The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2030-18

Conference on Research Frontiers in Ultra-Cold Atoms

4 - 8 May 2009

Observation of Fermi polarons in a tunable Fermi liquid of ultracold atoms

ZWIERLEIN Martin Wolfram

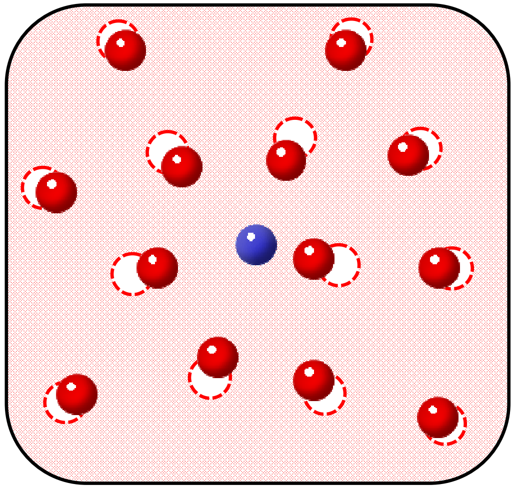
Massachusetts Institute of Technology MIT
Department of Physics
77 Massachusetts Avenue
Cambridge MA 02139
U.S.A.

Research Frontiers in Ultracold Atoms, ICTP, Trieste, Italy, May 7th, 2009

Fermi Polarons

- Building a Fermi Liquid from the Bottom Up -

Martin Zwierlein



Massachusetts Institute of Technology

Center for Ultracold Atoms at MIT and Harvard

$$$: NSF, AFOSR- MURI, Sloan Foundation

Swimming in the Fermi sea

What is the fate of a single impurity in a Fermi sea?

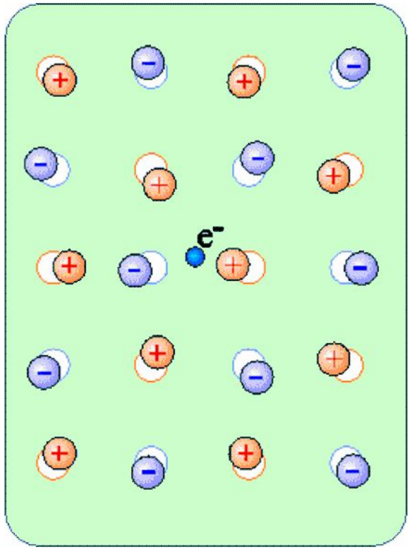
Crucial question for
- electron transport in lattices
- Kondo problem
(single magnetic impurity)
- mobility of ^{4}He in ^{3}He

…
- determines the properties of many condensed matter systems at low temperature

Polarons: The "N+1"-body problem

Polarons

- Historically:
  e^- interacting with lattice distortions (phonons)
  L. D. Landau, Phys. Z. Sowjetunion 3 664 (1933).
- Quasi-particle:
  Electron and its polarization cloud
- "Dressed" energy
- Weight *Z* – *probability of free propagation*
- Effective mass *m**



- Found "everywhere", important for colossal magnetoresistance, affects spectral function of High-T_C materials, applied to fullerenes, polymers, etc…

Theory: Landau, Froehlich, Feynman, Anderson

Impurities interacting with a Fermi sea

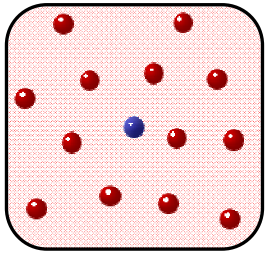
Example: Kondo effect

A spin impurity interacting with Fermi sea of electrons leads to increase in resistance at low temperatures

Our cold atom system:

Mobile impurity interacting with Fermi sea of atoms

Highly imbalanced mixture of two hyperfine states



- Highly controllable
- Tunable, resonant interactions
- All relevant parameters known:

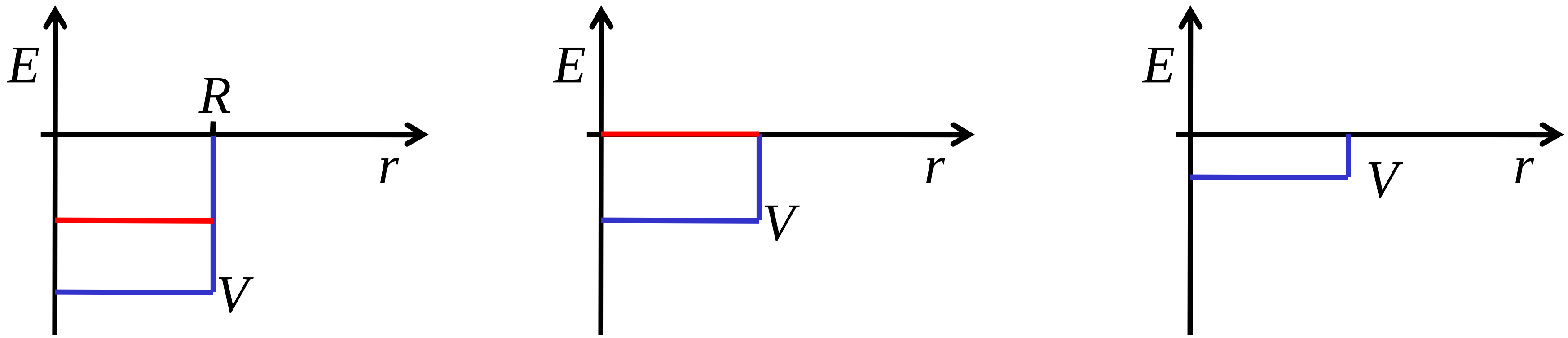
→ Allows quantitative test of many-body theories

- Polaron properties determine phase diagram of imbalanced Fermi mixtures

Tunable Interactions

Vary interaction strength between spin up and spin down

Example: tunable square well (with $k_F R \ll 1$):



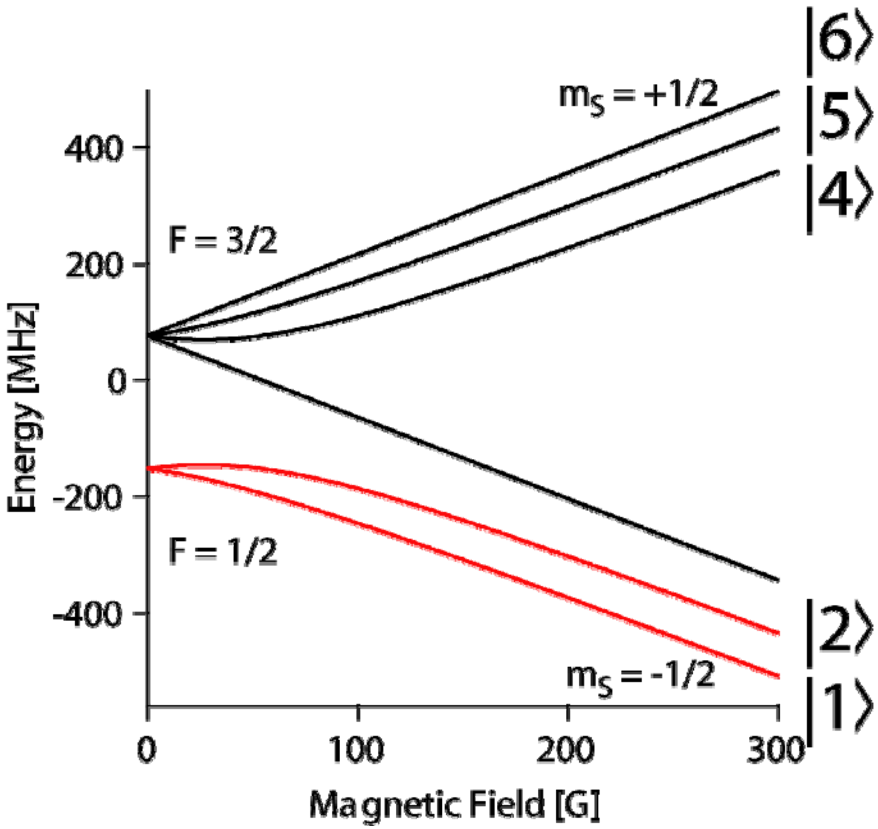
strong attraction	Resonance	weak attraction
deep bound state	*bound state appears*	*no bound state*

