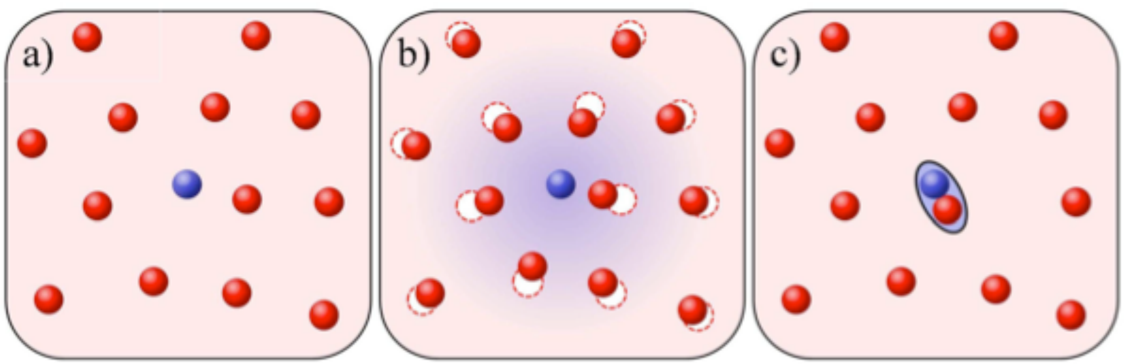
Observation of Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms

André Schirotzek, Cheng-Hsun Wu, Ariel Sommer, and Martin W. Zwierlein
Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Dated: February 17, 2009)

We have observed Fermi polarons, dressed spin down impurities in a spin up Fermi sea of ultracold atoms. The polaron manifests itself as a narrow peak in the impurities' rf spectrum that emerges from a broad incoherent background. We determine the polaron energy and the quasiparticle residue for various interaction strengths around a Feshbach resonance. At a critical interaction, we observe the transition from polaronic to molecular binding. Here, the imbalanced Fermi liquid undergoes a phase transition into a Bose liquid coexisting with a Fermi sea.



Groupmeeting April 8th 2009

Another recent paper

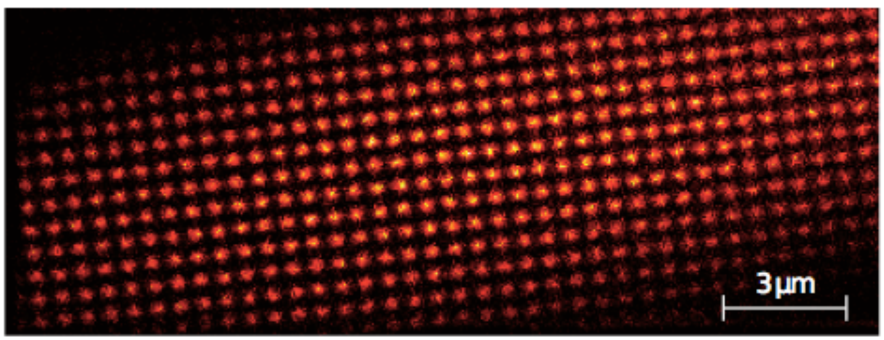
Experimental demonstration of single-site addressability in a two-dimensional optical lattice

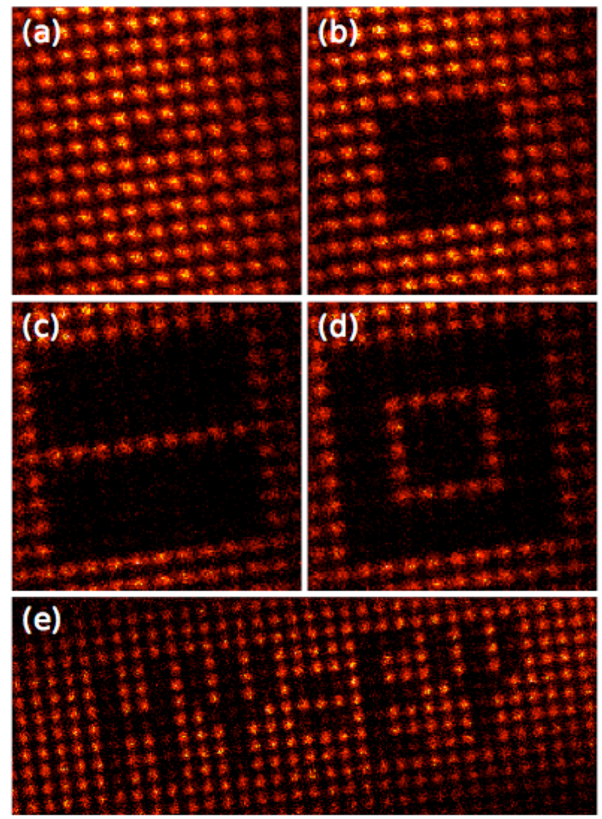
Peter Würtz,[1] Tim Langen,[1] Tatjana Gericke,[1] Andreas Koglbauer,[1] and Herwig Ott[1,2,*]

[1]*Institut für Physik, Johannes Gutenberg-Universität, 55099 Mainz, Germany*

[2]*Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany*

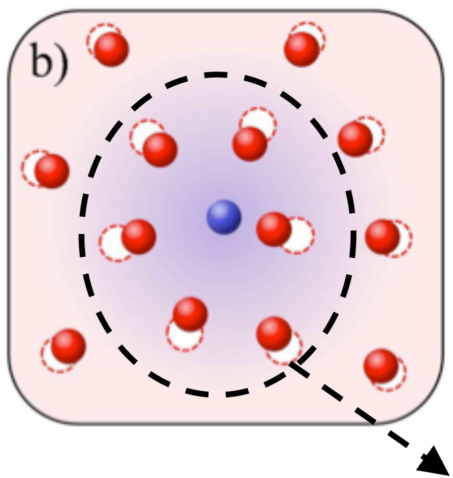
(Dated: March 27, 2009)





Motivation

- "The fate of a single impurity interacting with its environment determines the low-T behaviour of many condensed matter systems."
- Eg. An e^- moving in a lattice, displacing nearby ions, creating a localized polarization.



Polaron *a quasiparticle*

Polaron properties

- **Self energy:**

$$\frac{\Delta E}{\hbar\omega} = -\alpha$$

- **Effective mass:**

$$\frac{m*}{m} = 1 + \frac{\alpha}{6} + .0236\alpha^2$$

*Apparently, this effective mass is the key to understanding **Colossal Magnetoresistance** and the **Kondo effect***

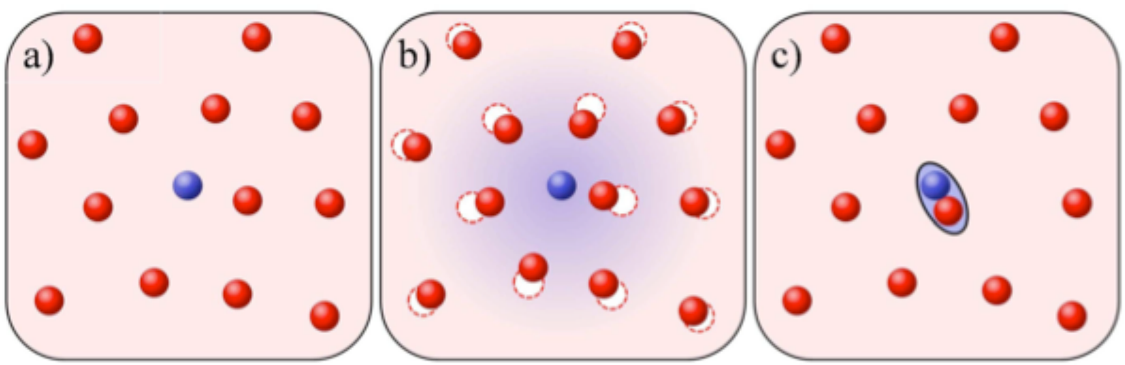
This experiment

- **Prepare a heavily imbalanced Fermi gas (many $|\uparrow\rangle$, few $|\downarrow\rangle$)**

