Spin polarons and molecules in strongly interacting atomic Fermi gases

Pietro Massignan
ICFO & Universitat Autonoma, Barcelona

work done in collaboration with:
Georg Bruun (Copenhagen & Trento), Henk Stoof (Utrecht), Chris Pethick (Copenhagen),
Maciej Lewenstein (ICFO) and Anna Sanpera (U.A. Barcelona)

FerMix meeting, Trento, June 2009

Pairing and superfluidity in Fermi systems

- Strongly-correlated Fermi gases:
  - neutron stars (huge and hot)
  - quark-gluon plasma and high-T_c superconductors
  - atomic gases (tiny and ultracold)

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

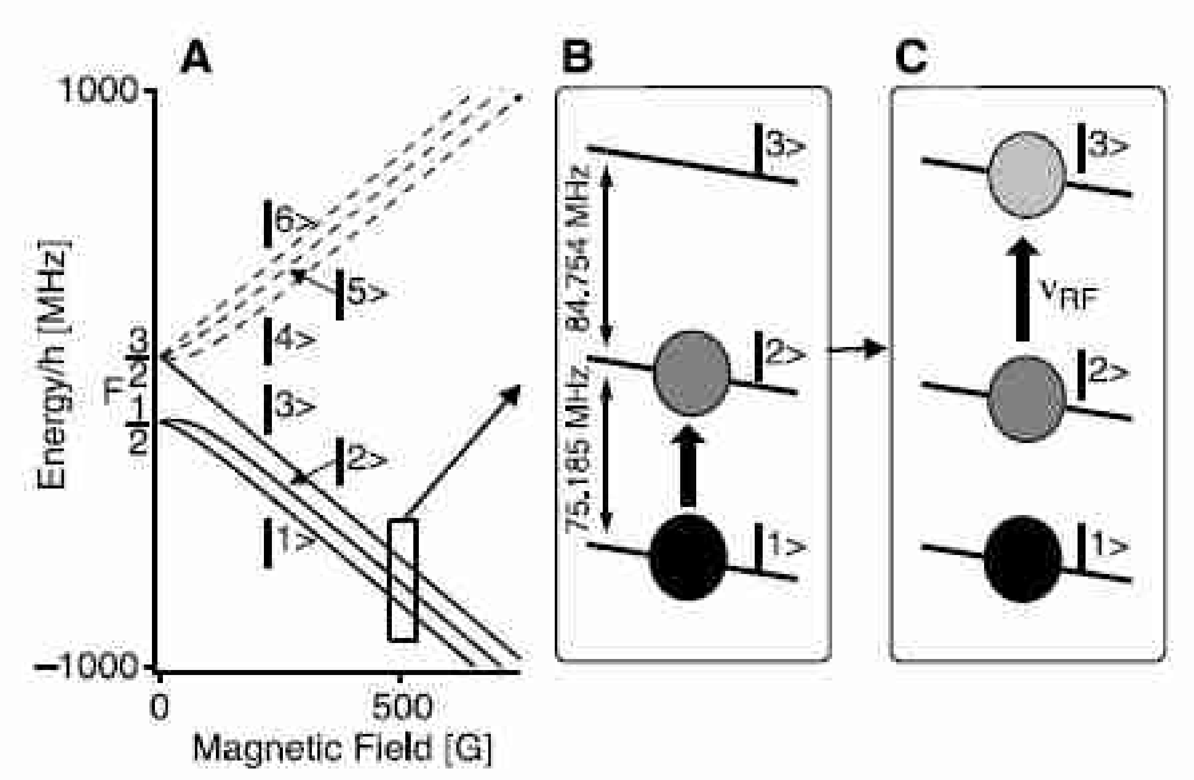
- Rf measurements: a tool to probe interactions, onset of pair correlations and presence of molecules.

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

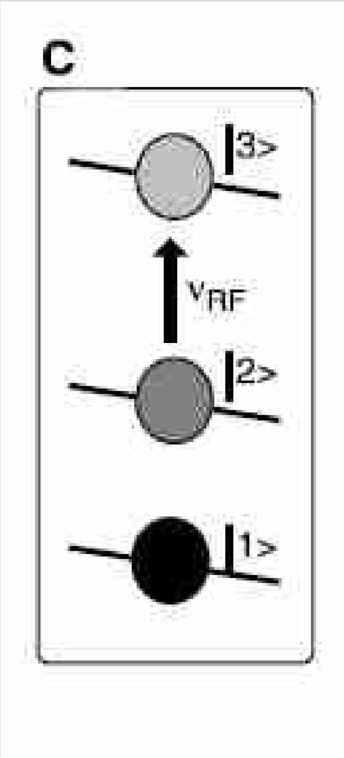
By the end of the talk I wish you will know more about:

- Basics of RF spectroscopy
- Our model for the normal state ($T>T_F$)
- What can we learn from the spectral function?
- Spectra of balanced and imbalanced systems
- How many pairs in the BEC-BCS crossover?
- An impurity in a Fermi sea: polaron vs. molecule
- (... + topological modes and Dirac fermions in BF mixture)

Level structure in ^{6}Li



Radio-frequency spectroscopy

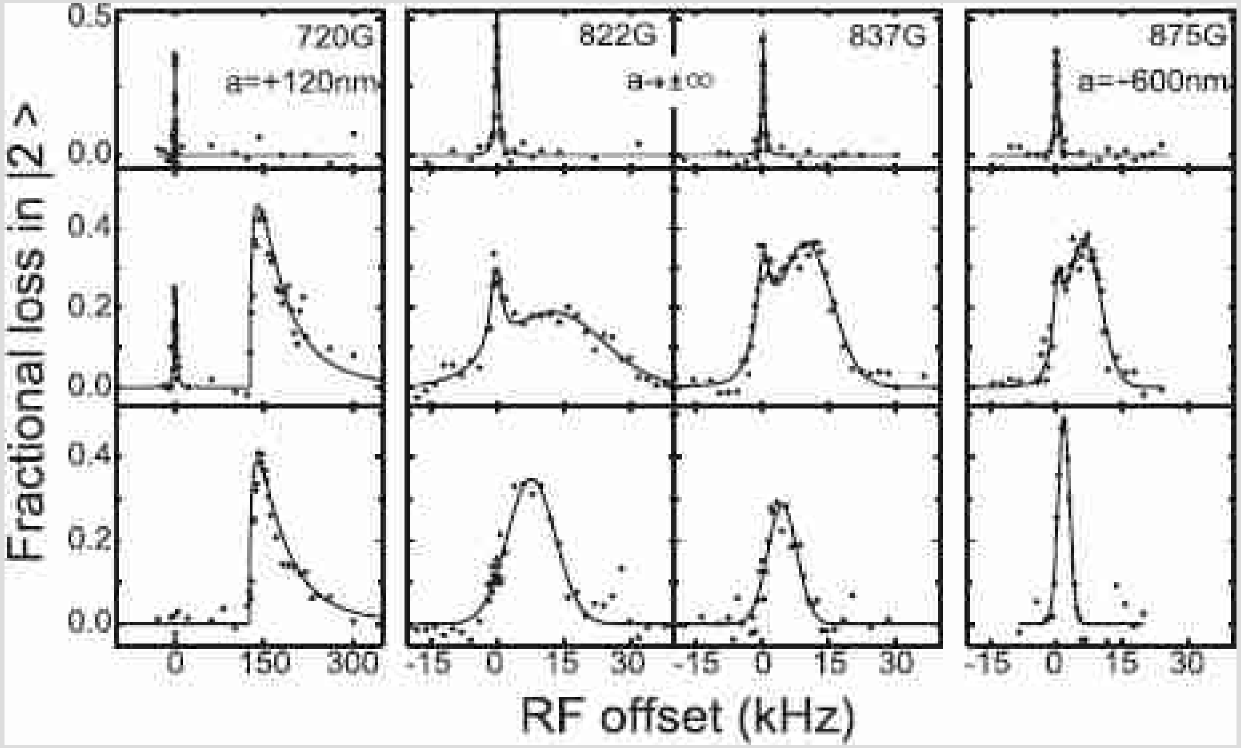


BEC Unitarity BCS

$T \gg T_F$

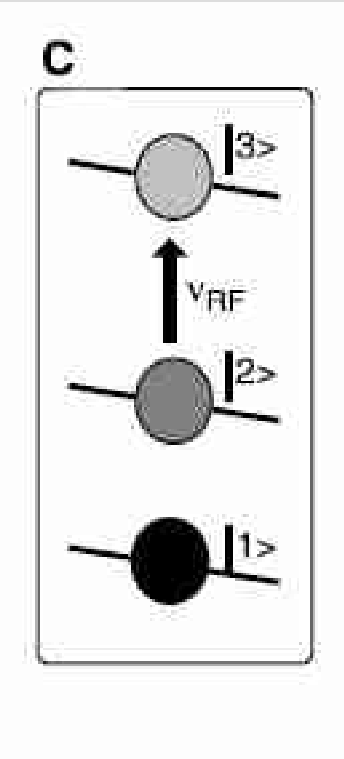
$T \sim 0.5 T_F$

$T \ll T_F$



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

Linear response theory



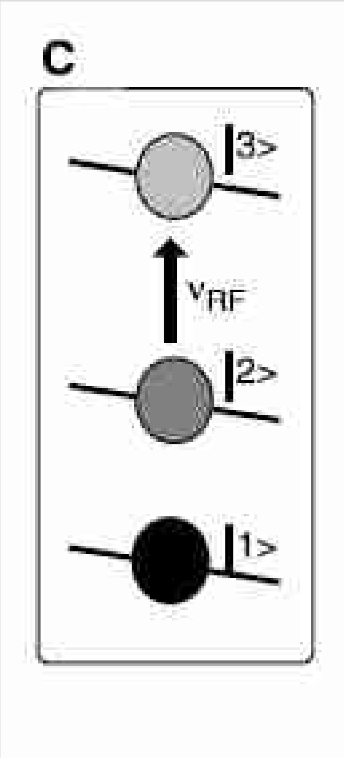
$$H_{\rm rf} = \frac{\Omega}{2}\int d\mathbf{r}\left[e^{-i\omega t}\psi_3^\dagger(\mathbf{r},t)\psi_2(\mathbf{r},t) + \text{h.c.}\right]$$