scattering length

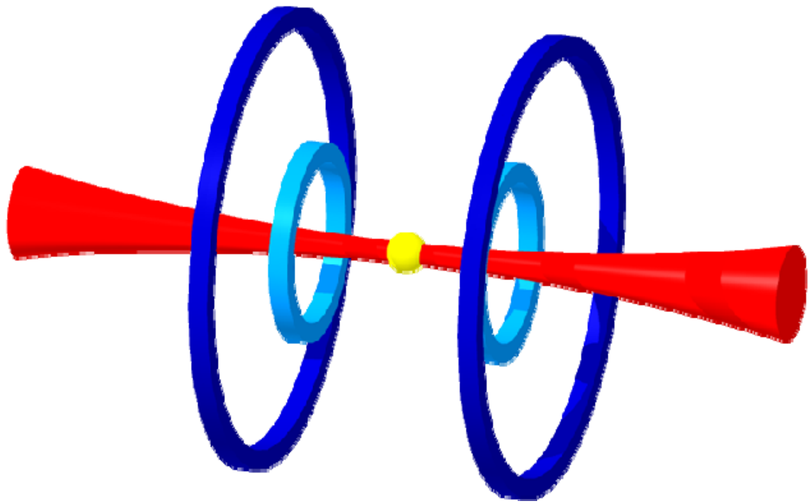
$a > 0$	$a \to \pm\infty$	$a < 0$

Preparation of an interacting Fermi system in Lithium-6

Electronic spin: S = ½, Nuclear Spin: I = 1
→ (2I+1)(2S+1) = 6 hyperfine states



Optical trapping @ 1064 nm

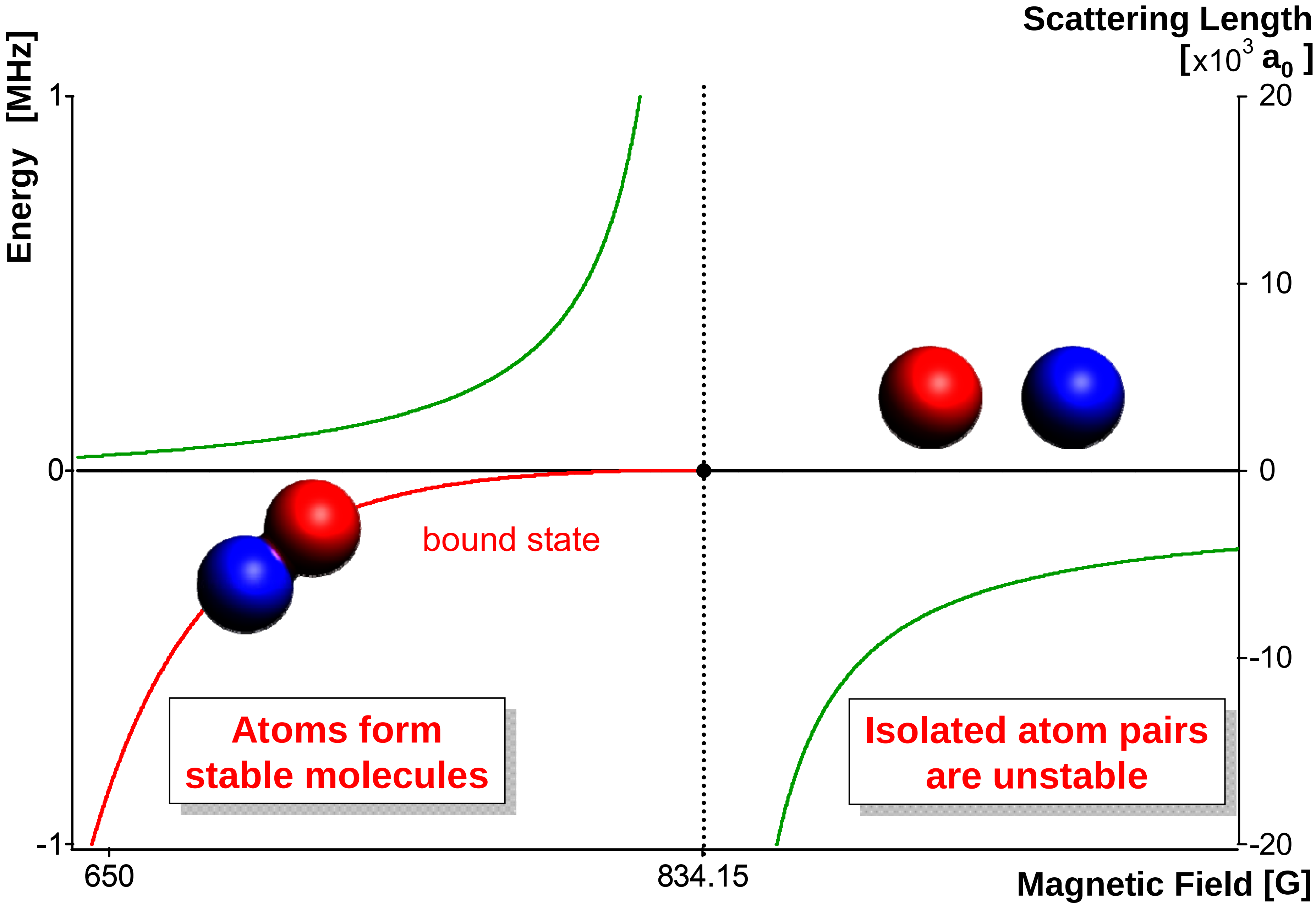


ν_{axial} = 10-20 Hz
ν_{radial} = 50–200 Hz
E_{trap} = 0.5 - 5 μK

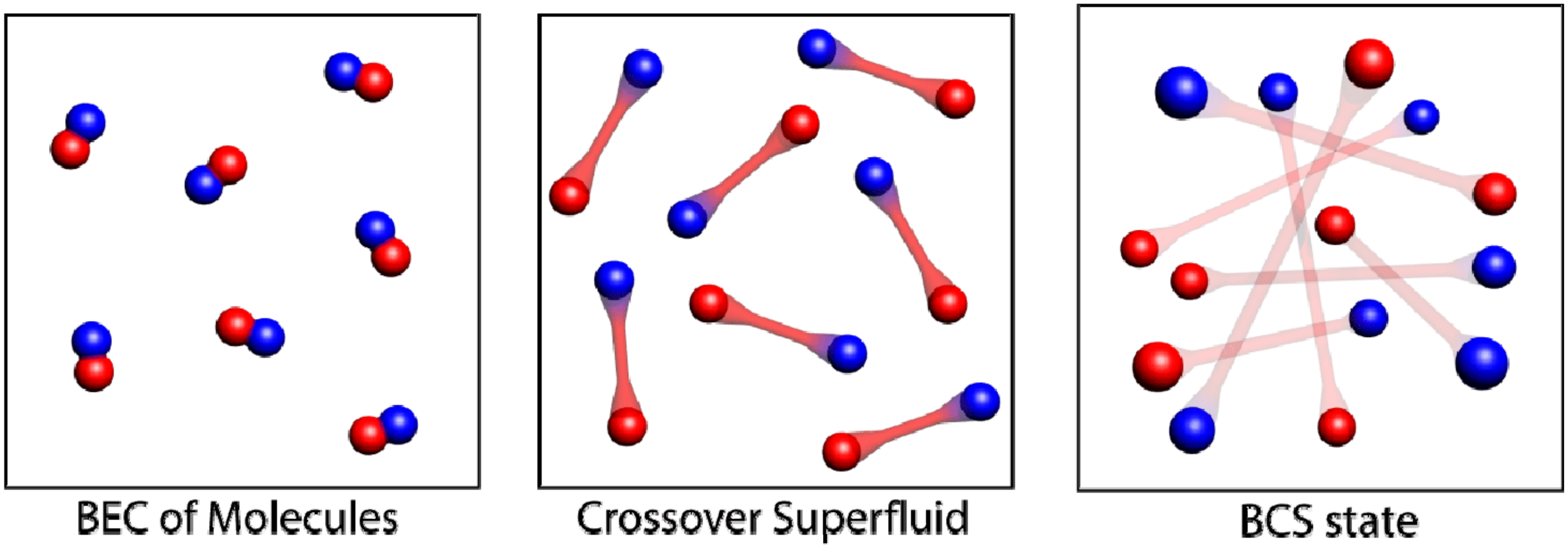
At high fields, states |1> and |2> have large and negative scattering length