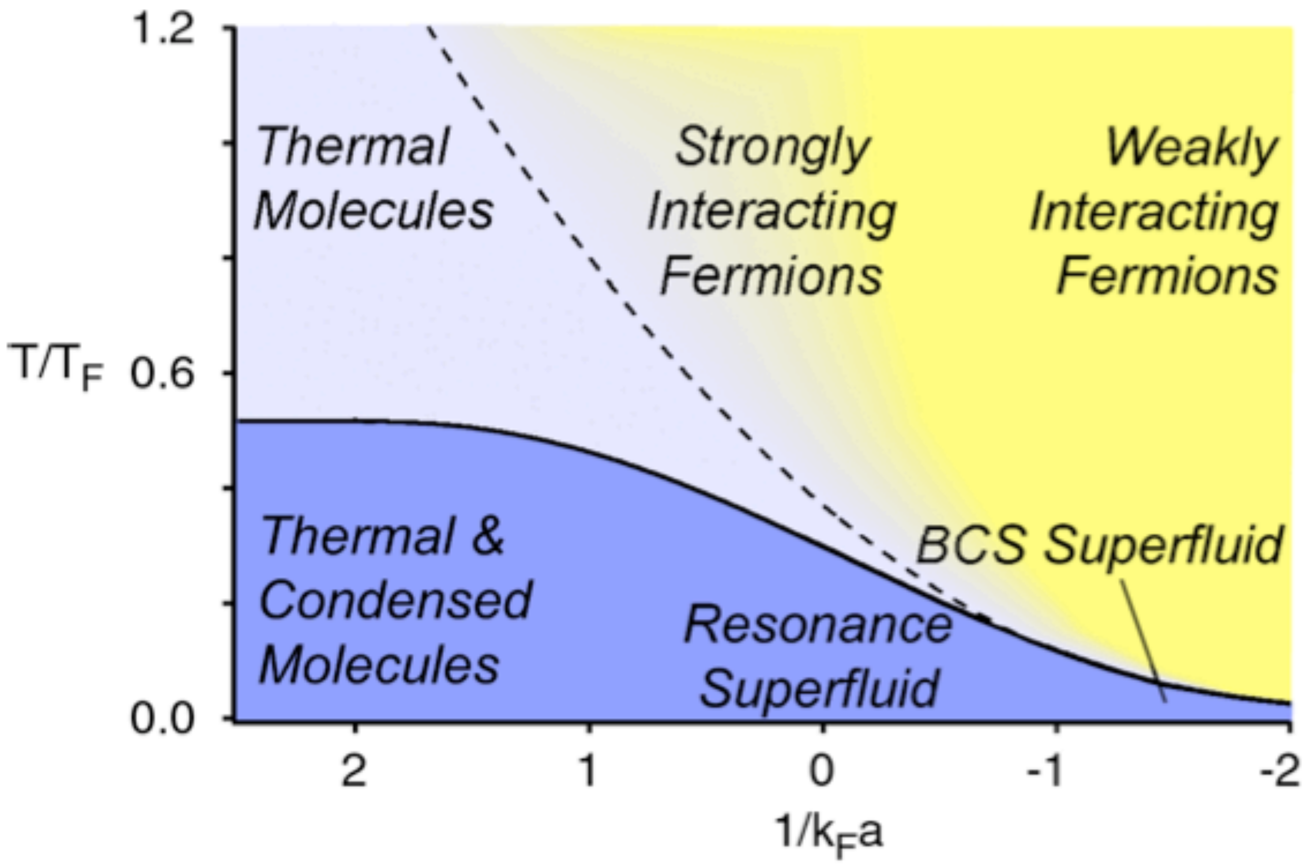
  environment impurity

- **Vary the interaction strength:** $1/k_F a$

- **Rf Spectroscopy to probe interaction energy of system:**

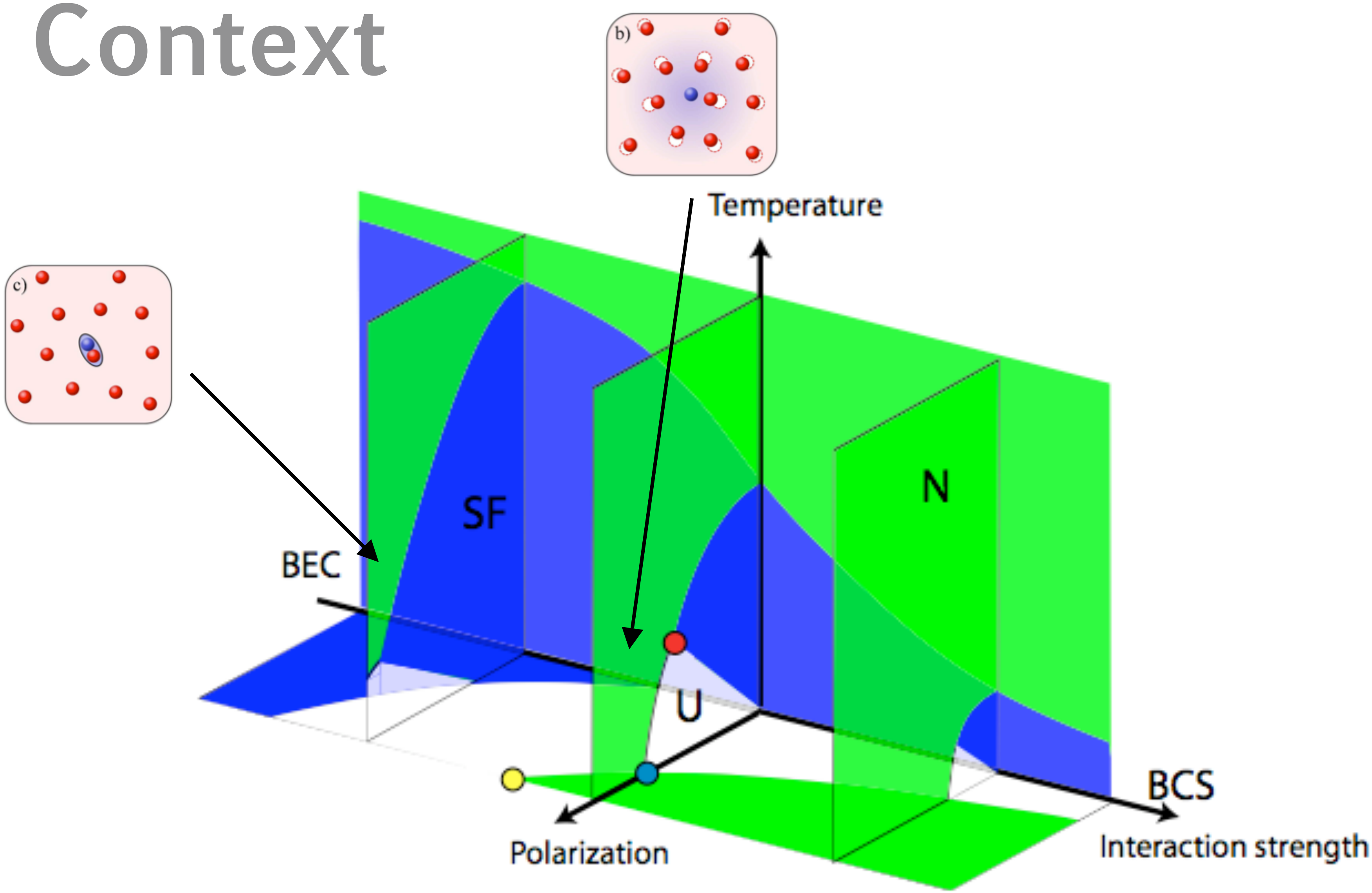


Context



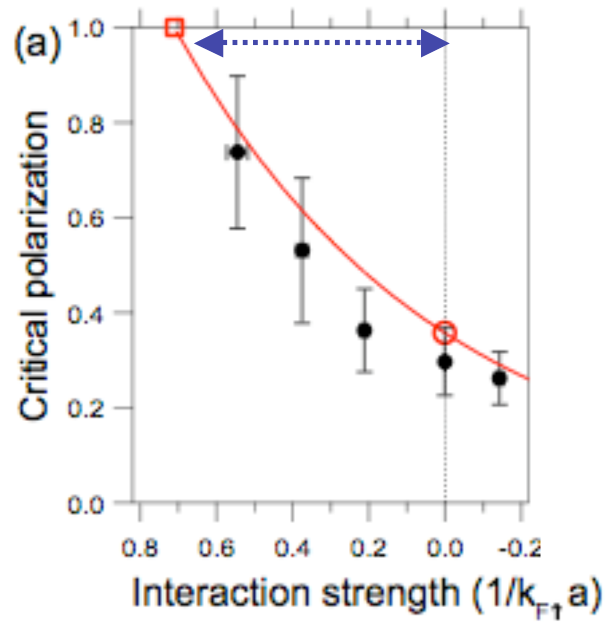
1.2
0.6
0.0
T/TF
Thermal
Molecules
Strongly
Interacting
Fermions
Weakly
Interacting
Fermions
Thermal &
Condensed
Molecules
BCS Superfluid
Resonance
Superfluid
2
1
0
-1
-2
1/kFa