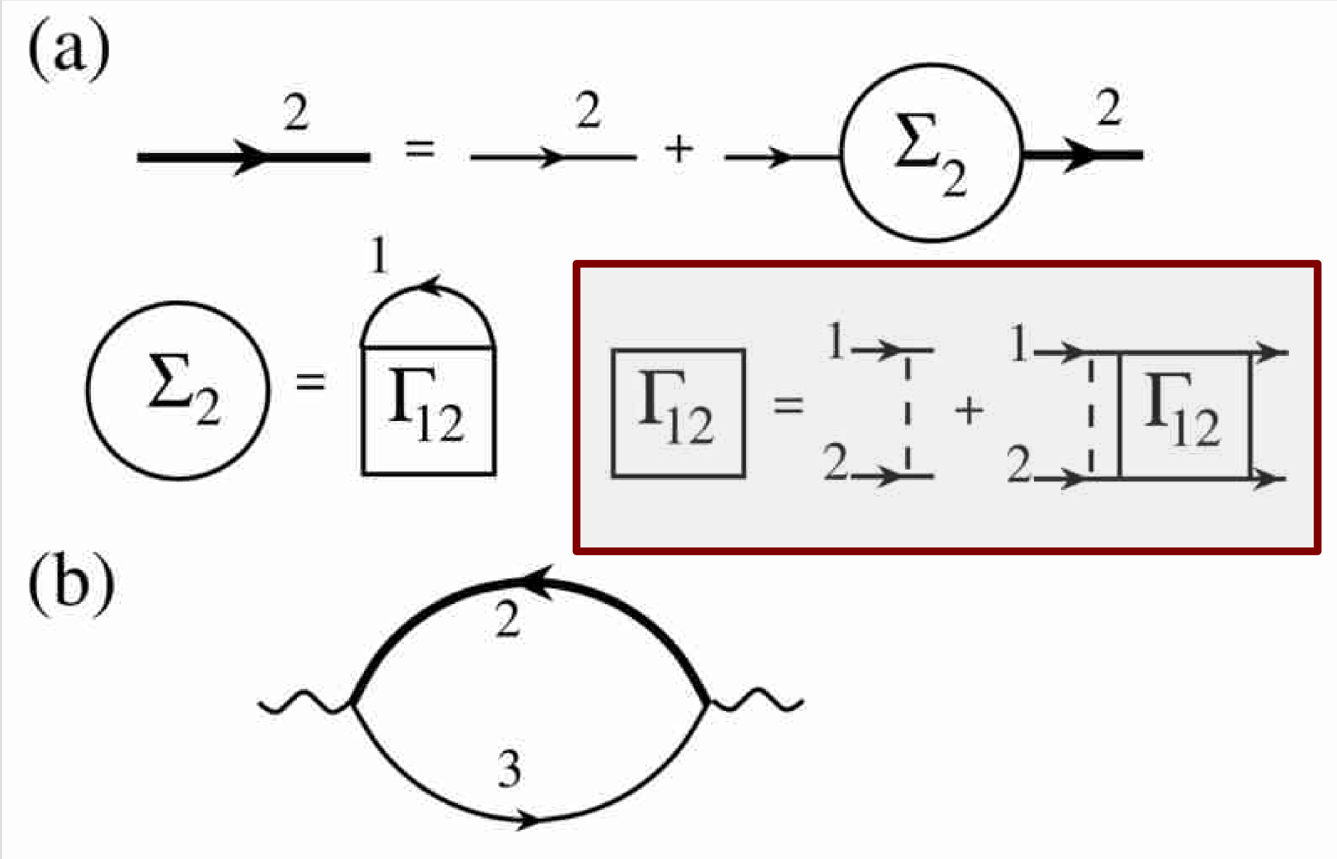
$$\text{Transition rate: } R(\omega) \propto -\int d\mathbf{r}d\mathbf{r}'\text{Im}\mathcal{D}(\mathbf{r},\mathbf{r}',\omega)$$

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

{...}: retarded 2-3 flip correlation function

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





Spectral function $A_2(k,\omega) = -2\mathrm{Im}[G_2(k,\omega)]$

(we take into account the strong 1-2 interaction, while we neglect the weaker 1-3)

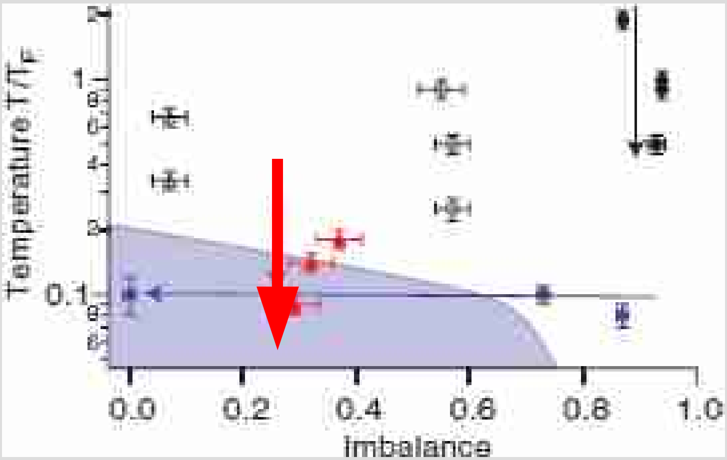
Pairing Without Superfluidity: The Ground State of an Imbalanced Fermi Mixture

C. H. Schunck,* Y. Shin, A. Schirotzek, M. W. Zwierlein,† W. Ketterle

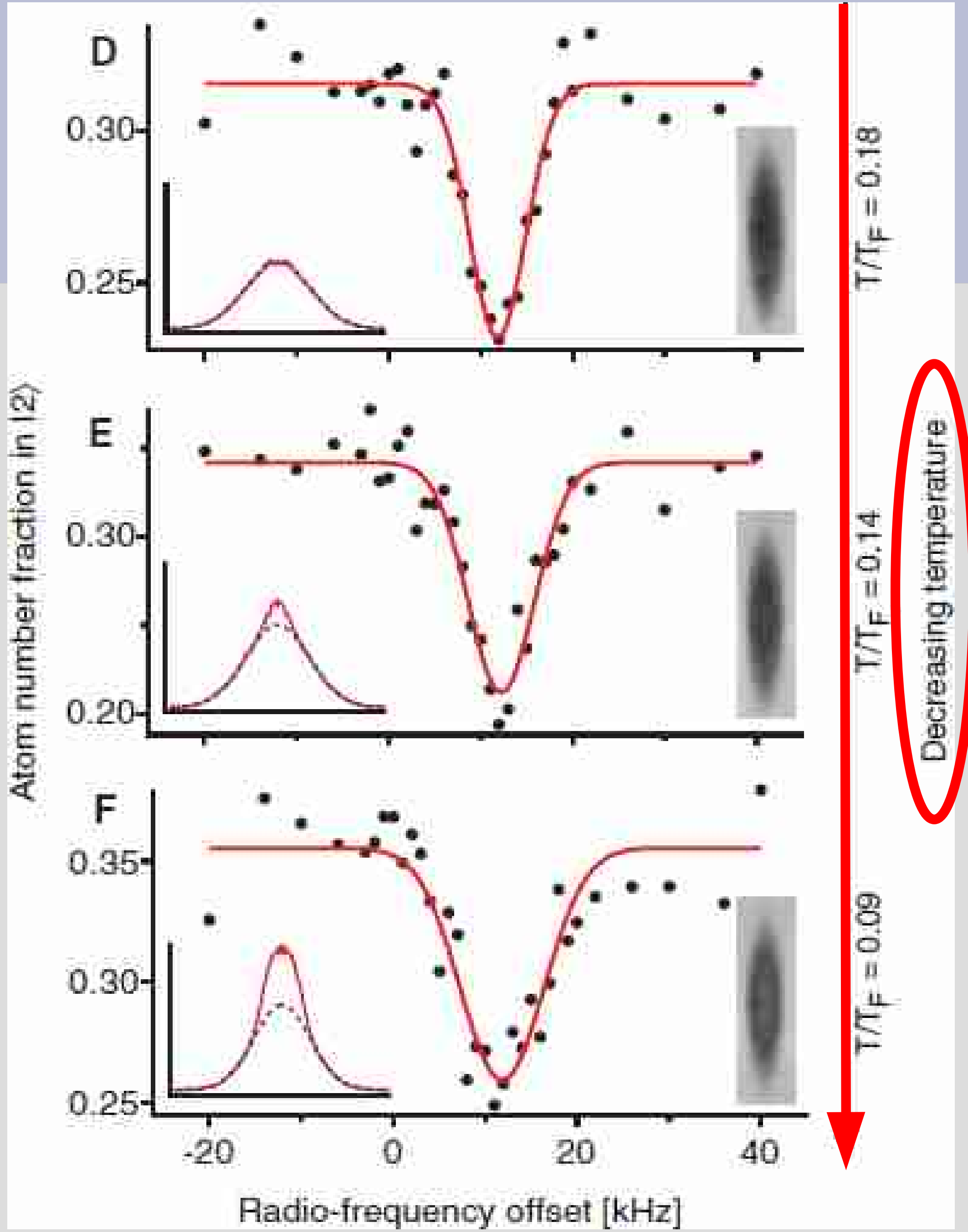
Science (2007)

RF spectra do not reveal the normal-SF transition

(while density profiles do)



