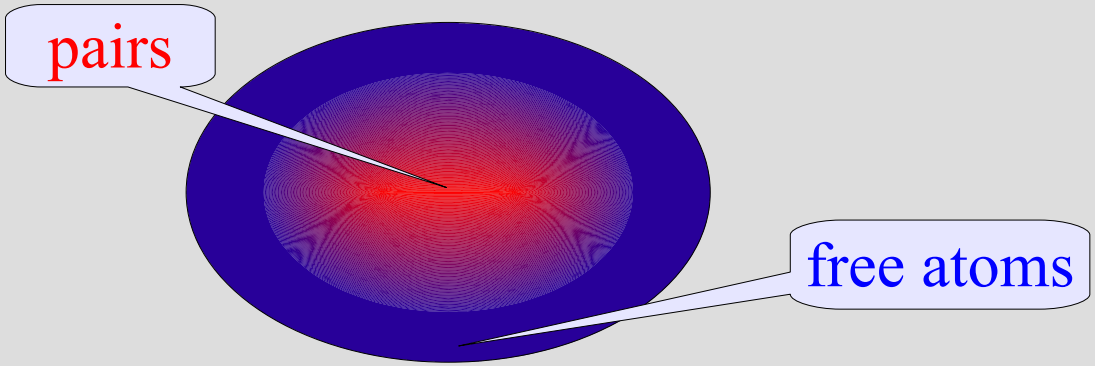
Atoms coexist with molecules for $T<E_b$

Binding energy $E_b \propto \frac{1}{(k_F a)^2}$

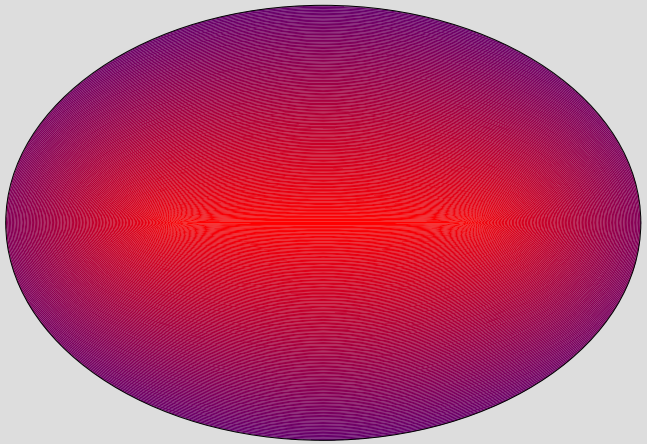
Conclusions

- At unitarity no ***local*** coexistence of free atoms and pairs at any imbalance for $T>T_c$

  (the double-peak structure comes from the trap)