Context

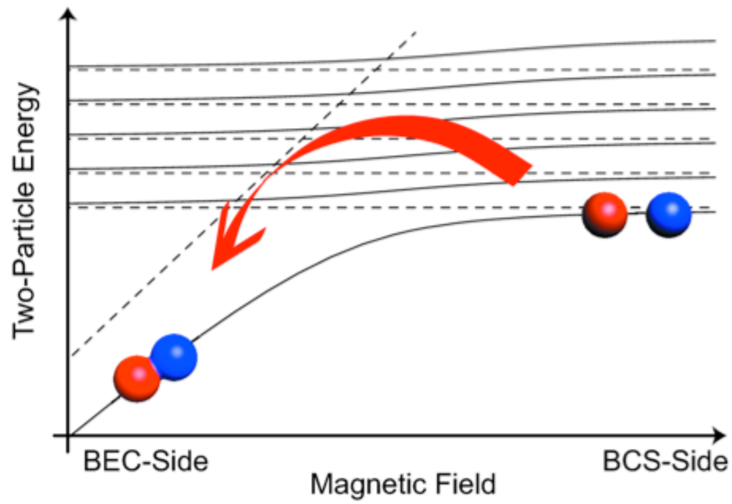

b)
c)
Temperature
SF
N
BEC
U
BCS
Polarization
Interaction strength

Can this Bose-Condense?

Clogston-Chandrasekhar limit: $\delta_{CC} \approx \frac{3}{2}\frac{\Delta}{\mu}$

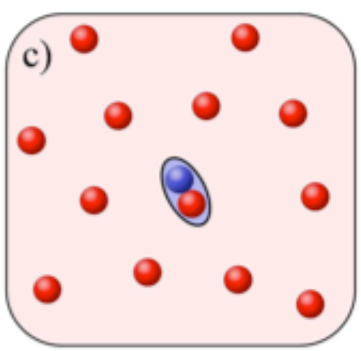


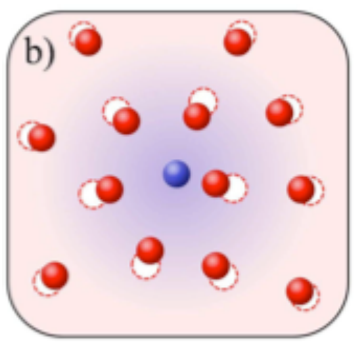
The interesting question (I think)



Pairs

vs





Pairs to Polaron

Overview

Preparation of polarized Fermi Gas

review

Rf spectroscopy and clock shifts

Homogeneous Rf spectroscopy

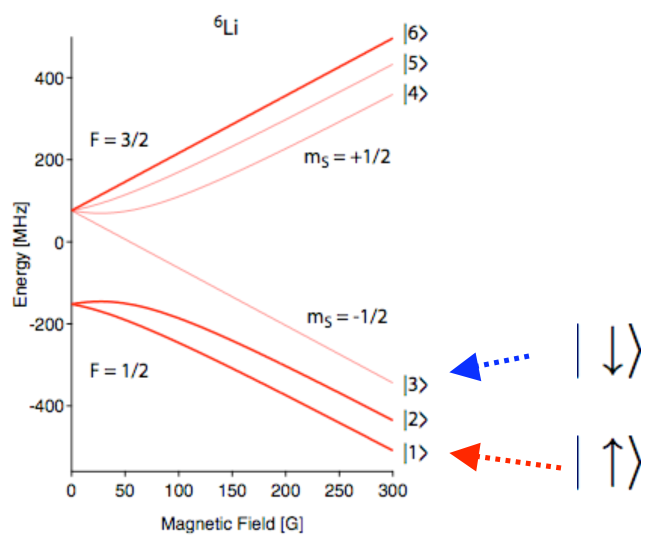
Observing polarons varying $1/k_F a$

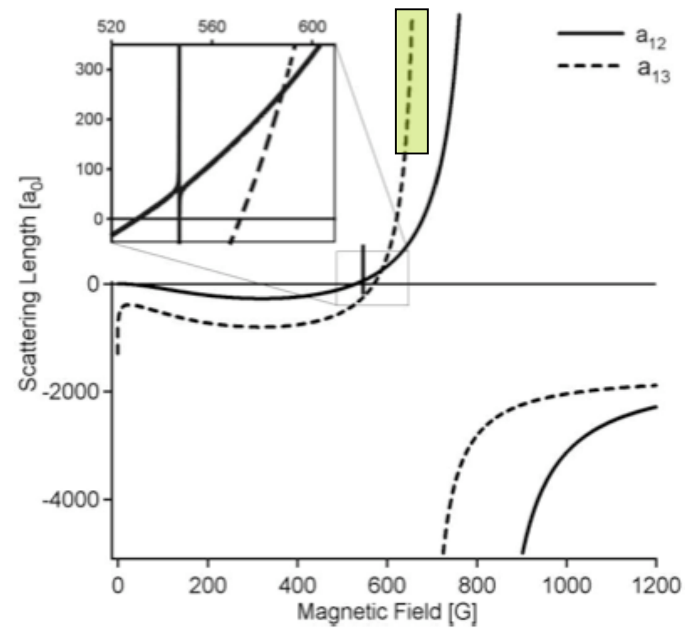
Observing polarons varying impurity concentration

Polaron residue Z

Polarization of DFG

- Prepare spin-polarized $|\uparrow\rangle$ gas of ^{6}Li in lowest hyperfine state in 690G magnetic field.



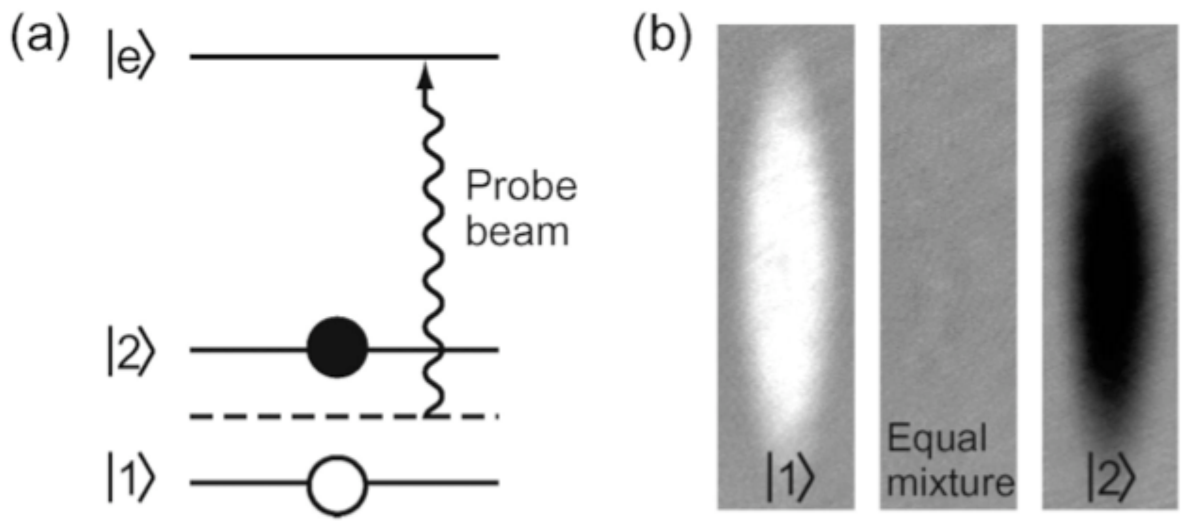


- Transfer small fraction (~5%) to $|\downarrow\rangle$ via a Landau-Zener sweep:

$$P_{|\uparrow\rangle \to |\downarrow\rangle} = 1 - \exp\left(-2\pi \frac{\omega_R^2}{\dot{\delta}}\right)$$