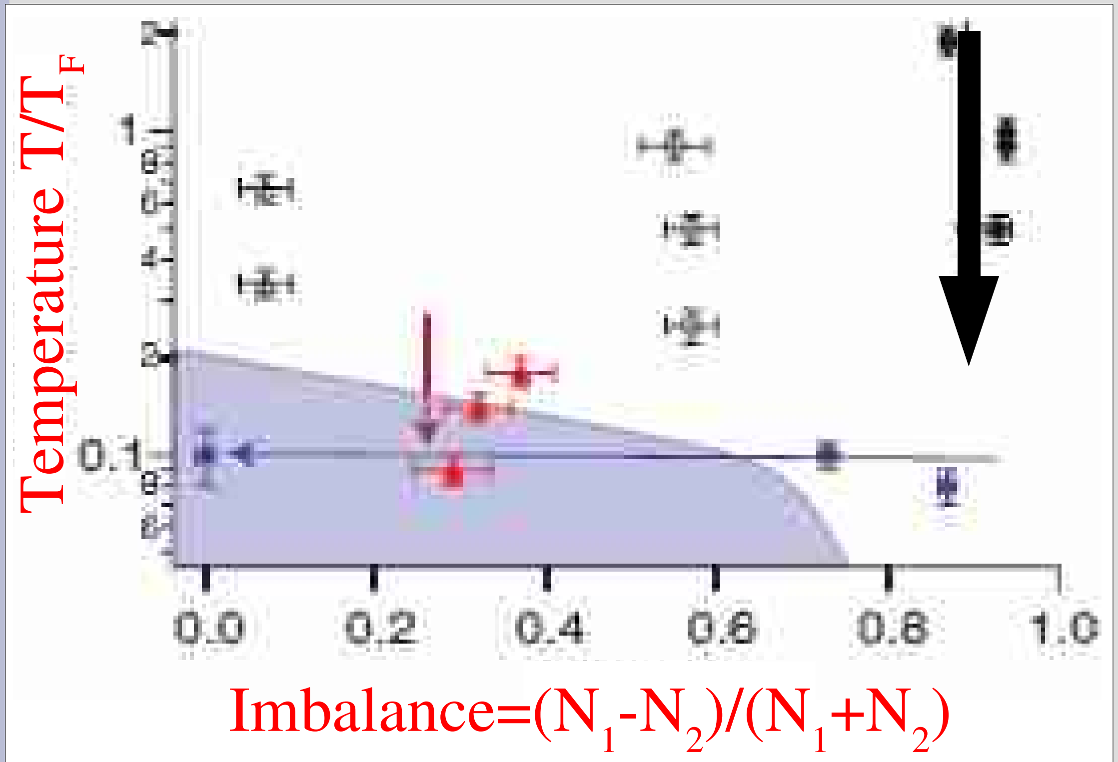
Imbalance=$(N_1-N_2)/(N_1+N_2)$

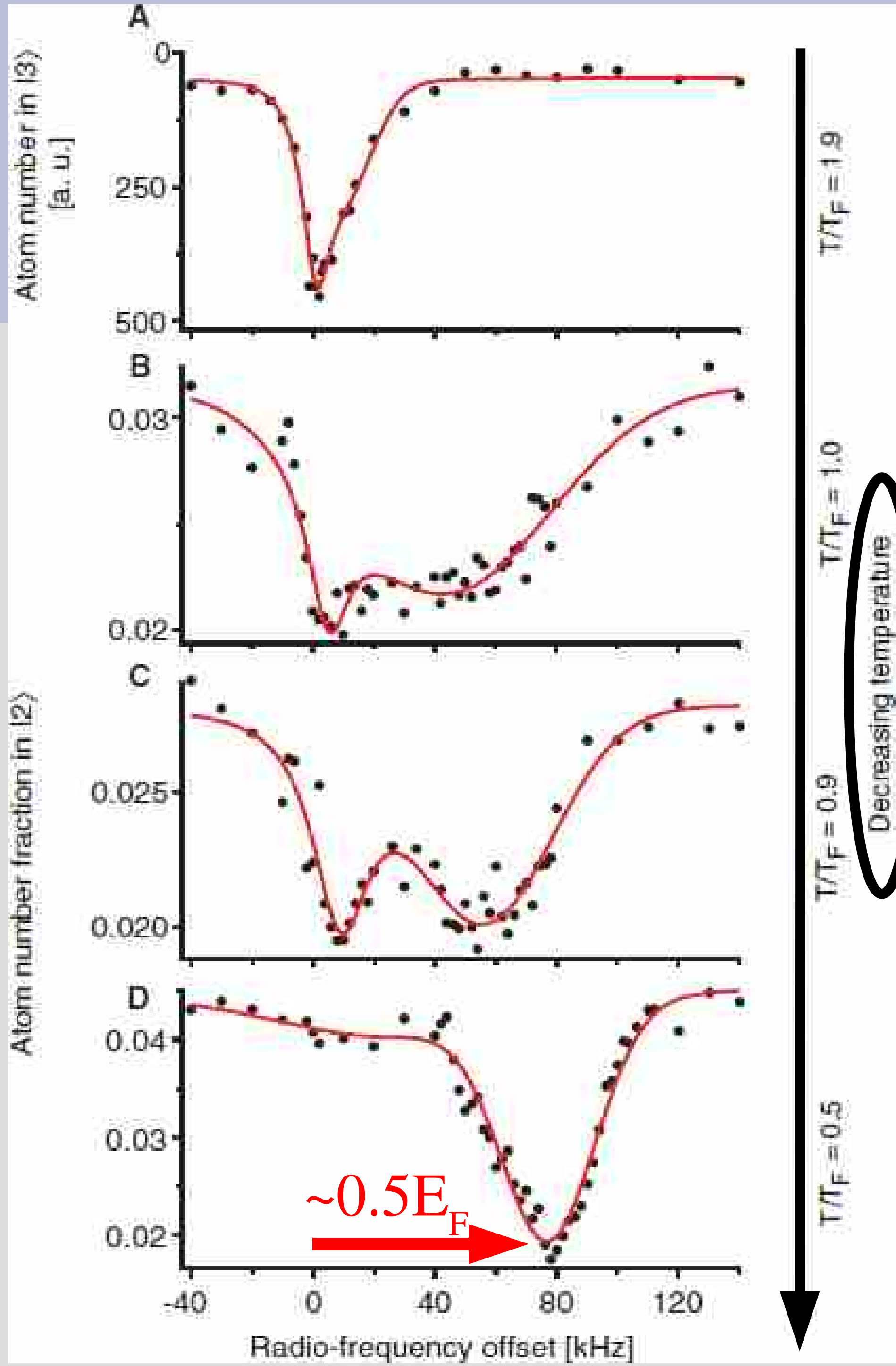


Pairing Without Superfluidity: The Ground State of an Imbalanced Fermi Mixture

C. H. Schunck,* Y. Shin, A. Schirotzek, M. W. Zwierlein,† W. Ketterle

Science (2007)





Large shift in the peak position signals strong interactions in the gas

Spectral function and spectrum
(no trap, unitarity)

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

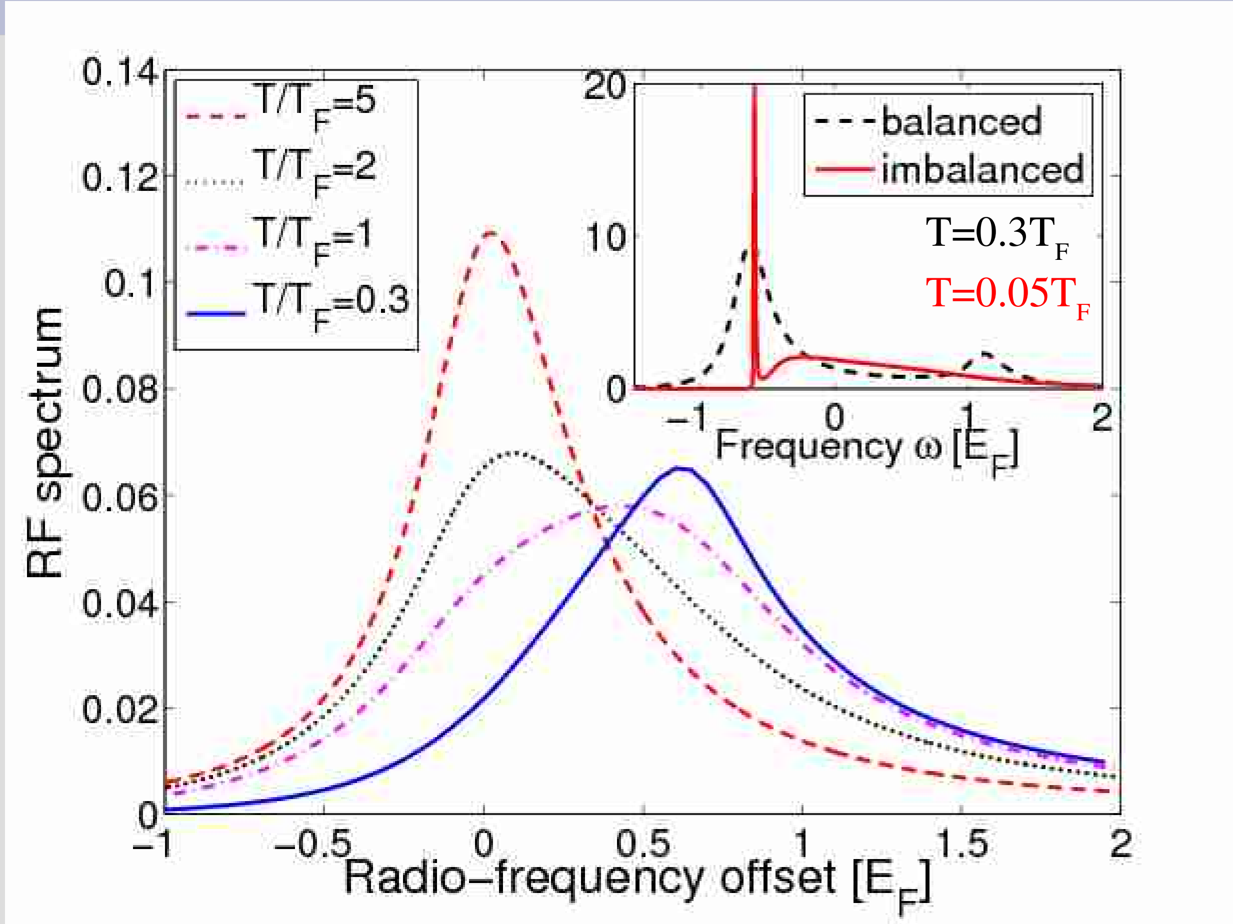
$$\xi_{2k} = k^2/2m - \mu_2$$

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

Pairing without superfluidity (*pseudogap* regime)

Inset: spectral function $A_2(k=0,\omega)$.

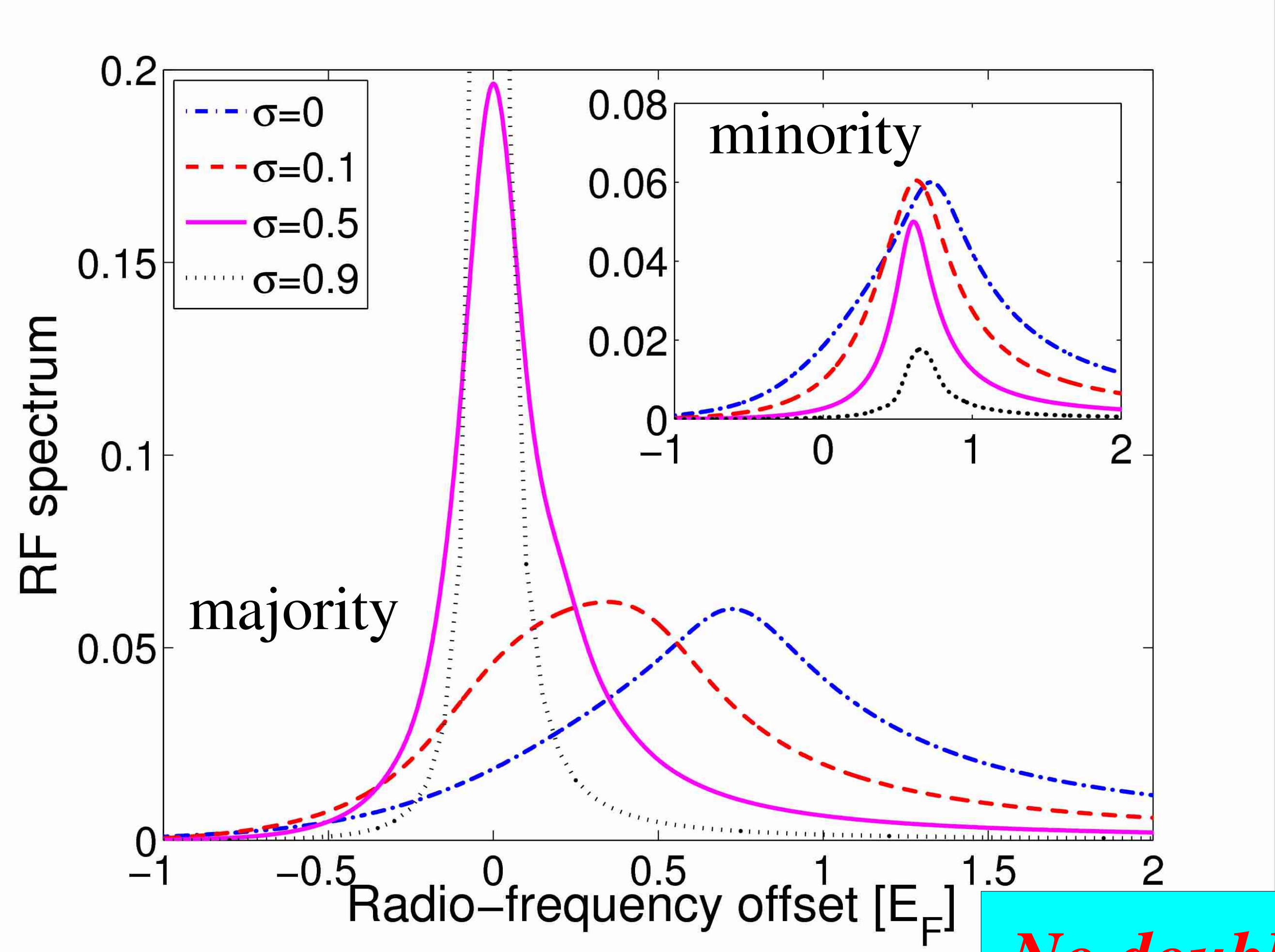
Main: spectrum for $n_1=n_2$.