$$a_{12} = -2100\ a_0$$

Feshbach Resonances

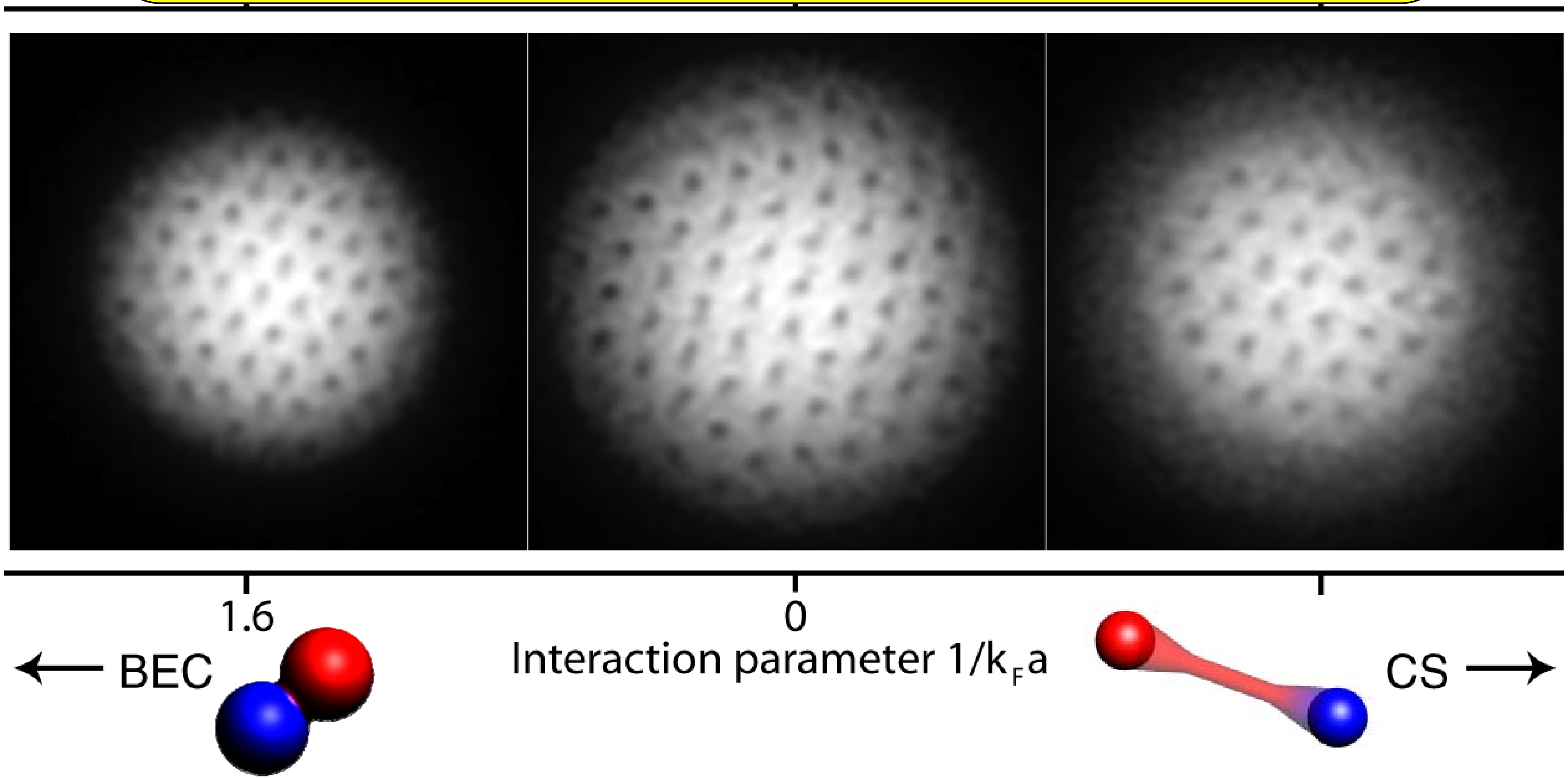


The BEC-BCS Crossover



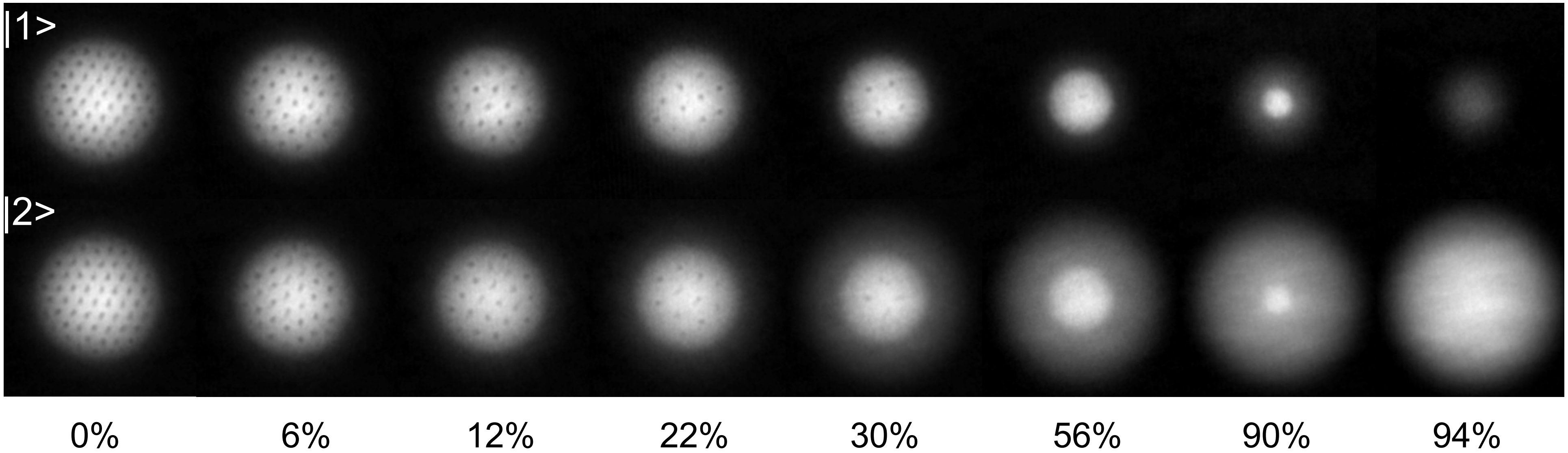
Vortex lattices in the BEC-BCS crossover

Establishes *superfluidity* and *phase coherence*
in gases of fermionic atom pairs