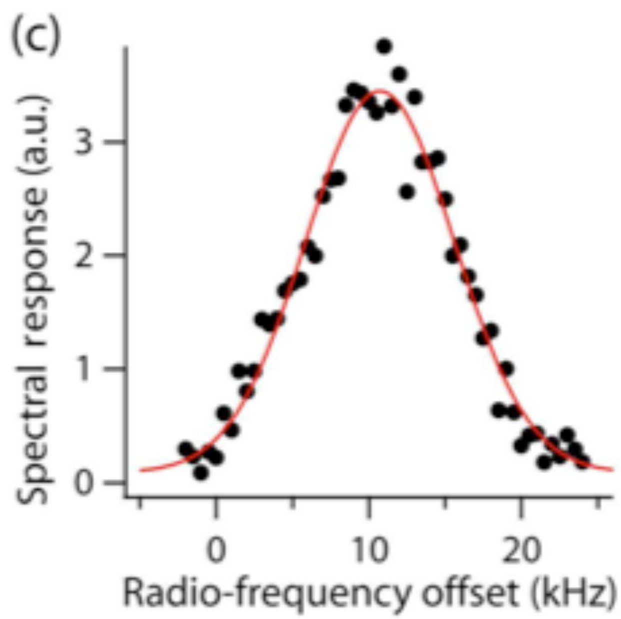
Polarization of DFG

- **Measure/check impurity concentration with phase contrast imaging:**

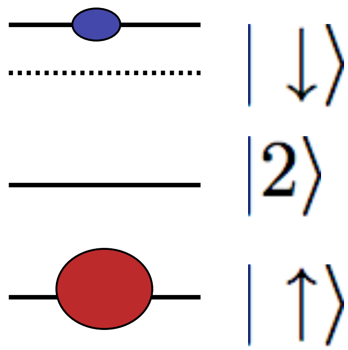


Rf Spectroscopy

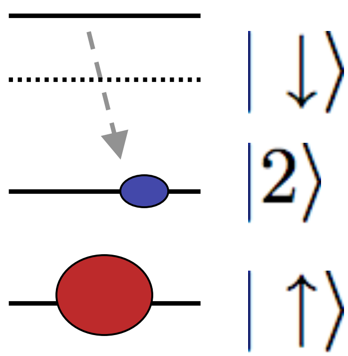
- Rf field couples hyperfine states.
- Long wavelength (~3m) -> whole system sees the same rf field
- Can use to detect *clock shifts* - density dependent shifts due to the interactions between atoms.



MF Rf Spectroscopy



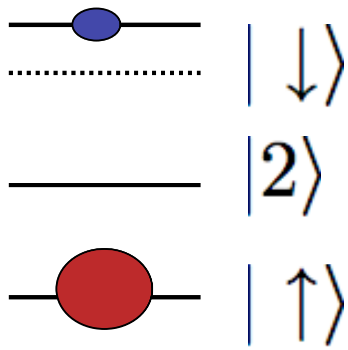
$$u = \frac{4\pi\hbar^2}{m} a_{\uparrow\downarrow} n_\uparrow n_\downarrow$$



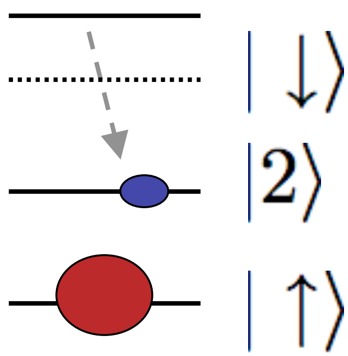
$$u = \frac{4\pi\hbar^2}{m} a_{\uparrow 2} n_\uparrow n_2$$

Mixture	B_0[G]	Rf transition	$a_f[a_0]$
(1,2)	834	$\|2\rangle \rightarrow \|3\rangle$	$a_{13} \approx -3300$
(2,3)	811	$\|2\rangle \rightarrow \|1\rangle$	$a_{13} \approx -3560$
(1,3)	691	$\|1\rangle \rightarrow \|2\rangle$	$a_{23} \approx +1140$
(1,3)	691	$\|3\rangle \rightarrow \|2\rangle$	$a_{12} \approx +1450$

MF Rf Spectroscopy

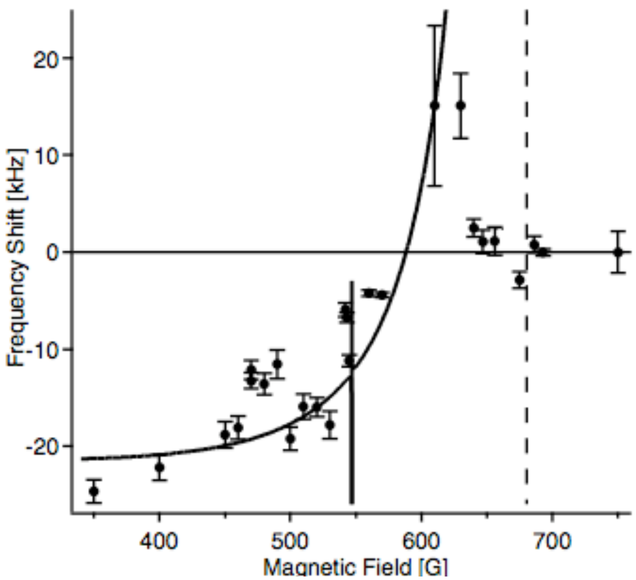


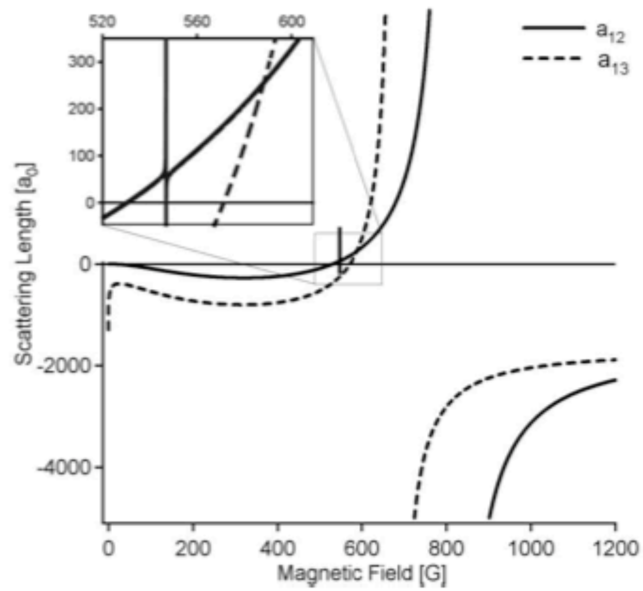
$$\hbar\omega_{\text{rf offset}} = \frac{4\pi\hbar^2}{m} n_\uparrow \left(a_{\uparrow 2} n_2 - a_{\uparrow\downarrow} n_\downarrow\right)$$