P. Massignan et al., PRA 77 031601R (2008).

No double peaks in the spectrum, even in the pseudogap regime!

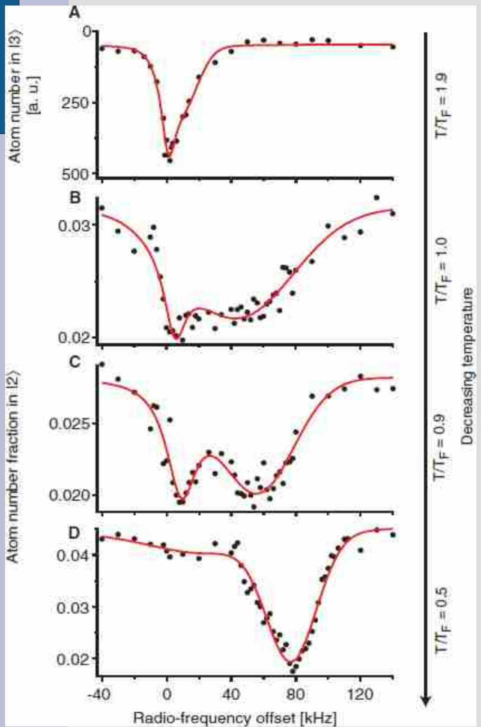
Spectrum of an imbalanced gas at unitarity

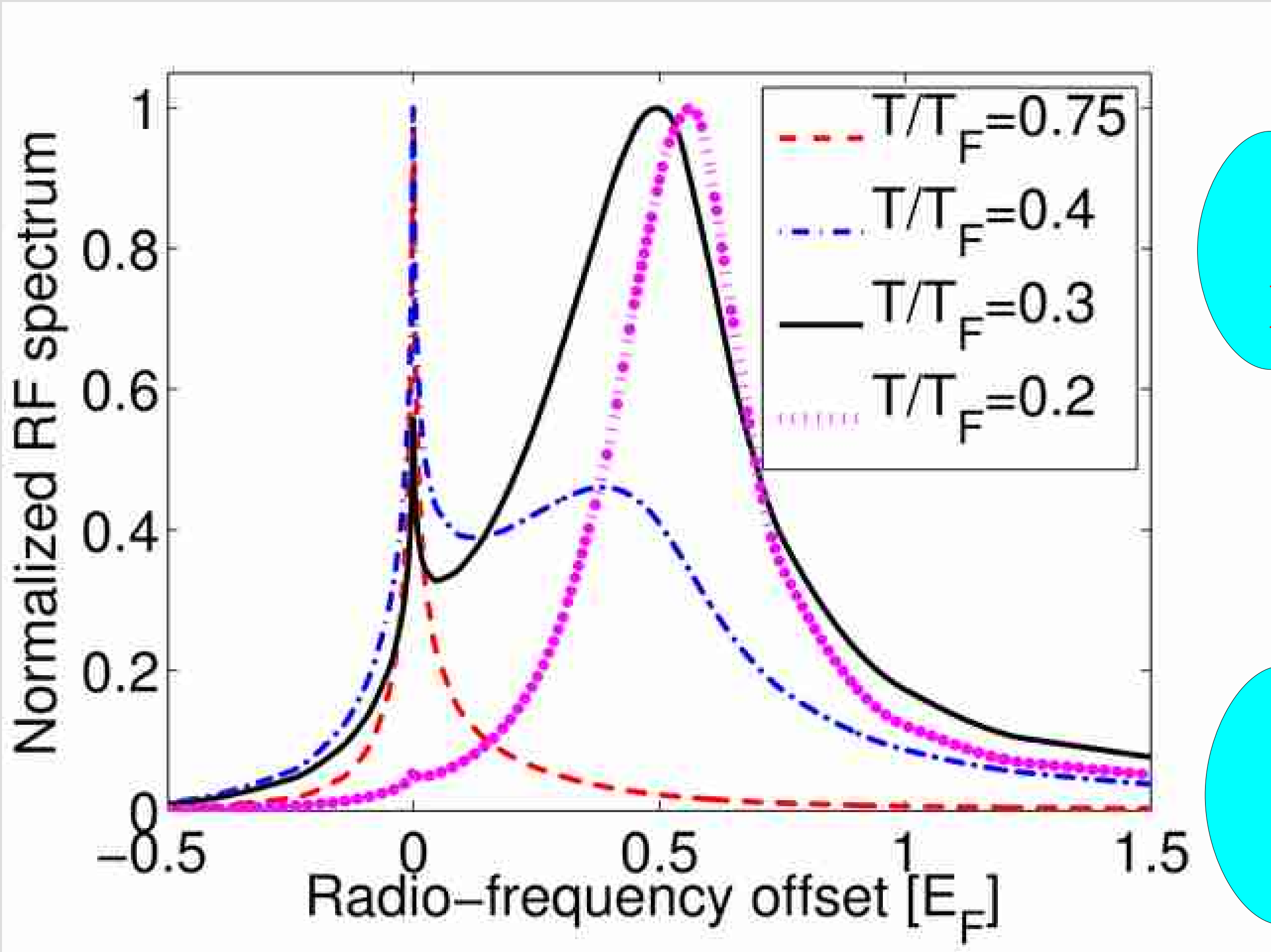


minority peak position independent of imbalance

No double peaks in the spectrum, even in the pseudogap regime!