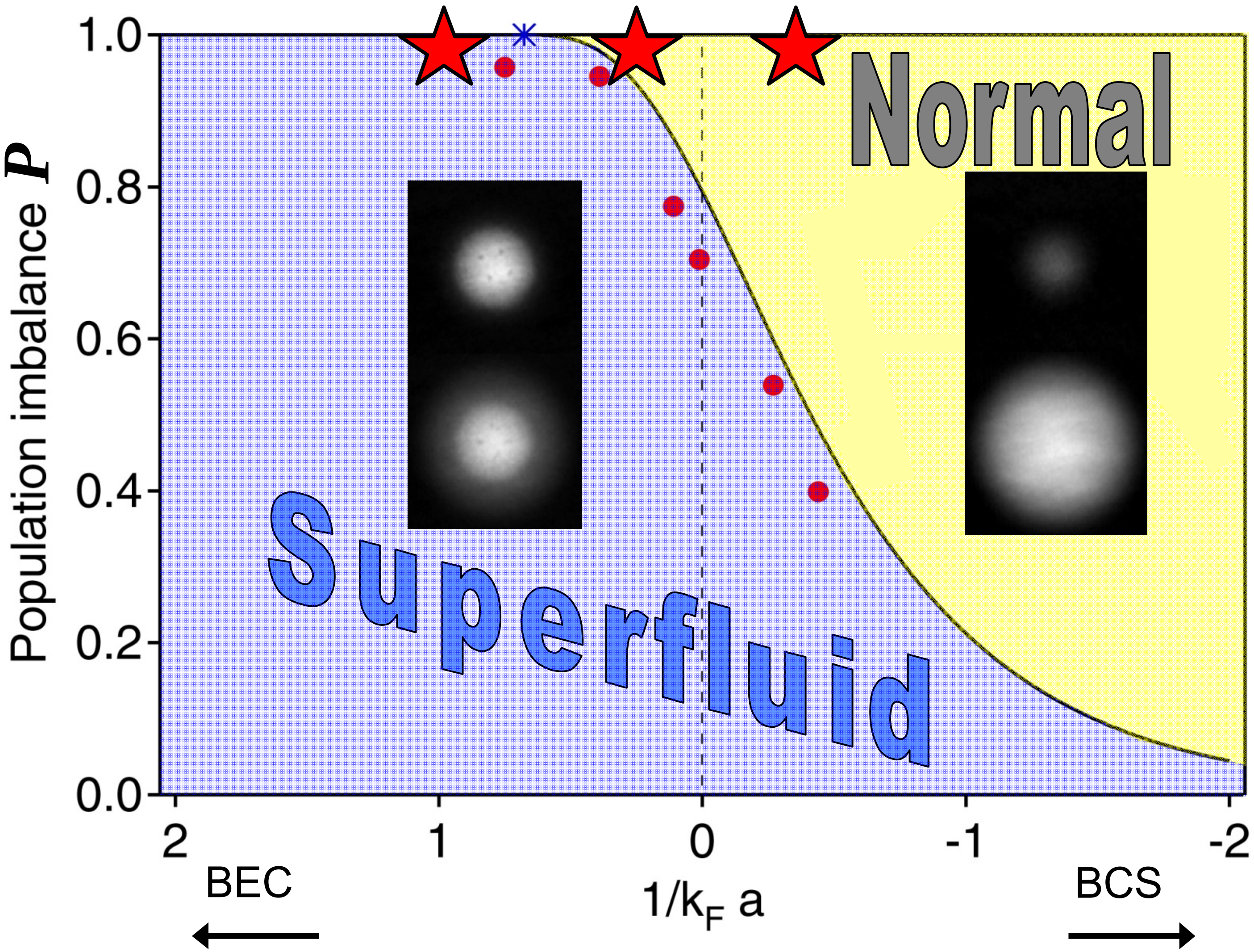
M.W. Zwierlein, J.R. Abo-Shaeer, A. Schirotzek, C.H. Schunck, W. Ketterle,
Nature 435, 1047-1051 (2005)

Fermionic Superfluidity with Imbalanced Spin Populations



M.W. Zwierlein, A. Schirotzek, C.H. Schunck, W. Ketterle,
Science 311, 492 (2006)

Phase Diagram for Unequal Mixtures

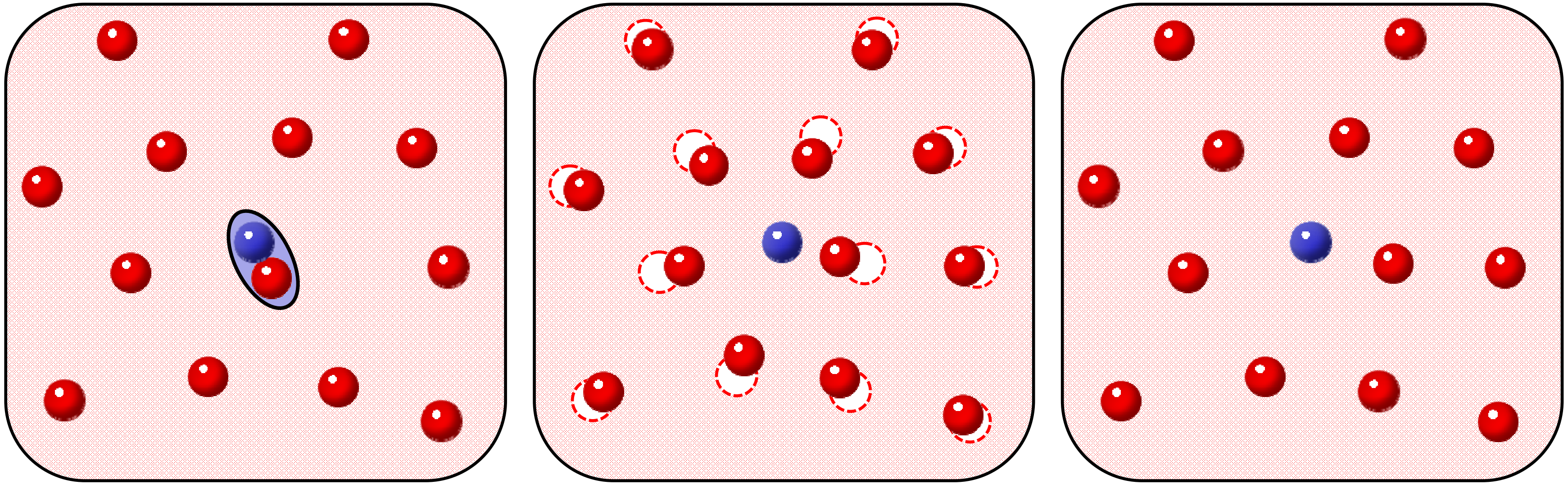


Breakdown: Critical polarization P_c $\propto$ Gap Δ

M.W. Zwierlein, A. Schirotzek, C.H. Schunck, W. Ketterle,
Science 311, 492 (2006)

Swimming in the Fermi Sea

Molecule | Polaron | Mean Field



strong attraction

$$\frac{\hbar^2}{ma^2}$$

?

Energy

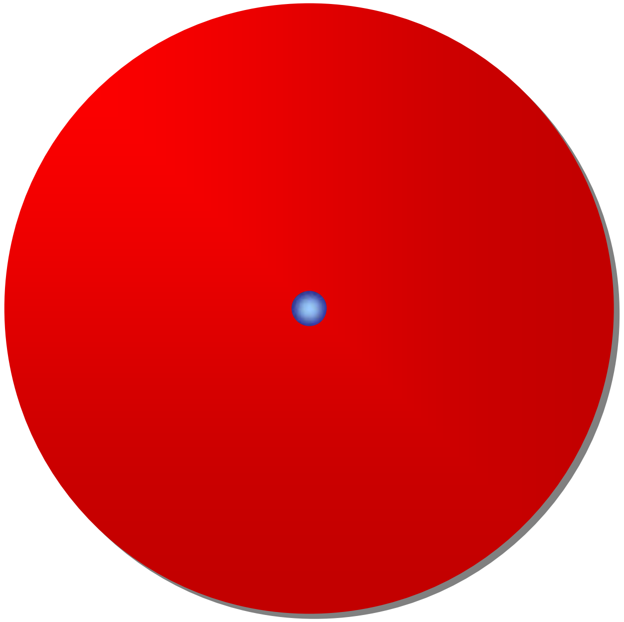
weak attraction

$$\frac{4\pi\hbar^2 a}{m} n_\uparrow$$

Theory: Chevy, Lobo, Giorgini, Stringari, Prokof’ev, Svistunov, Sachdev, Sheehy, Radzihovsky, Lamacraft, Combescot, Sa de Melo

Swimming in the Fermi sea

A single $|\downarrow\rangle$ atom immersed in a $|\uparrow\rangle$ cloud
with unitarity limited interactions