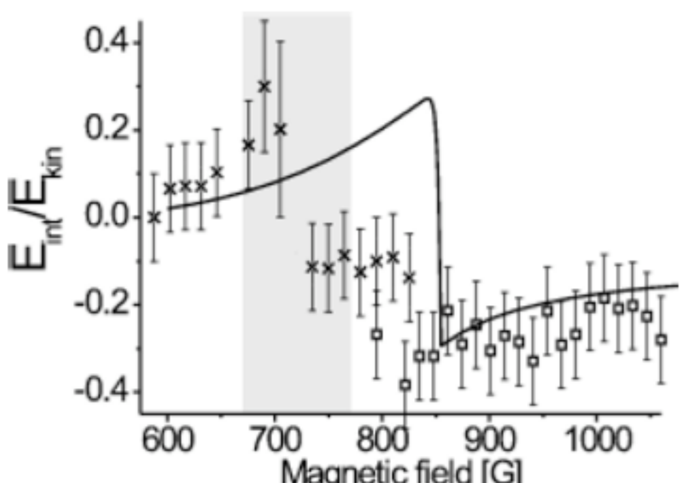


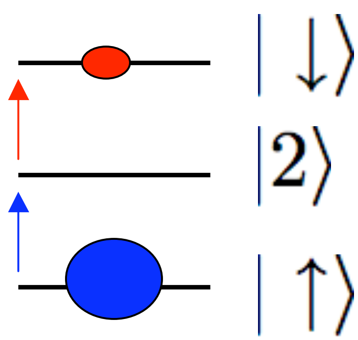
Mixture	B_0[G]	Rf transition	$a_f[a_0]$
(1,2)	834	$\|2\rangle \rightarrow \|3\rangle$	$a_{13} \approx -3300$
(2,3)	811	$\|2\rangle \rightarrow \|1\rangle$	$a_{13} \approx -3560$
(1,3)	691	$\|1\rangle \rightarrow \|2\rangle$	$a_{23} \approx +1140$
(1,3)	691	$\|3\rangle \rightarrow \|2\rangle$	$a_{12} \approx +1450$

Strongly interacting Rf

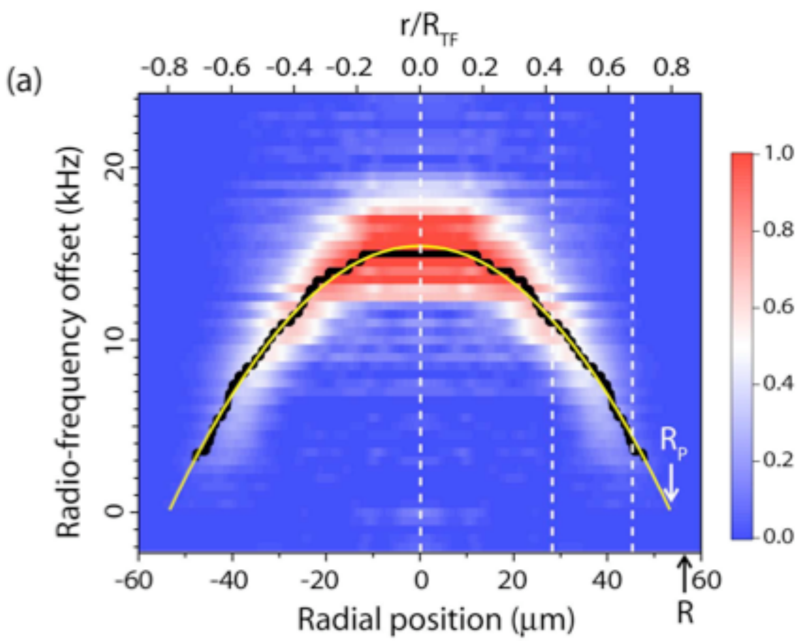








Spatially resolved Rf

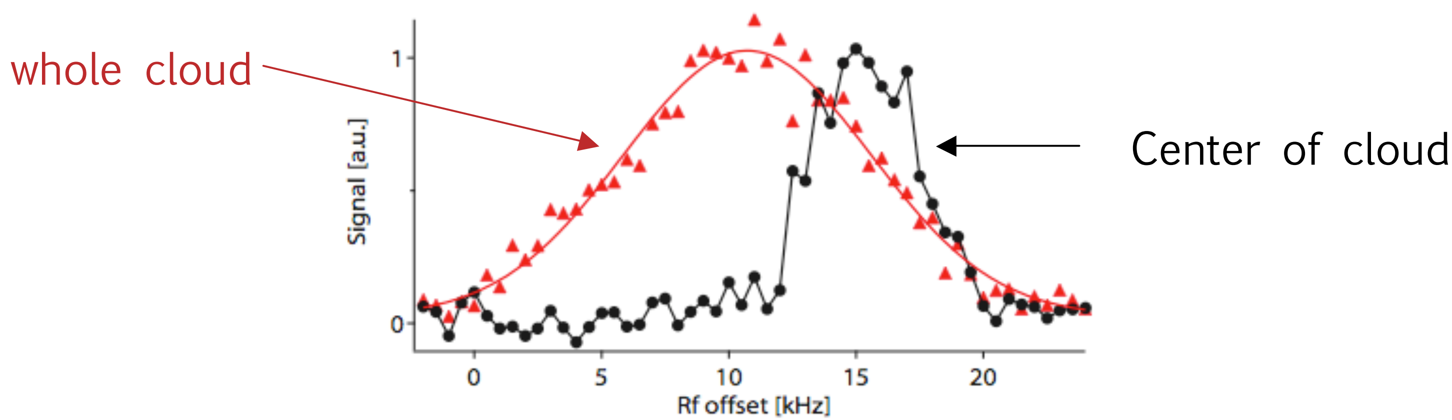


This says:

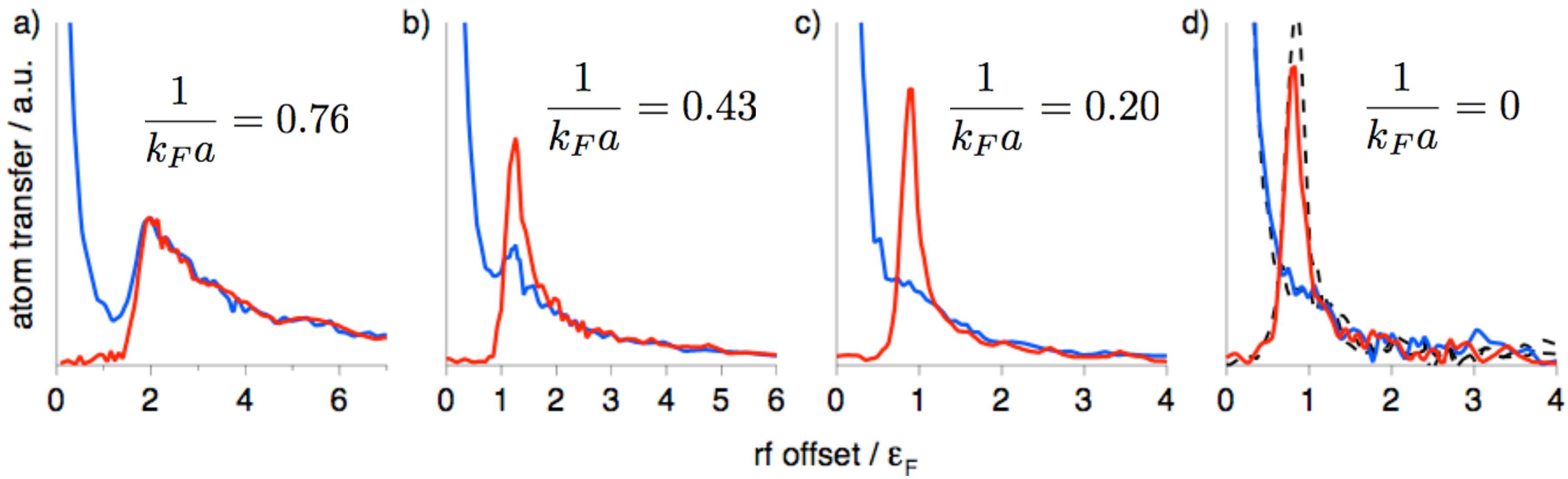
i) Different parts of the cloud are resonant with different offset ν_{rf}