Minority spectrum of an imbalanced **trapped** gas at unitarity





no fitting parameters

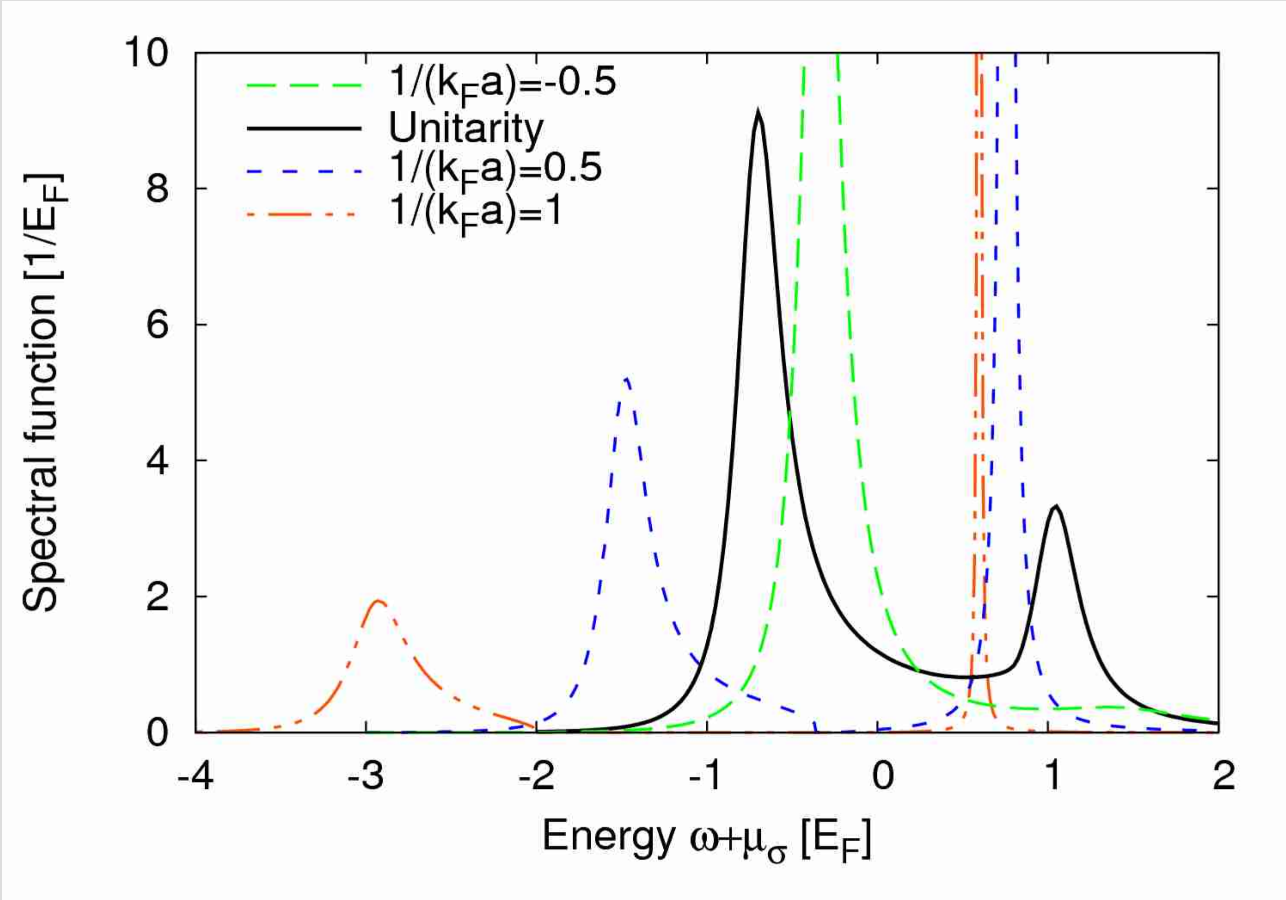
peak position independent of imbalance

$N_2/N_1=5\%$

P. Massignan et al., PRA 77 031601R (2008).

Spectral function $A_2(k=0,\omega)$ across the crossover

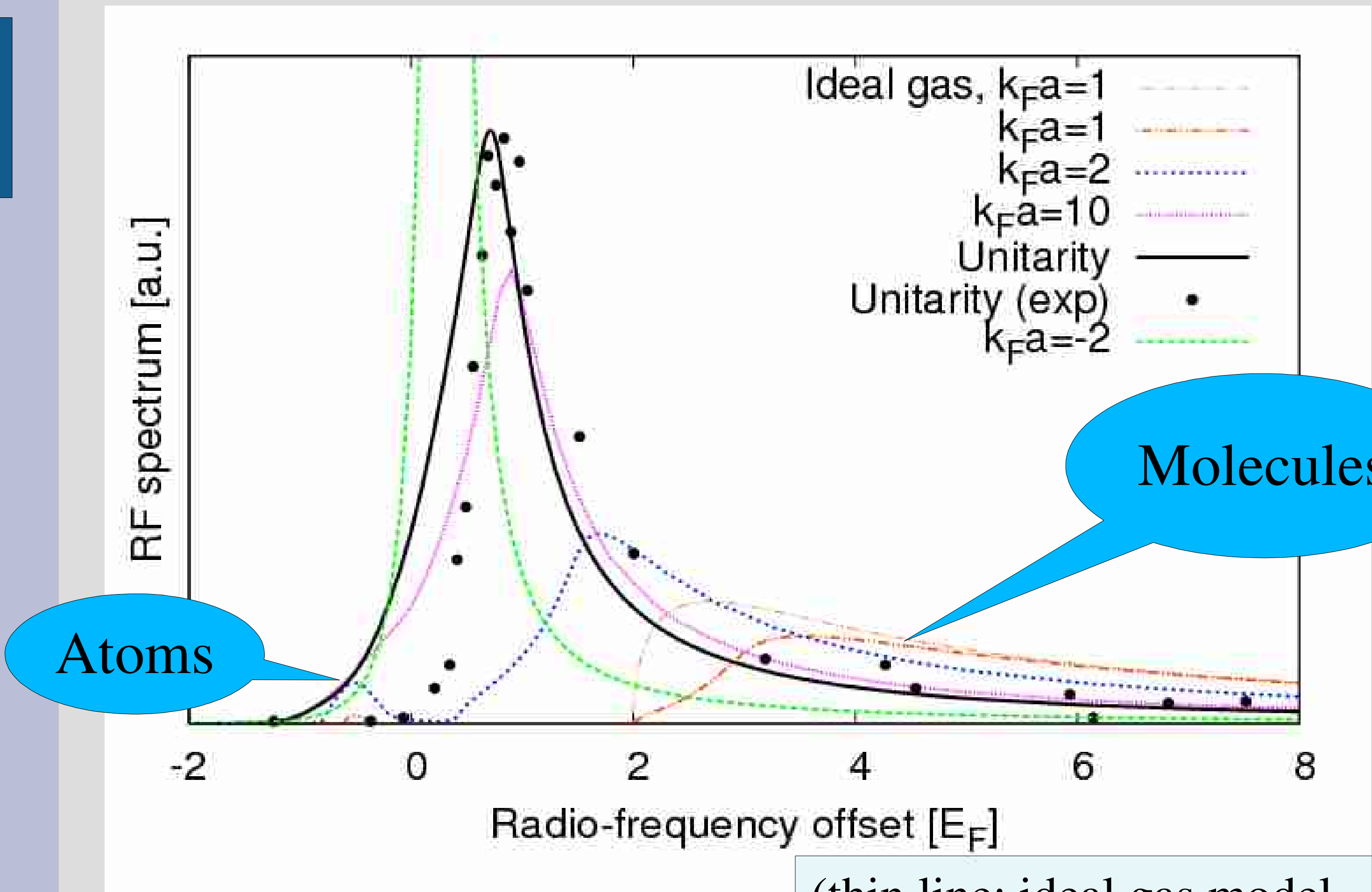
(**no trap**, $n_1=n_2$, $T=0.3T_F$)



a real gap in the spectral function opens for $1/(k_F a)>0.5$

Spectrum across the crossover

(no trap, $n_1=n_2$, $T=0.3T_F$)



1) Stable molecules appear when a gap opens in A_2

2) Atoms coexist with molecules for $T<E_b$

Binding energy: $\frac{E_b}{E_F} \sim \frac{2}{(k_F a)^2}$

Exp: Schunck et al., Nature 2008

(thin line: ideal gas model, Yukawa molecular function)

P. Massignan et al., PRA 78 031602R (2008).

Number of "pairs/molecules" δn_σ in the ladder (NSR) approx.

Thermodynamic potential: $\Omega = \Omega_0 + \Delta\Omega$

NSR approx: $$\Delta\Omega = \int \frac{d^3k}{(2\pi)^3} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi i} \frac{\ln(1 - T\Pi^+) - \ln(1 - T\Pi^-)}{e^{\beta\omega} - 1}.$$

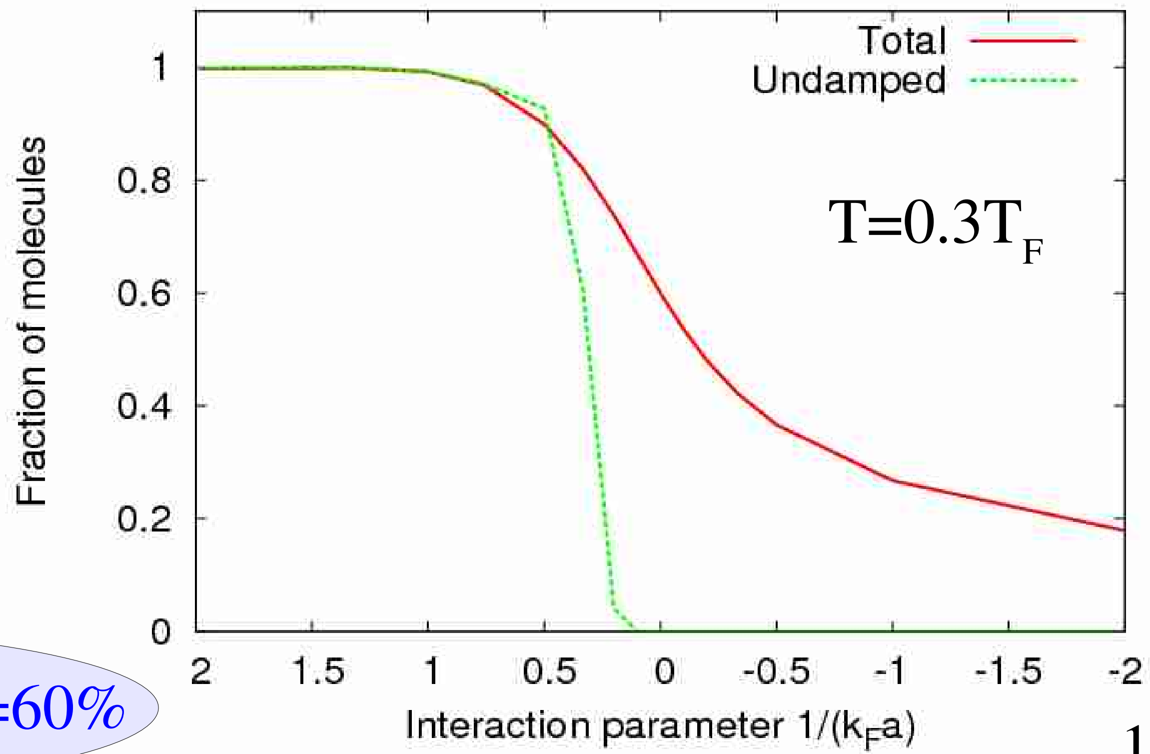
$$n_\sigma = -\partial_{\mu_\sigma}\Omega =$$

$$= n_\sigma^0 + \delta n_\sigma$$

$$n_\sigma^0 = \int \frac{d^3k}{(2\pi)^3}\left[e^{\beta(k^2/2m - \mu)} + 1\right]^{-1}$$

$$\delta n_\sigma = -\partial_{\mu_\sigma}\delta\Omega$$

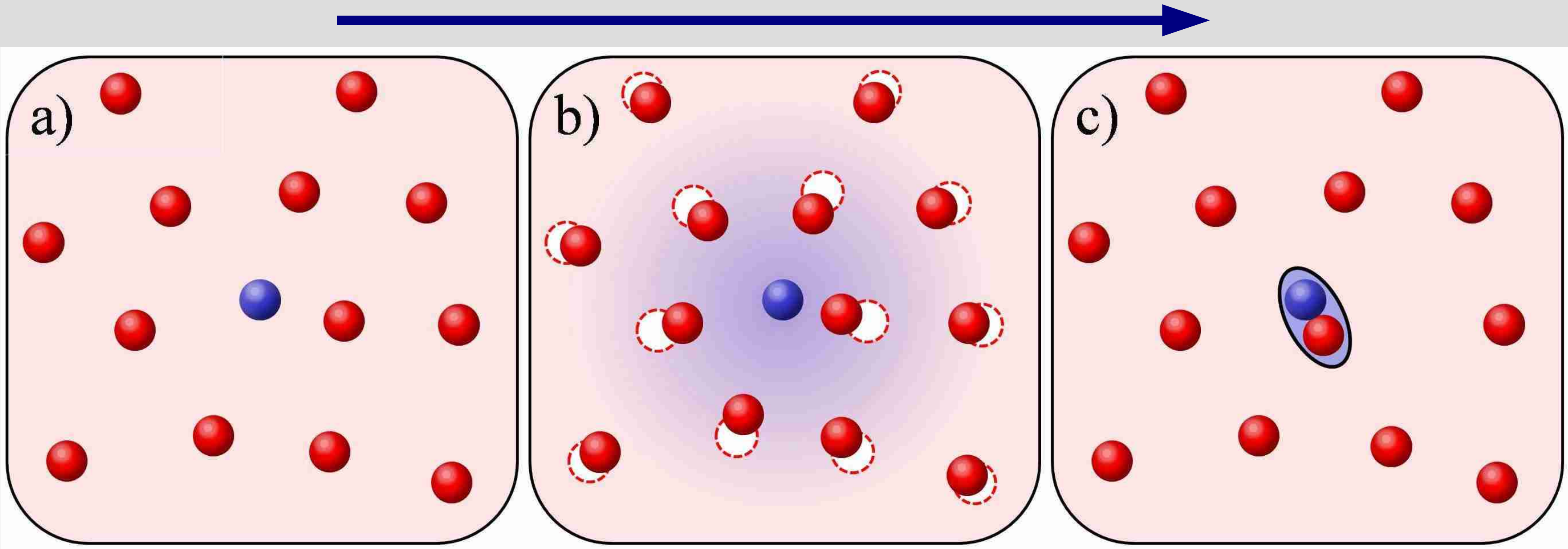
(σ = 1,2)



At $T=T_c$ and unitarity, δn_σ=60%

An impurity in a Fermi sea (the MIT experiment)

increasing attractive interaction



a free particle   a polaron   a molecule

A. Schirotzek et al., arXiv:0902.3021

The impurity problem (in Mattuck's imagination)