Binding energy must be universal

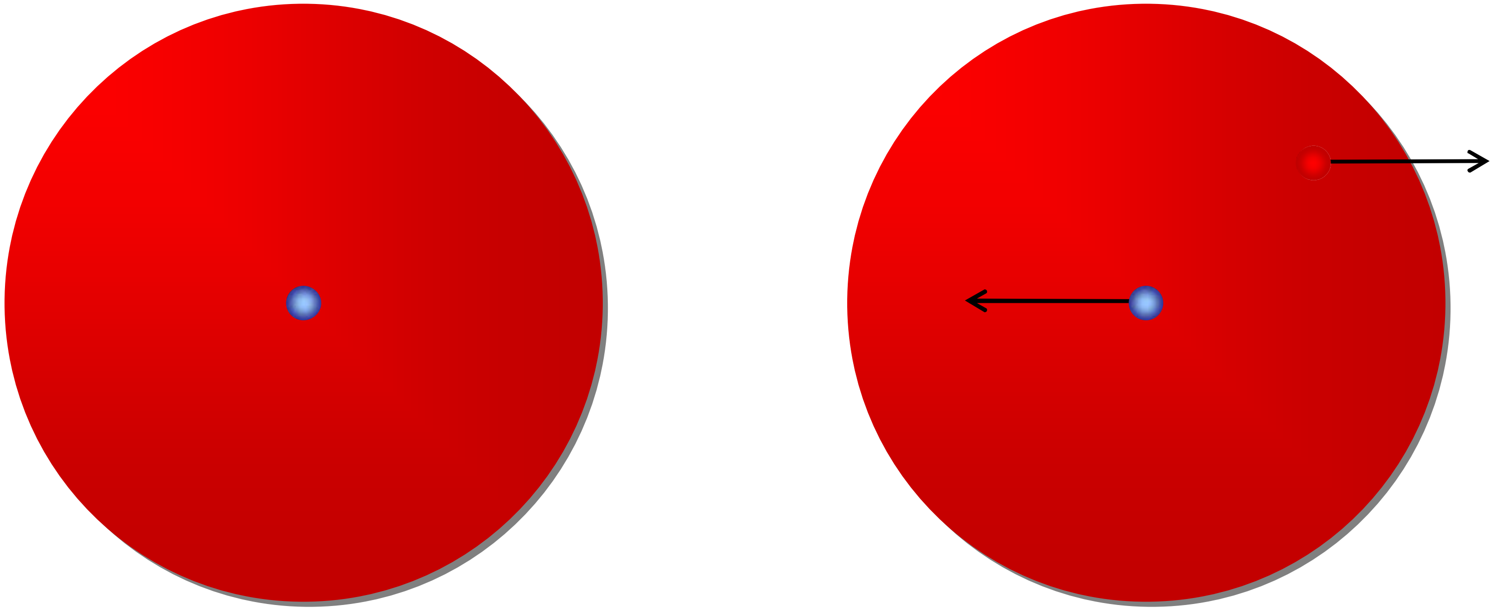
$$E_{\downarrow} = \gamma\, E_{F\uparrow}$$

$$\gamma = -0.6$$

F. Chevy PRA **74**, 063628 (2006), Variational Cooper pair Ansatz
C. Lobo, A. Recati, S. Giorgini, S. Stringari, PRL **97**, 200403 (2006), Monte-Carlo

Swimming in the Fermi sea

$$|\Psi\rangle = \phi_0 |\mathbf{0}\rangle_\downarrow |FS\rangle_\uparrow + \sum_{q<k_F}^{k>k_F} \phi_{\mathbf{qk}} |\mathbf{q}-\mathbf{k}\rangle_\downarrow c^\dagger_{\mathbf{k}_\uparrow} c_{\mathbf{q}_\uparrow} |FS\rangle_\uparrow$$



F. Chevy PRA **74**, 063628 (2006), Variational Cooper pair Ansatz

C. Lobo, A. Recati, S. Giorgini, S. Stringari, PRL **97**, 200403 (2006), Monte-Carlo

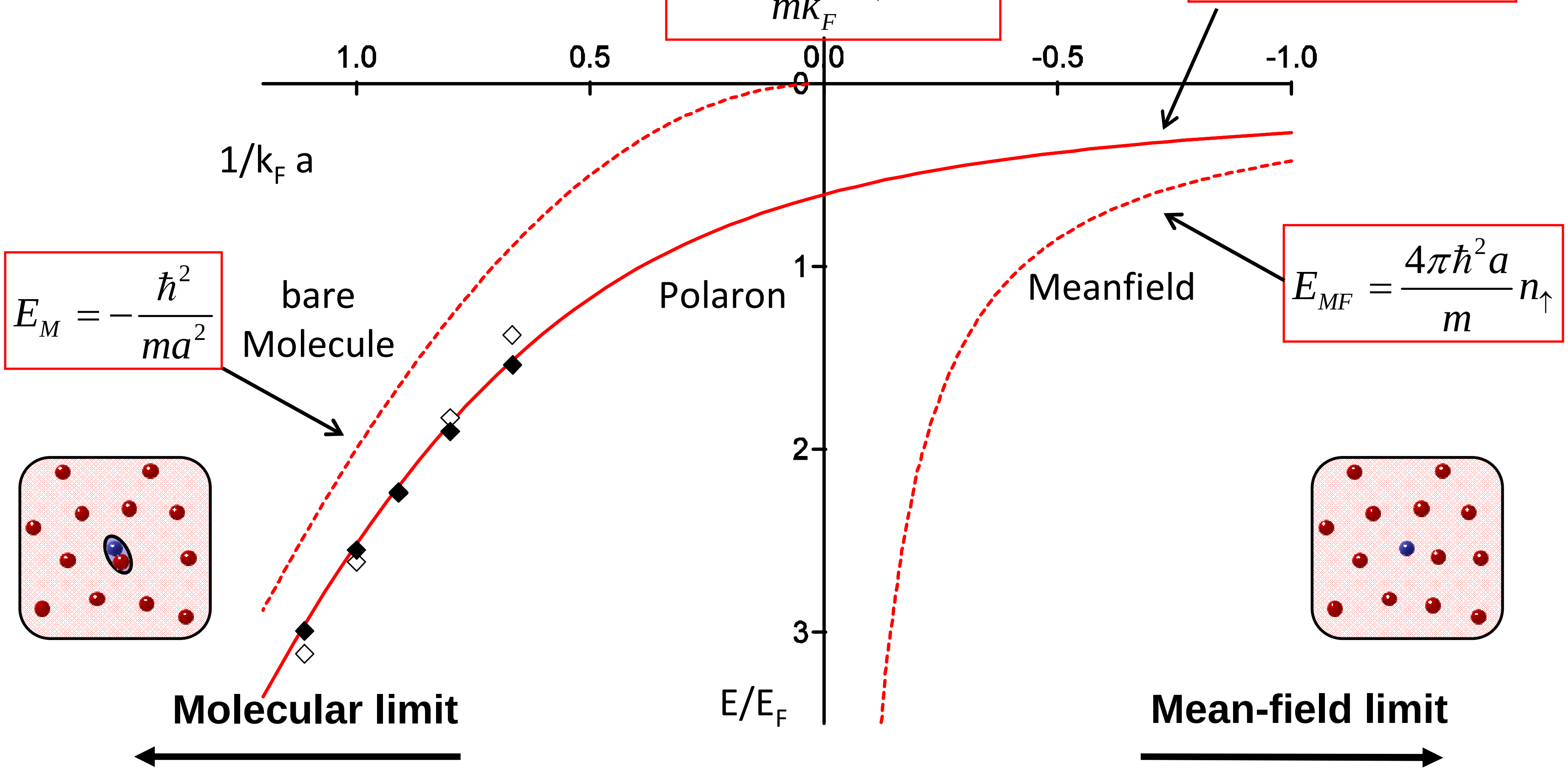
Polaron Energy

$$E = \frac{1}{\Omega}\sum_{q<k_F} \frac{1}{\frac{m}{4\pi\hbar^2 a} + \frac{1}{\Omega}\sum_{k>k_F}\left(\frac{1}{\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{q}} + \varepsilon_{\mathbf{q-k}} - E} - \frac{1}{2\varepsilon_{\mathbf{k}}}\right) - \frac{1}{\Omega}\sum_{q<k_F}\frac{1}{2\varepsilon_{\mathbf{q}}}}$$

$$E = \Sigma(E)$$

$$E = c\frac{\hbar^2}{mk_F}n_\uparrow = cE_F$$

$$E = \frac{4\pi\hbar^2\,\mathrm{Re}(f)}{m}n_\uparrow$$



Variational approach/T-Matrix: F. Chevy PRA 74, 063628 (2006), R. Combescot and S. Giraud, PRL 101, 050404 (2008), R. Combescot et al.,PRL 98, 180402 (2007)