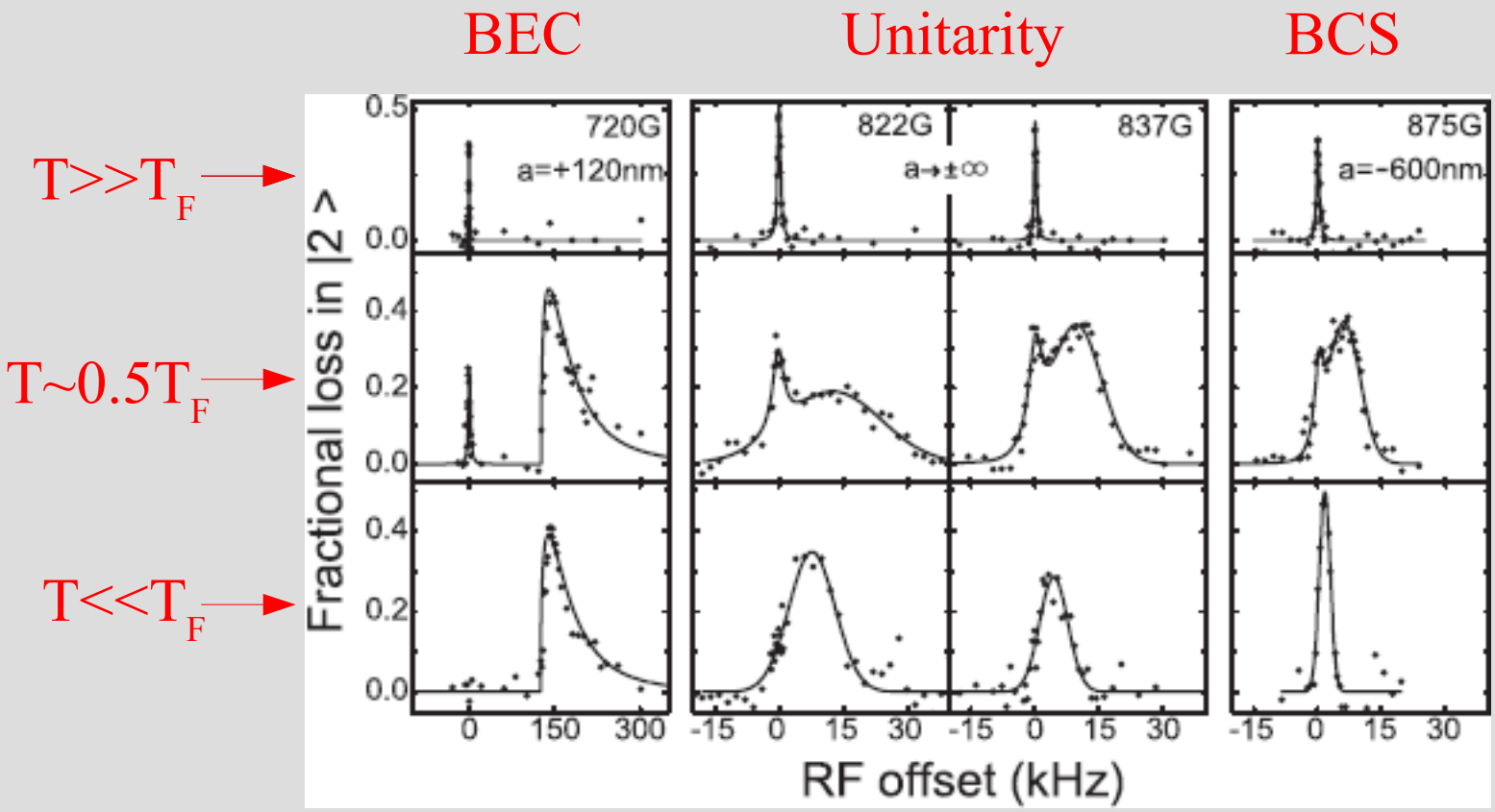


- Only on the BEC side of the resonance $(0<k_F a<1)$ unpaired atoms coexist locally with molecules