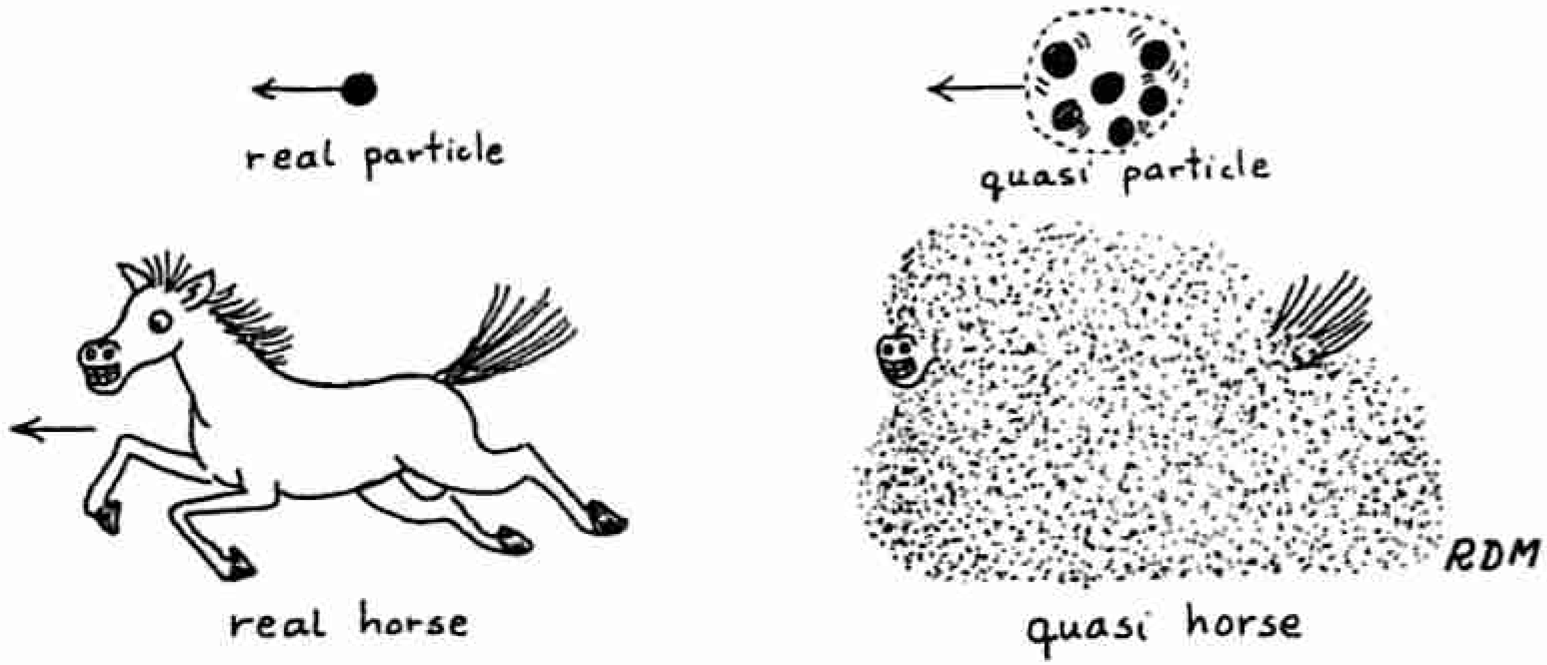
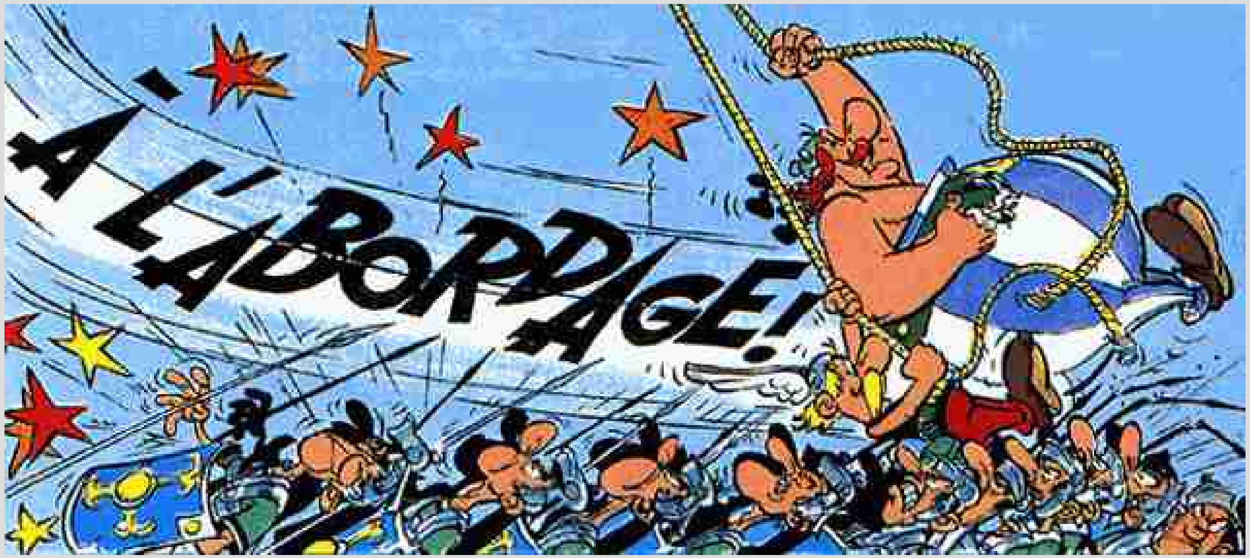


Fig. 0.4 *Quasi Particle Concept*

The impurity @ FerMix

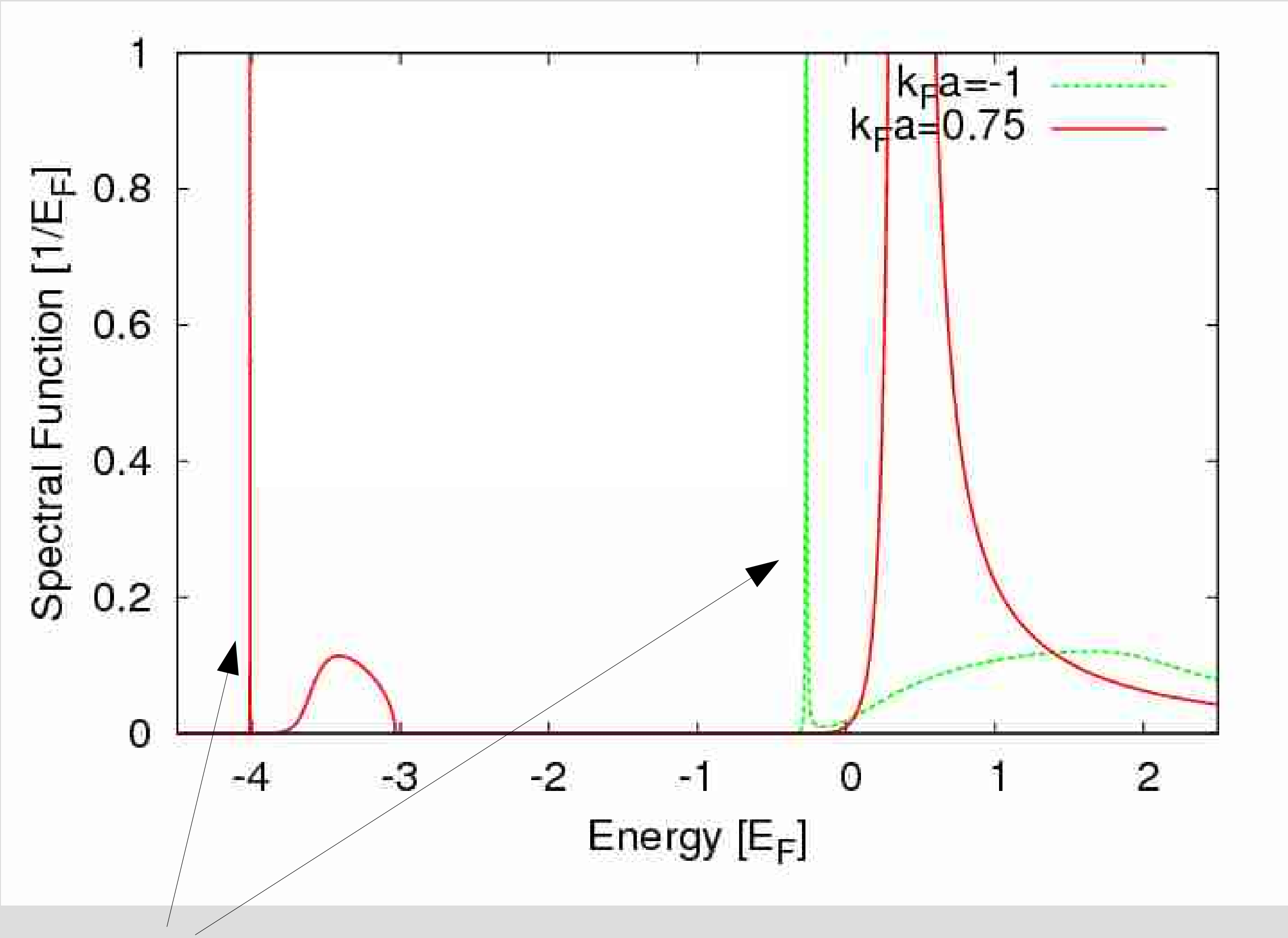
the free particle

the polaron



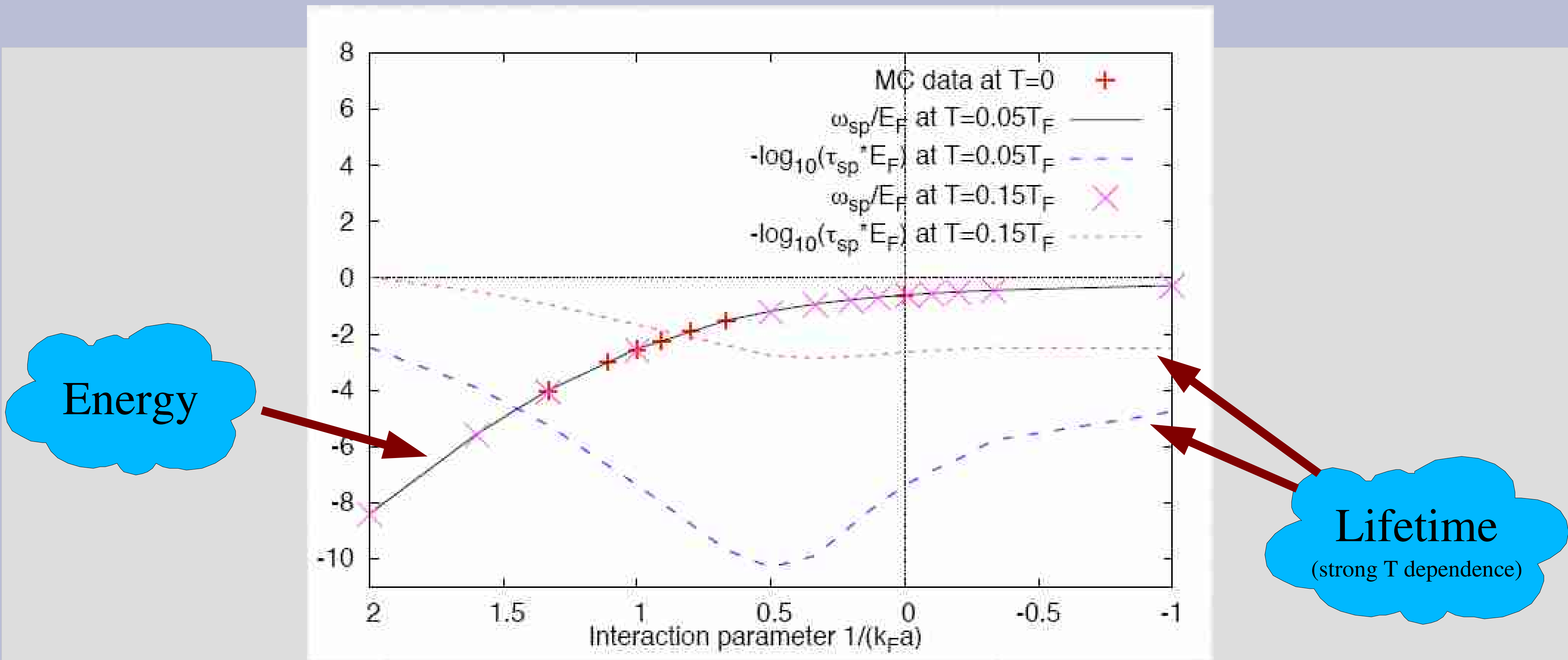
the molecule
(heteronuclear?)