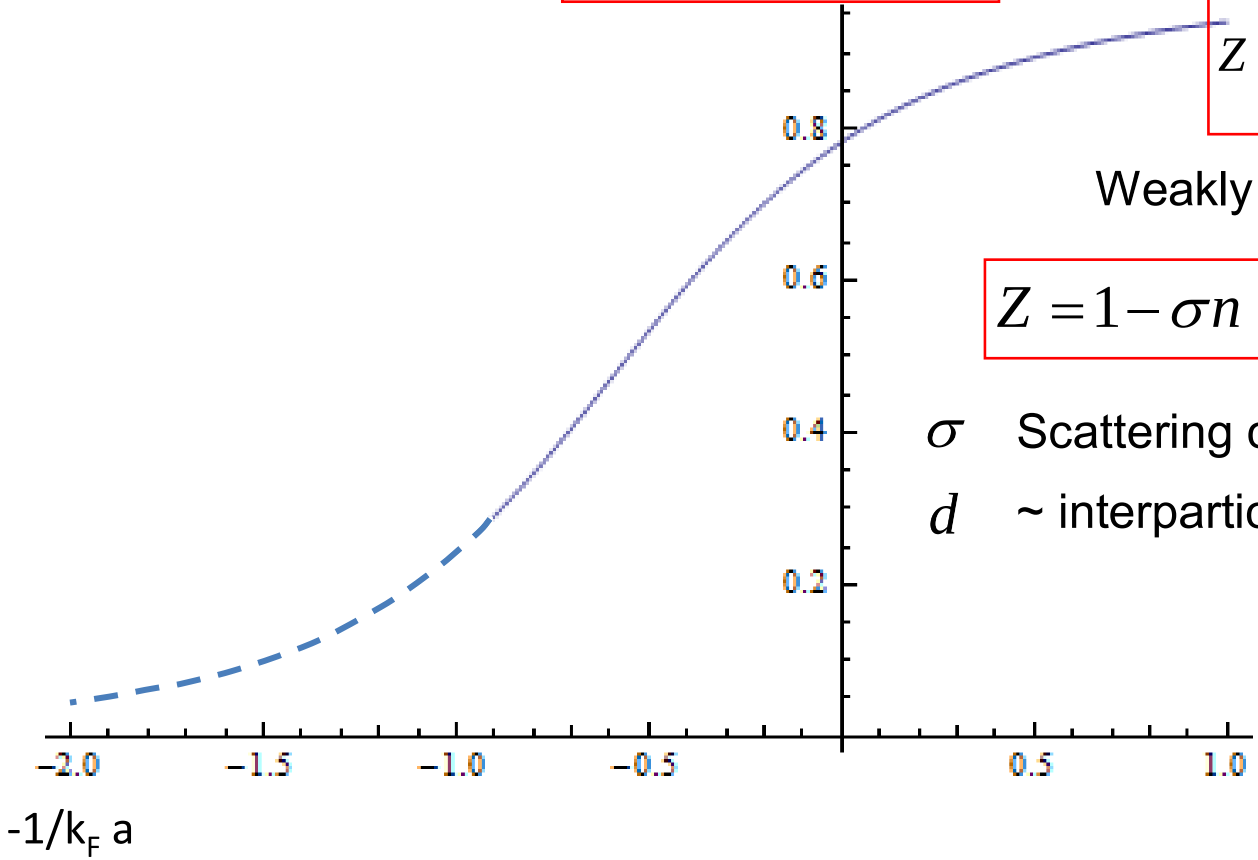
Diagrammatic Monte-Carlo: N. V. Prokof'ev and B. V. Svistunov, PRB 77, 125101 (2008)

T-matrix/ladder approximation: P. Massignan, G. Bruun and H. Stoof, PRA 78, 031602 (2008)

Polaron Quasi-particle weight = Probability of free propagation

$$Z = |\varphi_0|^2 = \frac{1}{1 - \frac{\partial}{\partial E}\frac{1}{\Omega}\sum_{q<k_F}\frac{1}{\frac{m}{4\pi\hbar^2 a} + \frac{1}{\Omega}\sum_{k>k_F}\left(\frac{1}{\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{q}} + \varepsilon_{\mathbf{q-k}} - E} - \frac{1}{2\varepsilon_{\mathbf{k}}}\right) - \frac{1}{\Omega}\sum_{q<k_F}\frac{1}{2\varepsilon_{\mathbf{q}}}}}$$

$$Z = |\varphi_0|^2 = \frac{1}{1 - \frac{\partial}{\partial E}\Sigma(E)}$$



$$Z = 1 - \frac{4\pi}{k_F}\langle \mathrm{Im}\, f \rangle$$

Weakly interacting limit:

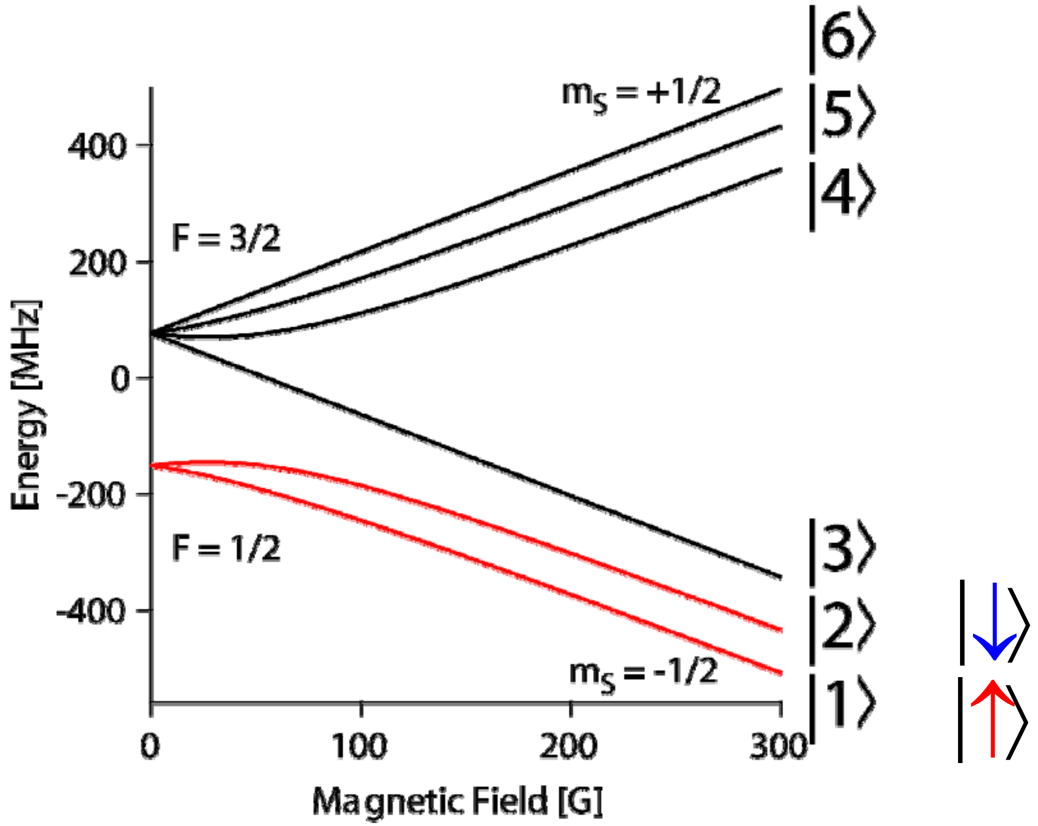
$$Z = 1 - \sigma n\, d = 1 - \mathrm{c}(k_F a)^2$$

σ Scattering cross section

d ~ interparticle distance $1/k_F$

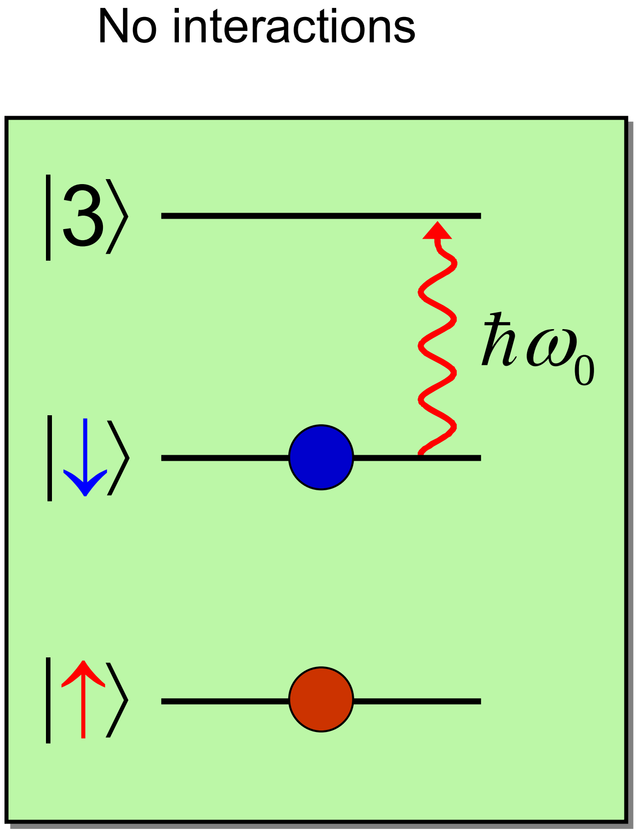
Can we measure the binding energy?