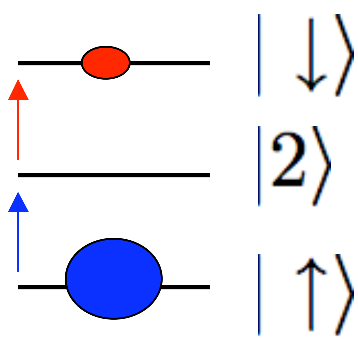
ii) ν_{rf}~n

iii) Reduces broadening 2x

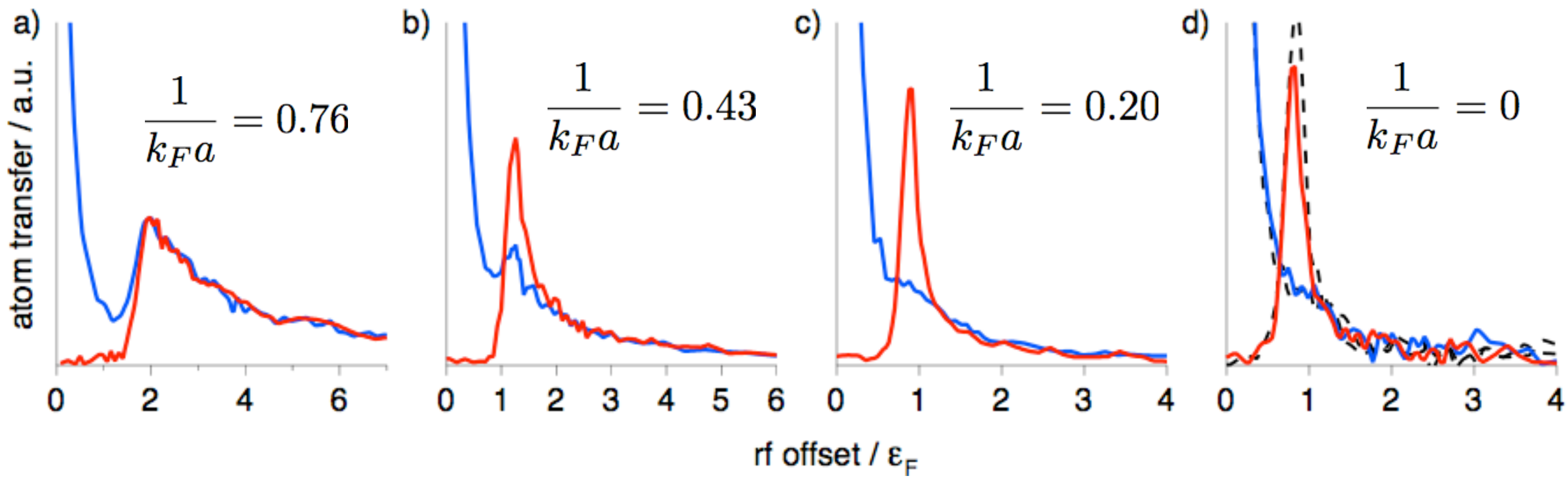


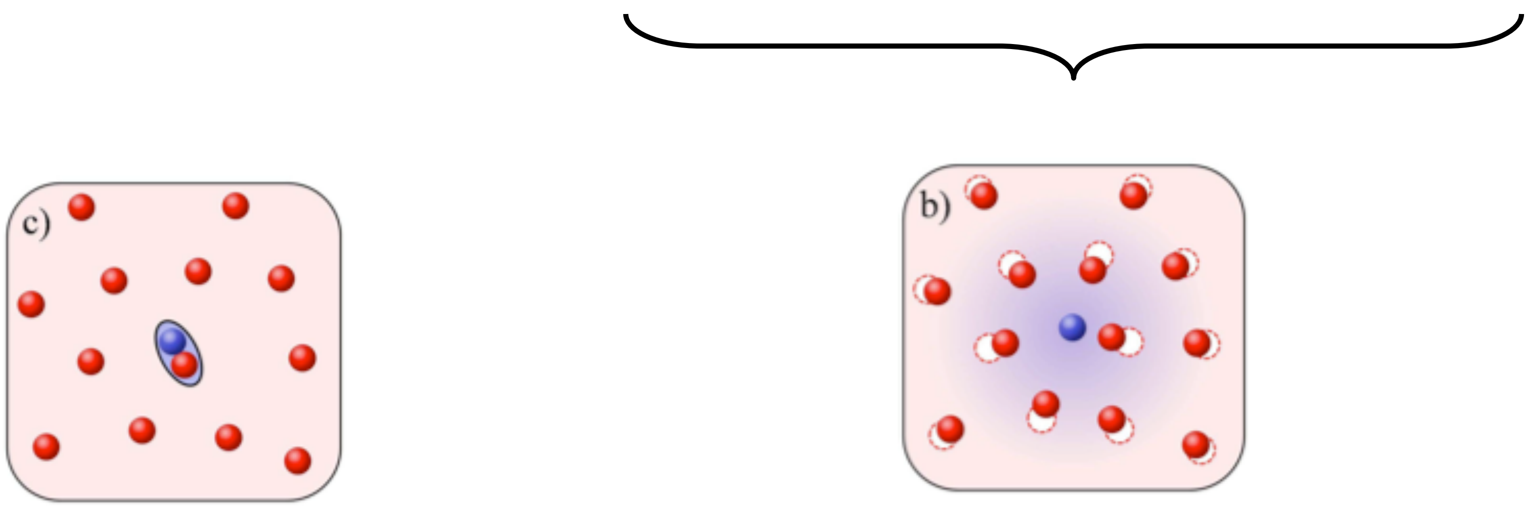
Pairs to Polarons



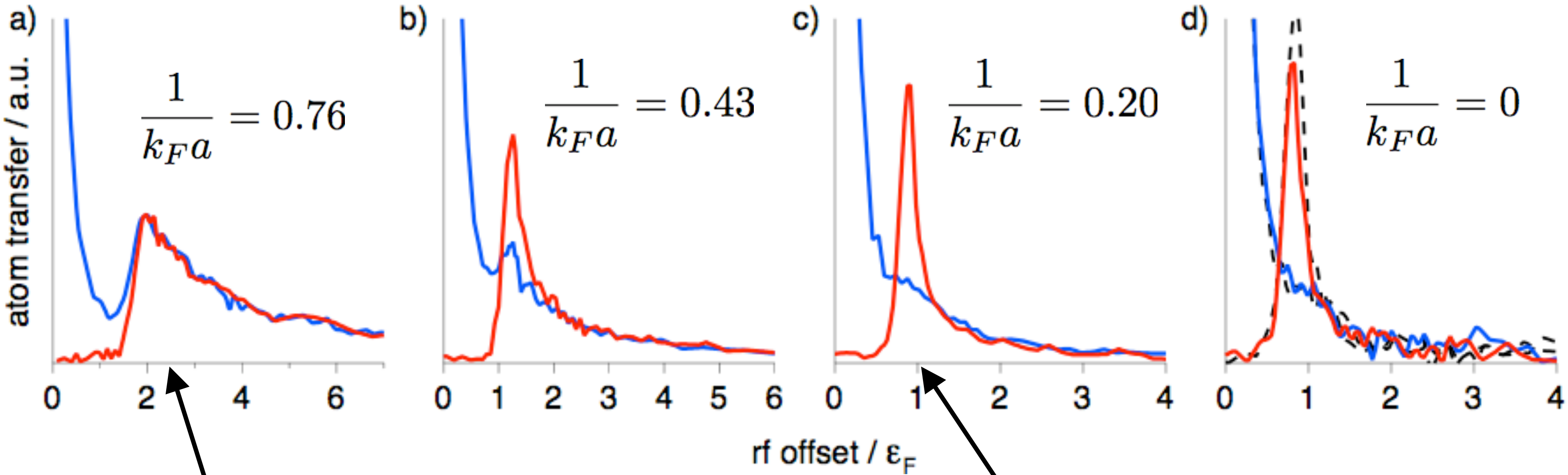


Pairs to Polarons





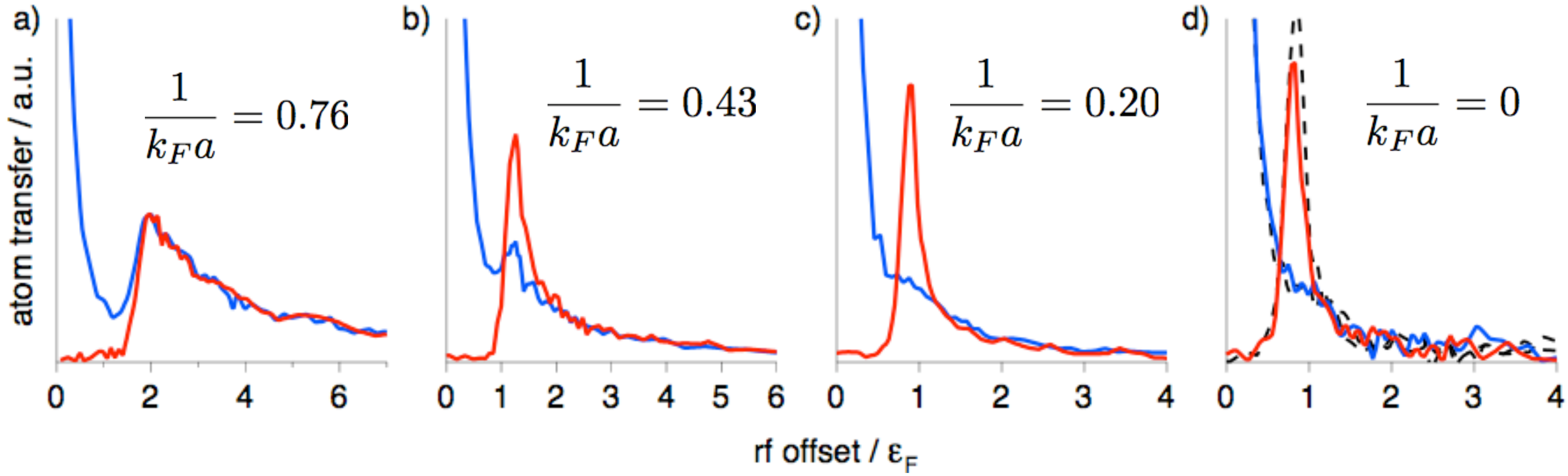
Pairs to Polarons



Molecular binding energy

Polaron binding energy

Pairs to Polarons