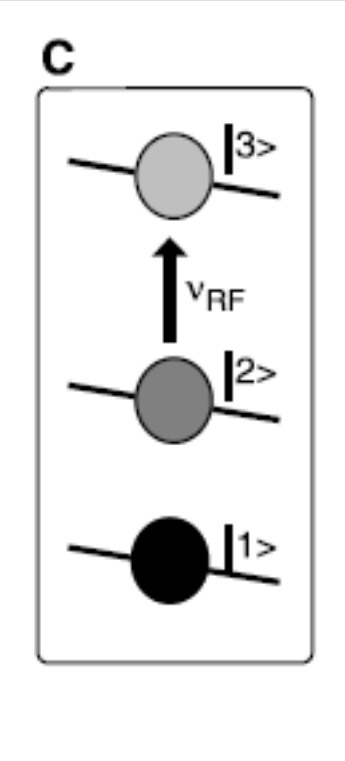


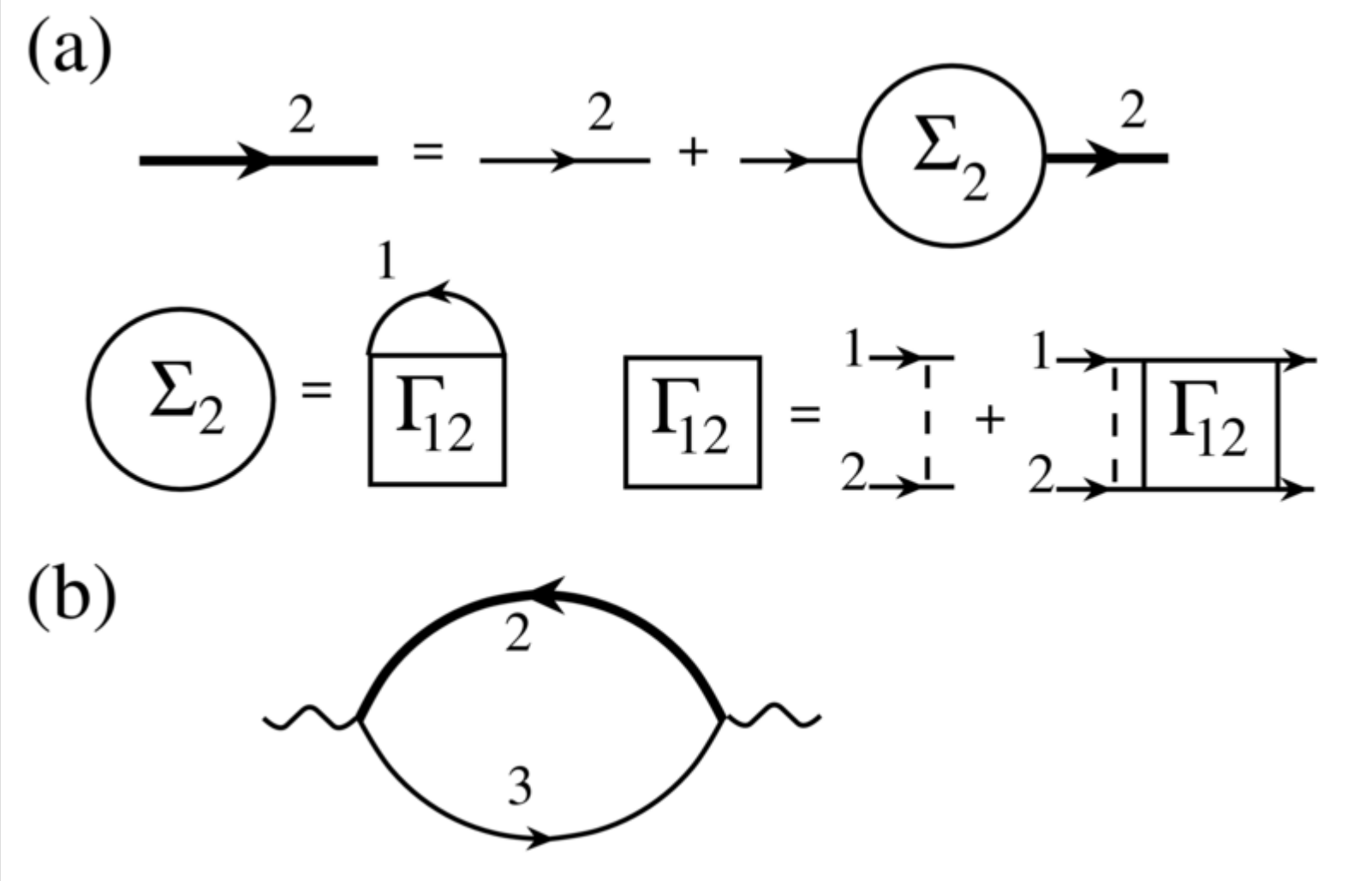
Radio-frequency spectra

C. Chin et al., (Science 2004).