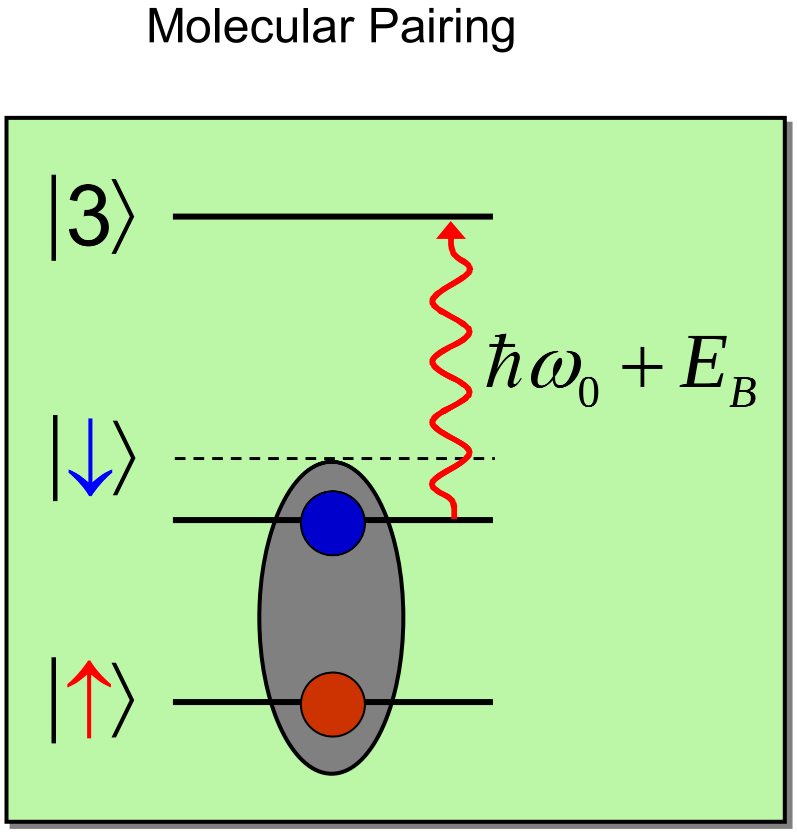
Radiofrequency spectroscopy



S. Gupta, Z. Hadzibabic, M.W. Zwierlein, C.A. Stan, K. Dieckmann, C.H. Schunck, E.G.M. van Kempen, B.J. Verhaar, and W. Ketterle, Science **300**, 1723 (2003)

Radiofrequency spectroscopy

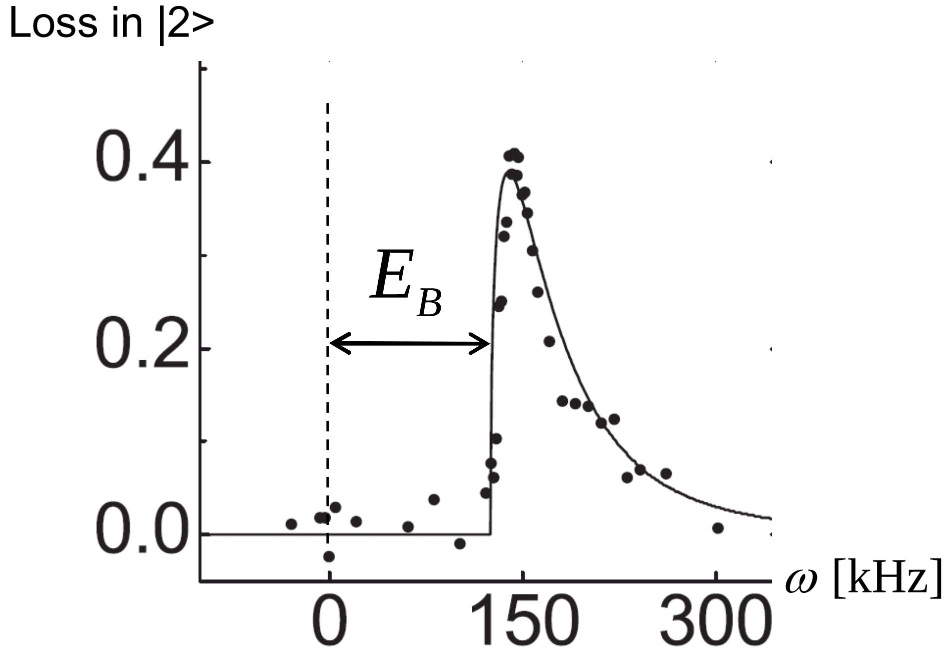




Photon energy = Zeeman + Binding + Kinetic energy

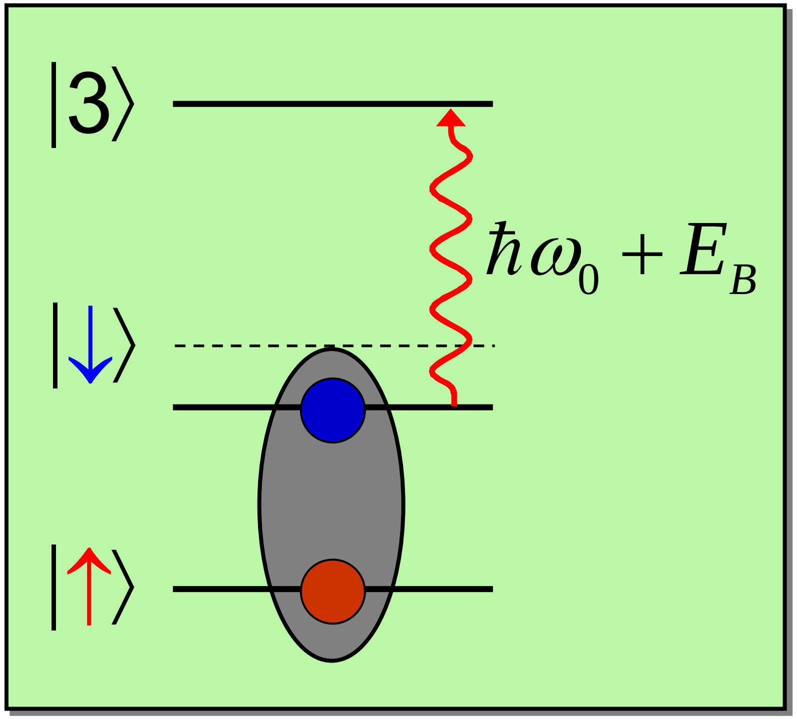
$$\hbar\omega = \hbar\omega_0 + E_B + 2\varepsilon_k$$

Radiofrequency spectroscopy



C.Chin et al. Science, **305**, 1128 (2004)