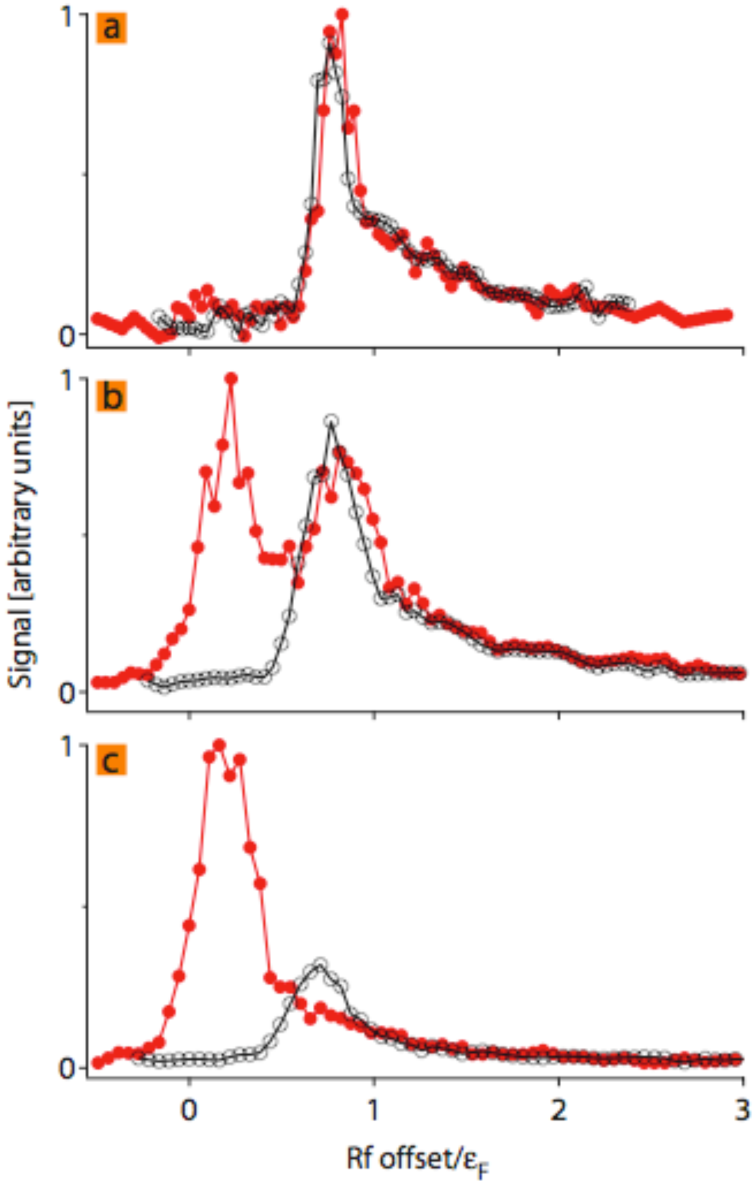


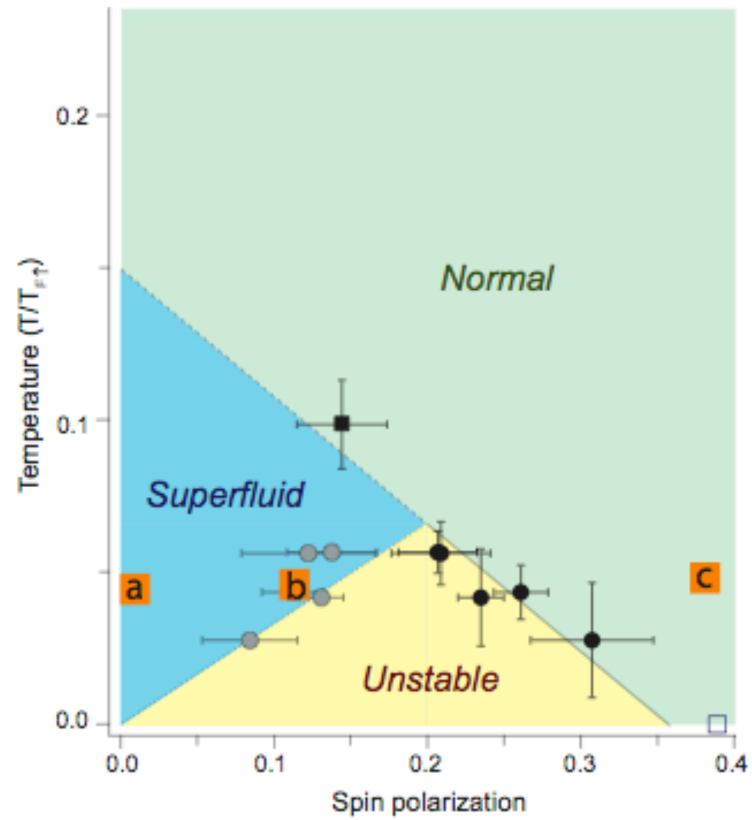
Comments:

i) Width of polaron peak consistent with a delta function, within experimental resolution.

ii) Polaron background matched by environment background. High rf means high k>>kF means distances short w.r.t. interparticle spacing means impurity interacts with only one environment particle.