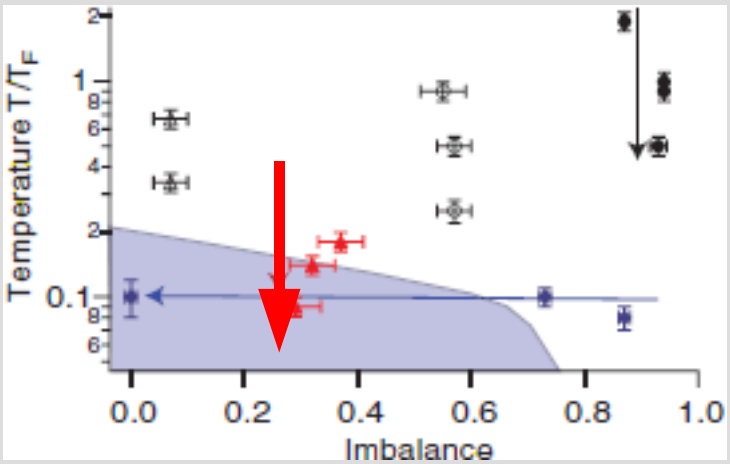


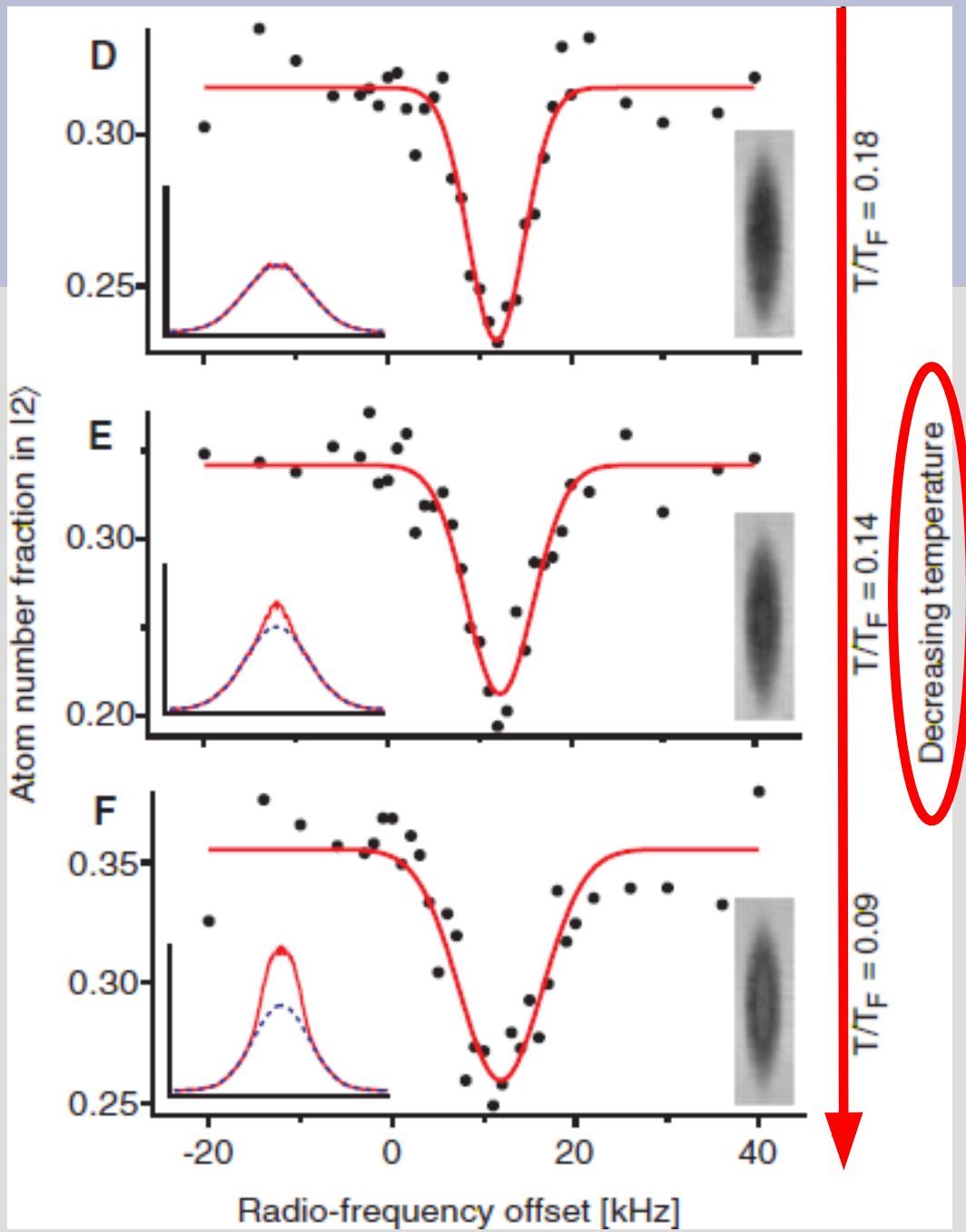
T-matrix and self-energy in the ladder approx.