An impurity in a Fermi sea: the spectral function



Narrow feature: a “polaron” (quasiparticle, MB).
It disappears in the BEC limit (2B).

Polaron energy and lifetime

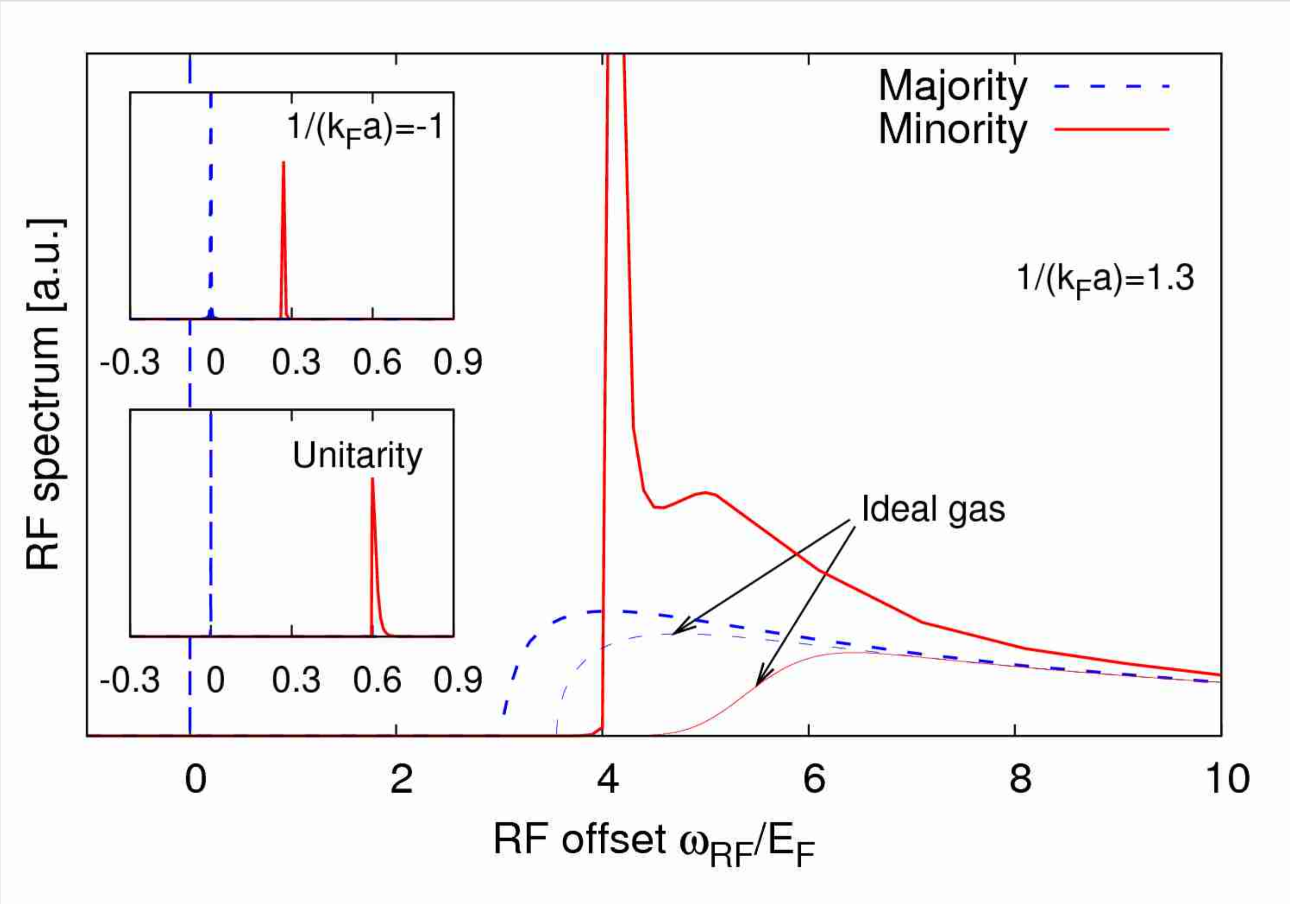


Energy fits with both Monte Carlo and experimental results

(Lobo, Recati, Giorgini and Stringari, PRL 2006; Prokof'ev&Svistunov, PRB 2008; Schirotzek et al., arXiv:0902.3021)

Damping strongly temperature dependent

An impurity in a Fermi sea: the spectrum

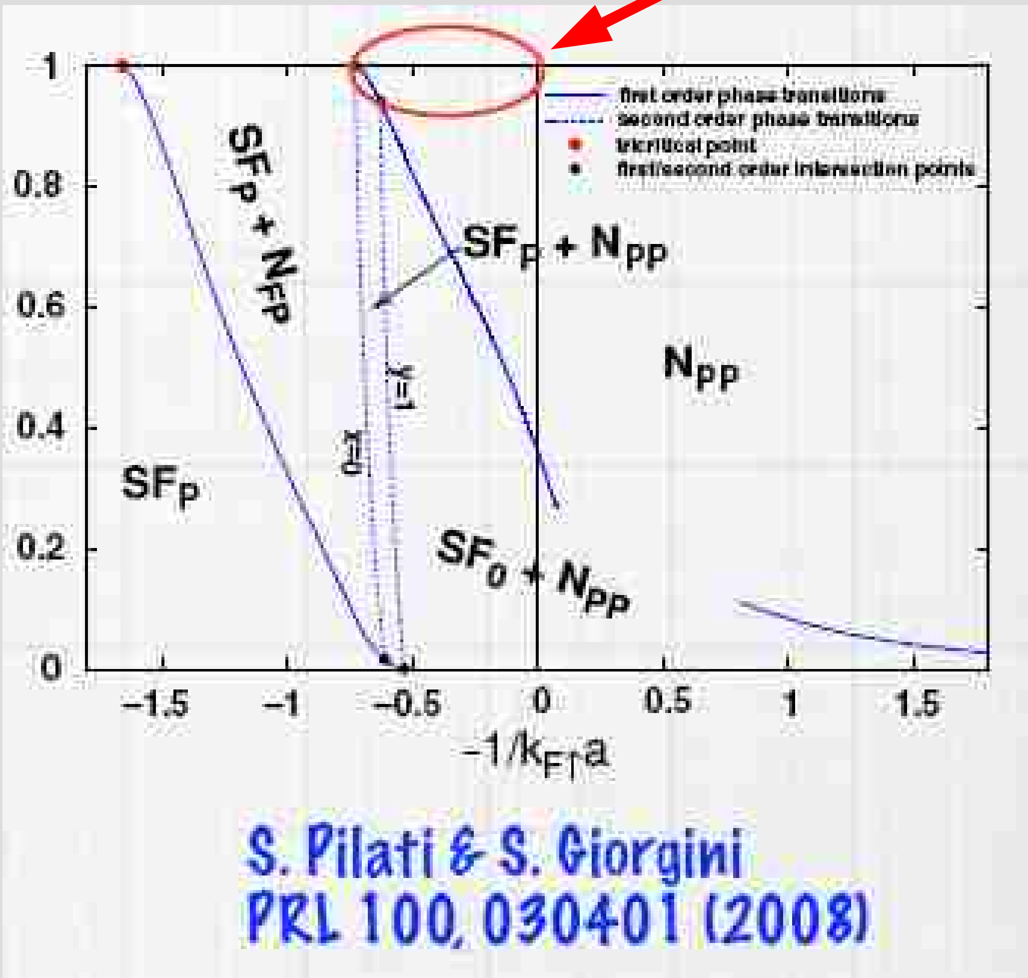


Ideal gas model:
Fermi Golden Rule +
Yukawa molecular function

The spectrum gives info. on both quasiparticle energy and molecular wavefunction

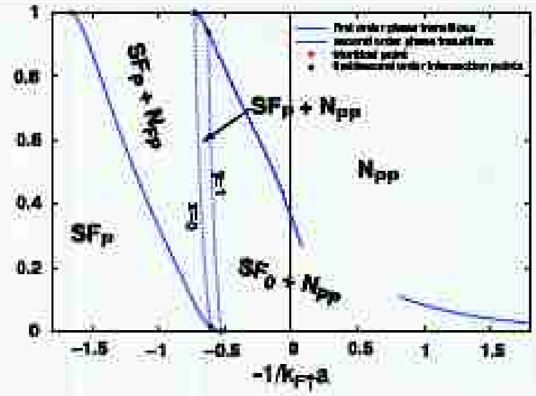
Phase diagram of an imbalanced Fermi gas