Results in context:





$$\frac{1}{k_F a} = 0$$

Polaron wavefunction

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

$$Z = |\varphi_0|^2$$

$$\Gamma(\omega) = 2\pi\hbar\Omega_R^2 \, Z\delta(\hbar\omega + E_\downarrow) + \Gamma_{\mathrm{incoh.}}(\omega)$$

Results *position of polaron peak*

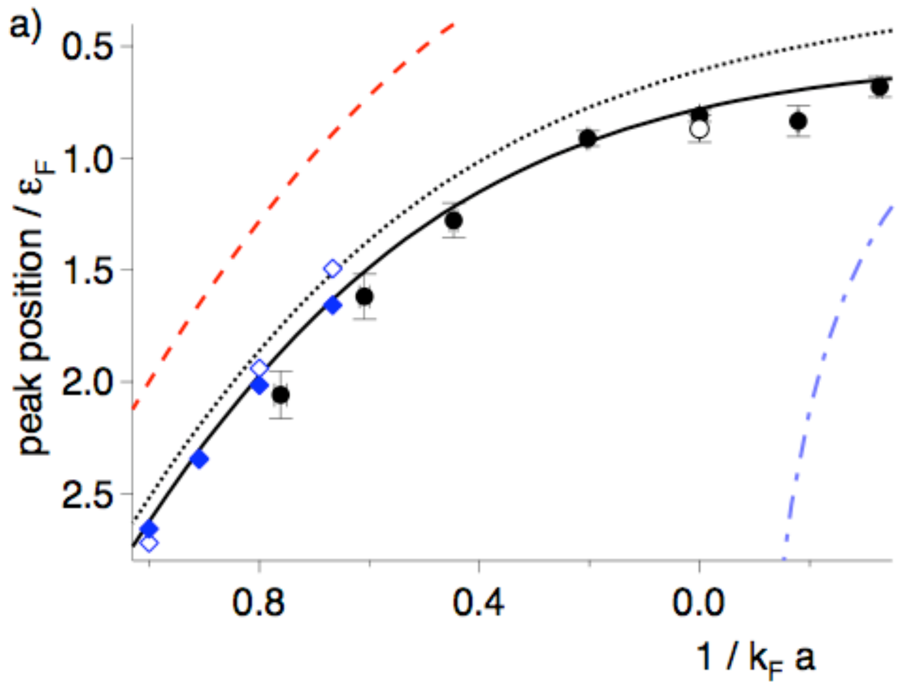


FIG. 3: Peak position of the impurity spectrum as a measure of the polaron energy $E_\downarrow$. a) polaron energy as a function of the interaction strength in the limit of low concentration $x = 5(2)\%$ (solid circles). Open circle: Reversed roles of impurity and environment. Dotted line: polaron energy from variational Ansatz Eq. (1) [5], the solid line including weak final state interactions. Dashed line: Energy of a bare, isolated molecule. Blue dash-dotted line: mean field energy. Solid (open) diamonds: Diagrammatic MC energy of the polaron (molecule) [13].

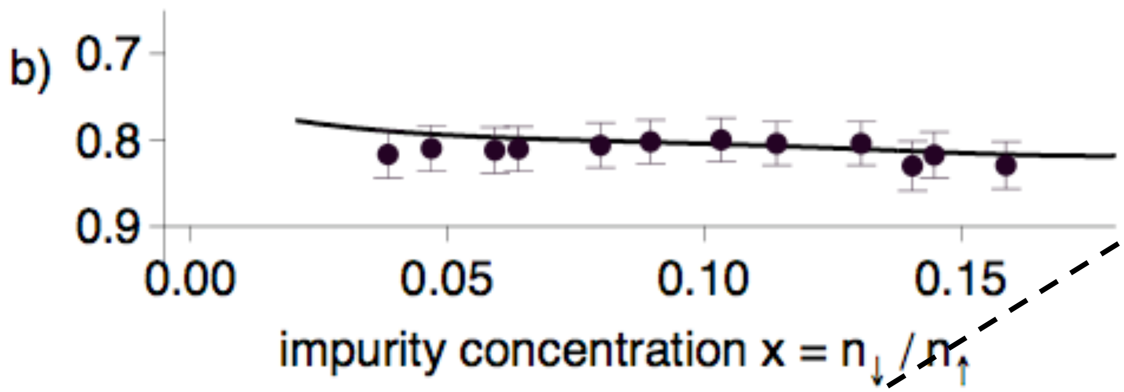
5% impurity

Found:

$$E_\downarrow = -0.64\,(7)\,\epsilon_F$$

$$E_\uparrow = -0.72\,(9)\,\epsilon_F$$

Results *varying the impurity concentration*



b) Peak position at unitarity ($1/k_F a = 0$) as a function of impurity concentration (solid circles). The line shows the expected peak position, $\hbar\omega_p/\epsilon_F = A + (1 - \frac{m}{m^*})x^{2/3} - \frac{6}{5}Fx + \frac{4}{3\pi}k_F a_{\mathrm{fe}}$, using the MC value $A = 0.615$ [13], the analytic result $m^* = 1.2$ [16], the weak repulsion between polarons with $F = 0.14$ [12] and weak final state interactions with scattering length a_{fe}.

Effective mass shifts resonance up

Polarons are weakly interacting

(repulsive), which shifts resonance down

Quasiparticle residue Z

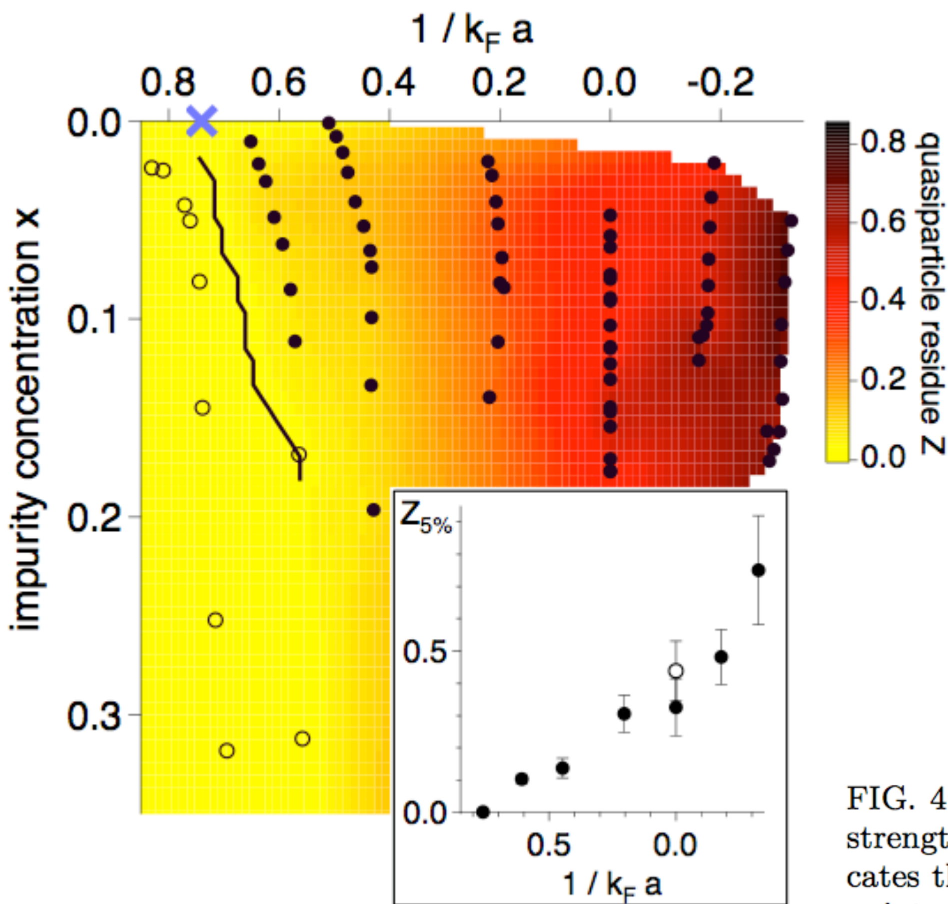


FIG. 4: Quasiparticle residue Z as a function of interaction strength and impurity concentration. The color coding indicates the magnitude of Z and is an interpolation of the data points shown in the graph. Open circles: Data points consistent with zero ($Z < 0.03$), solid circles: $Z > 0.03$, the solid line marking the onset of Z. Blue cross: critical interaction strength for the polaron-molecule transition from [12]. Inset: Z as a function of interaction strength in the limit of low impurity concentration $x = 5(2)\%$. Open circle: Reversed roles, $|1\rangle$ impurity in $|3\rangle$ environment.

Conclusions

- Observed Fermi Polarons
- Determined energy and residue, found that polaron-polaron interactions are weak.

Questions

- How does a weakly interacting polaron liquid connect to Fermi gas with cooper pairs?
- Can Fermion pair condensation be viewed as condensation of pairs of polarons of opposite spin?