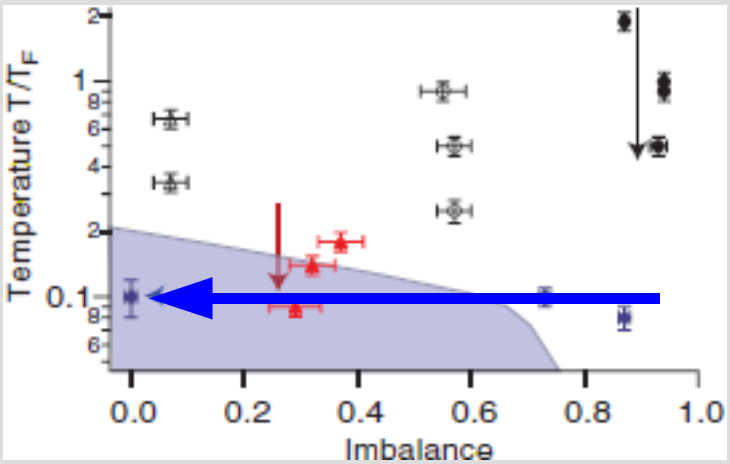


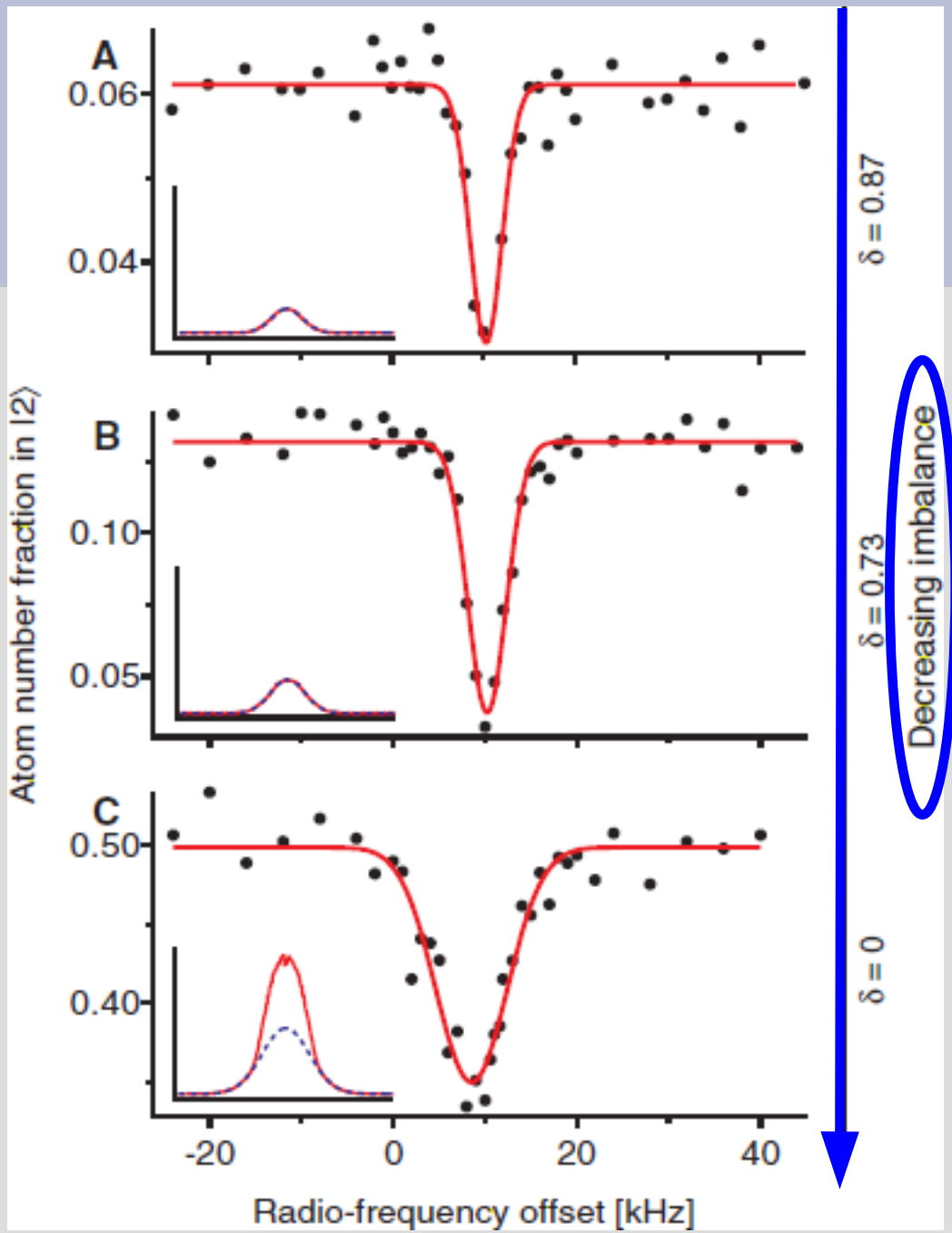
(at 834G interaction 1-2 is resonant, so neglect the 1-3)