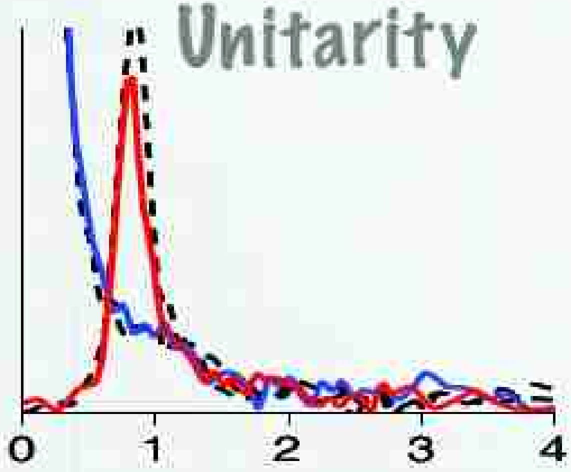
extreme imbalance, strong interactions

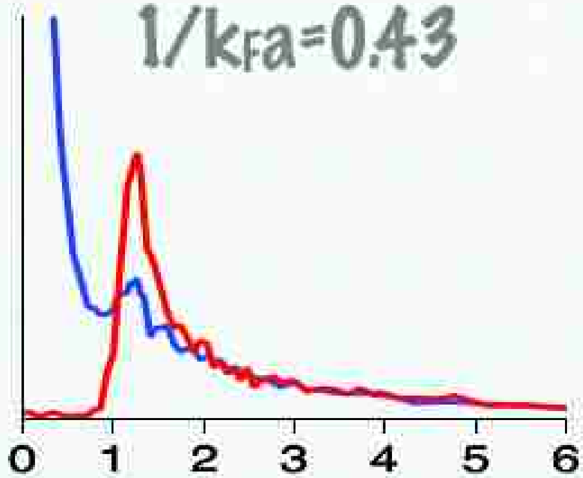


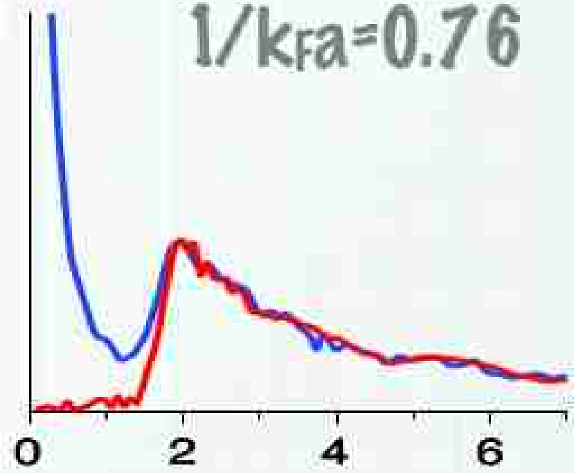
RF spectrum

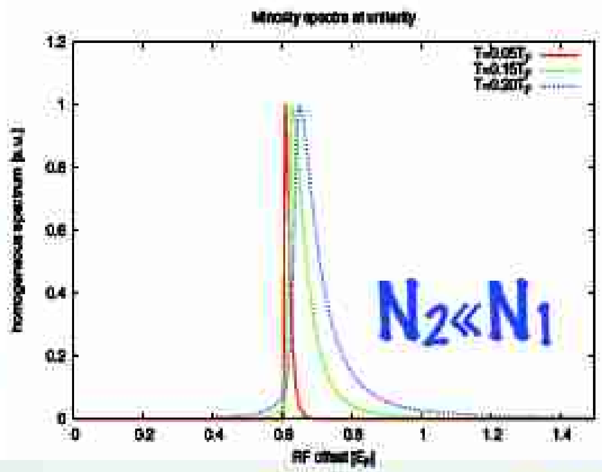
A. Shirotzek et al. arXiv:0902.302

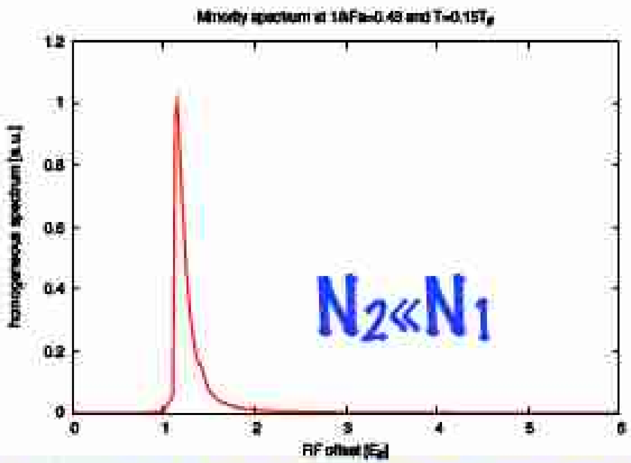


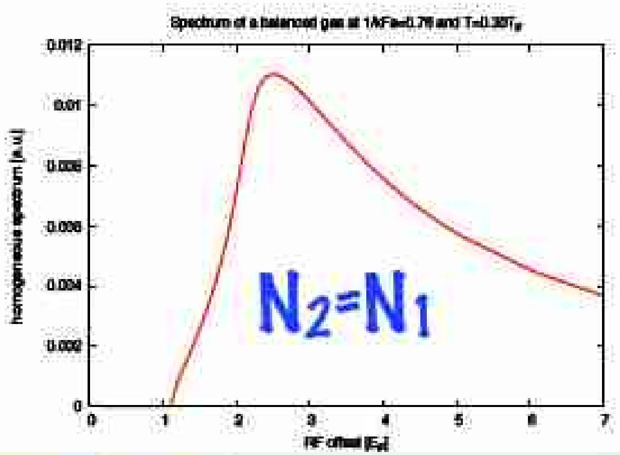










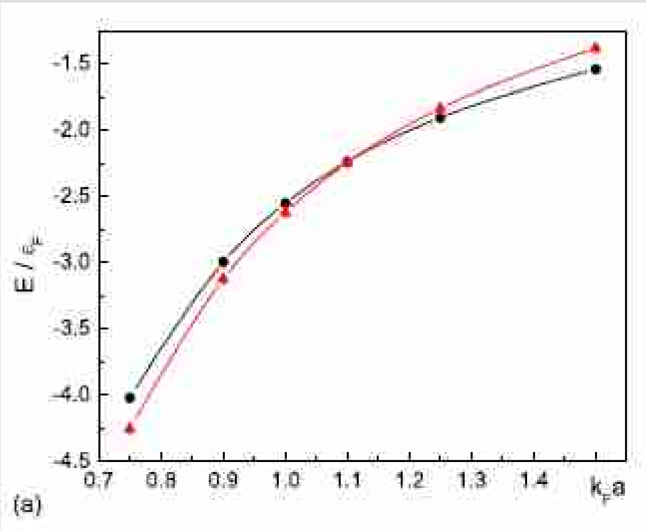


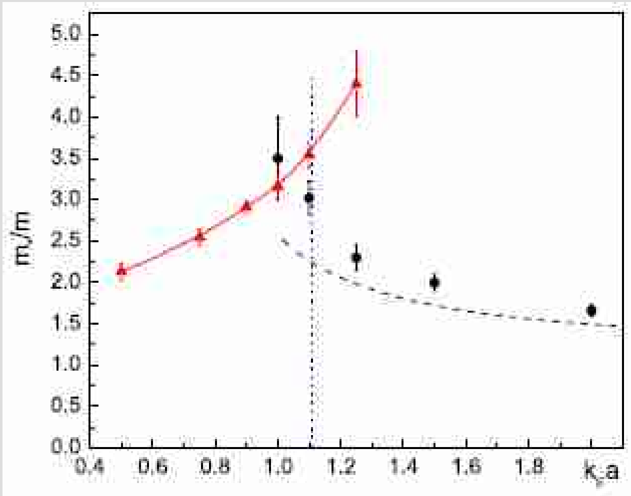
P. Massignan, G. M. Bruun & H. T. C. Stoof PRA 78 031602 (2008)

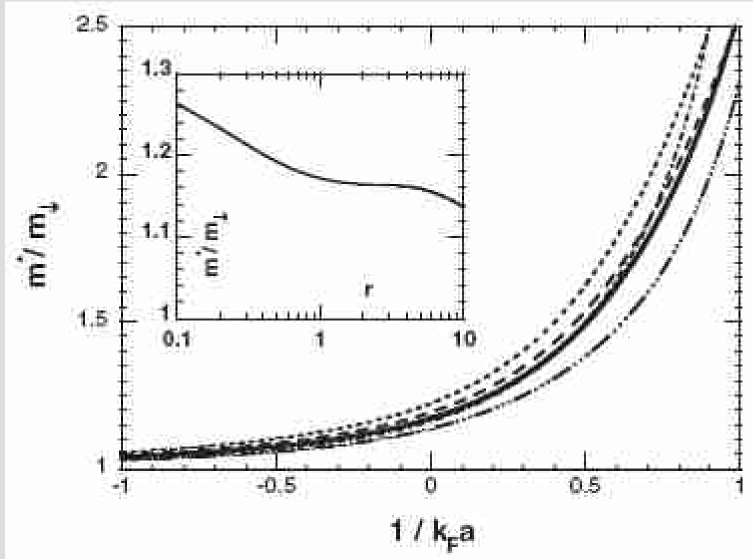
What happens to the impurity on the BEC side?

Energy

Effective mass m*







(Prokof'ev & Svistunov, PRB 2008)

(Combescot, Recati, Lobo & Chevy, PRL 2007)

Chevy Ansatz:

$$|\Psi\rangle = \varphi_0 \, |\mathbf{0}\rangle_\downarrow \, |FS\rangle_\uparrow + \sum_{|\mathbf{q}|<k_F<|\mathbf{k}|} \varphi_{\mathbf{kq}} c^\dagger_{\mathbf{k}\uparrow} c_{\mathbf{q}\uparrow} \, |\mathbf{q}-\mathbf{k}\rangle_\downarrow \, |FS\rangle_\uparrow$$

Is it possible to write a single Ansatz able to describe the transition from a polaron to a molecule? (work in progress..)

A cooking recipe for: Topological vortex modes and Dirac fermions in a BF mixture

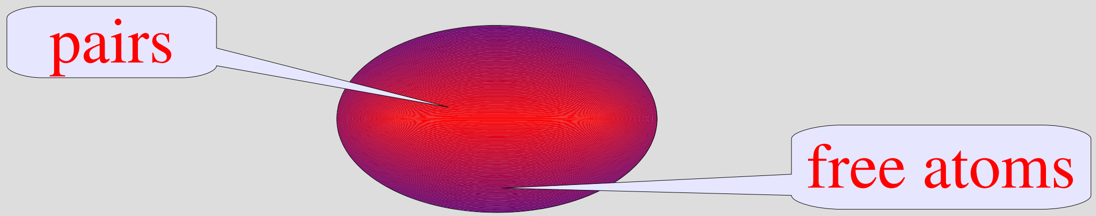
(ongoing work with M. Lewenstein and A. Sanpera)

- Ingredients:
  - An optical lattice in 2D
  - 1 boson/site in a Mott state, and some fermions ($0<F<1$)
- Method:
  - Integrate out the bosons to obtain composite fermions interacting with NN interactions (Lewenstein et al., PRL 2004)
  - A p-wave SF forms at $T<T_C=10\sim100$nK (stable against 3-body losses via a Quantum Zeno effect, see Han et al., arXiv:0905.2600)
- Serving suggestions:
  - This SF supports vortex modes with E=0, which have interesting topological properties and non-abelian statistics.
  - At half-filling for the fermions, Dirac fermions appear. Enjoy!

(to be published soon, please ask if interested)

Conclusions

- At unitarity there are no real molecules
  (double-peaks measured in the spectra come from the trap)



- BEC side $(0 < k_F a < 2)$: in a homogeneous gas free atoms coexist locally with stable molecules
- An impurity in a Fermi sea: a polaron (MB) at unitarity, a molecule in the BEC regime (2B).

Refs.: Massignan, Bruun and Stoof, PRA 77 031601R (2008) & PRA 78 031602R (2008).