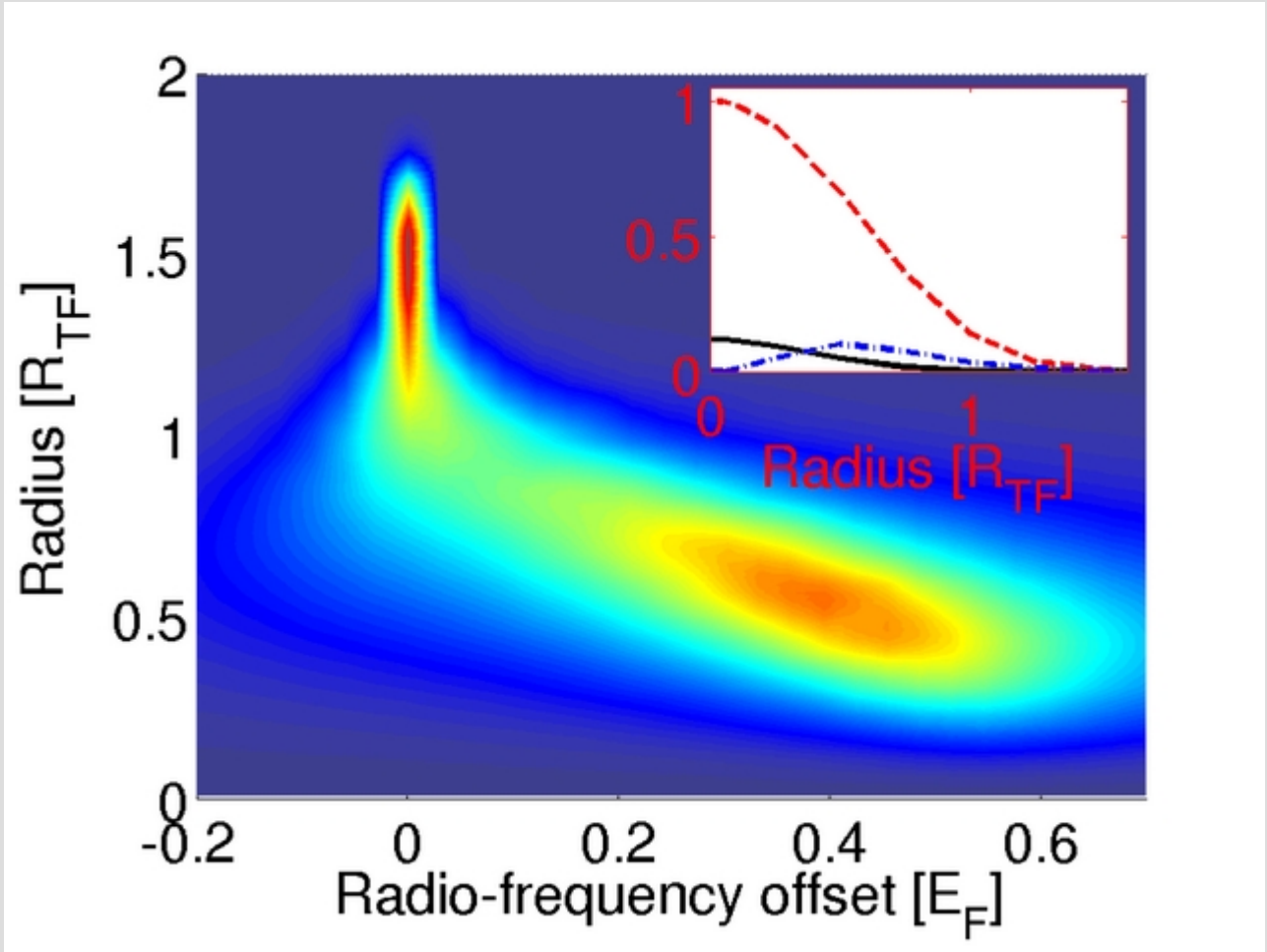
Imbalance=$(N_1-N_2)/(N_1+N_2)$





Imbalance=$(N_1-N_2)/(N_1+N_2)$

Integrand of the trapping average



$n_1(r)$

$n_2(r)$

$r^2 n_2(r)$

$T=0.4T_F$

Imbalance=0.9

Improvements

- The pairing peak appears at a lower T and is too shifted: include the 1-3 interaction and the Aslamazov-Larkin correction

(Baym et al., Punk et al.: shift ~ $\frac{1}{a_{12}} - \frac{1}{a_{13}}$)

- In the ladder approx. T_c is too high, include exchange interactions (Gorkov correction)