Molecular Pairing

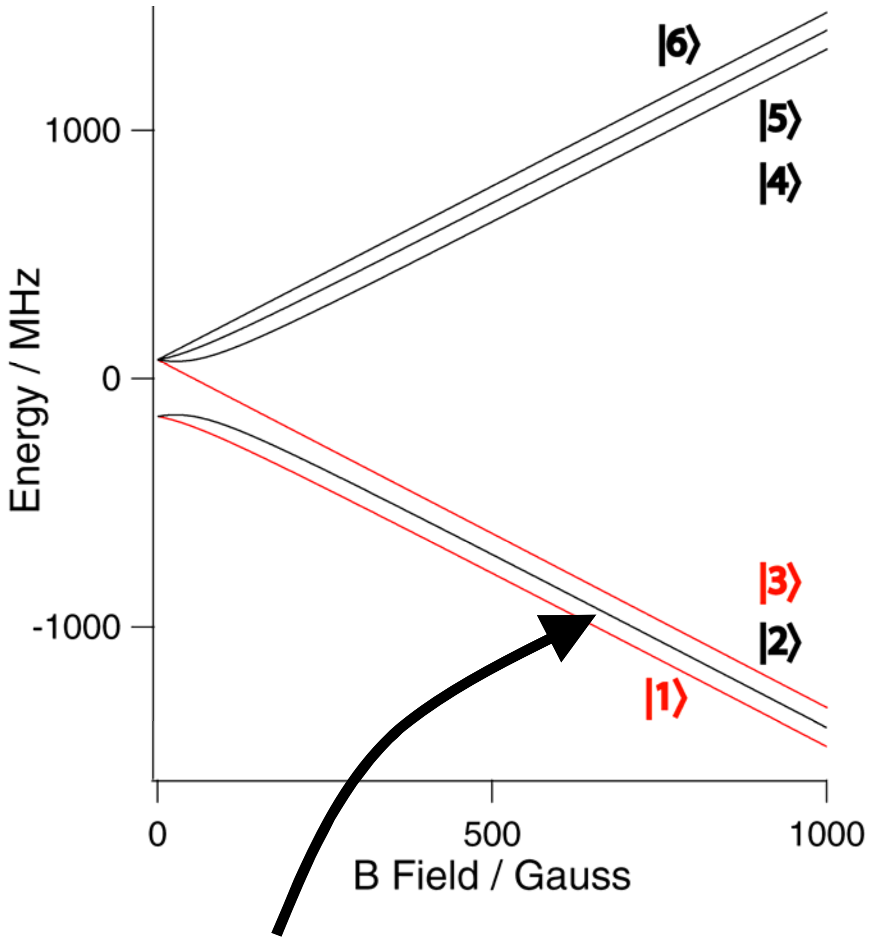


Photon energy = Zeeman + Binding + Kinetic energy

$$\hbar\omega = \hbar\omega_0 + E_B + 2\varepsilon_k$$

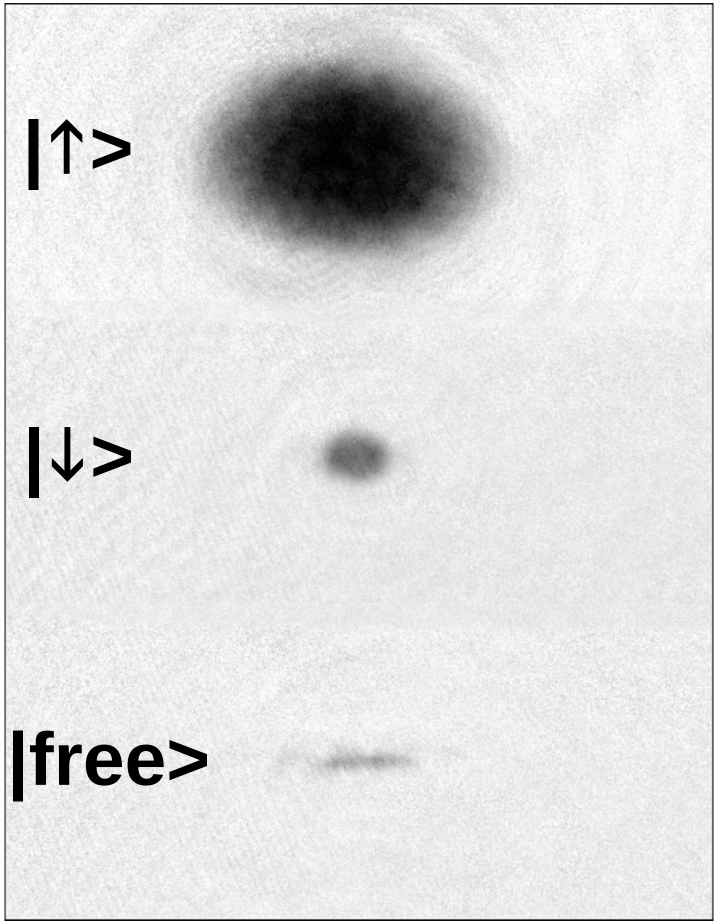
Experimental Realization

^{6}Li - Atom: 6 hyperfine states



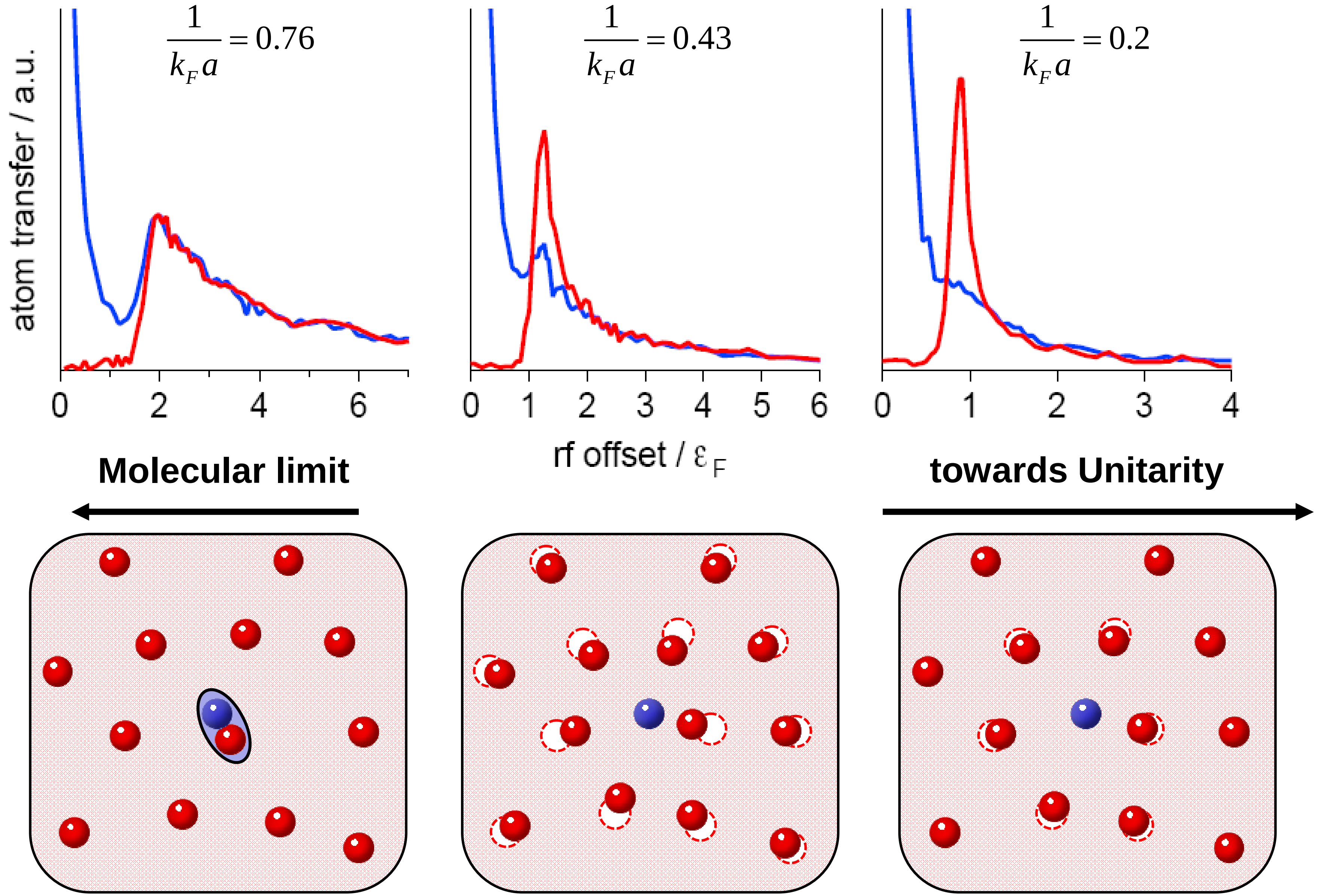
Feshbach Resonance at 690G

RF spectroscopy



- Spatially resolved
- 3D reconstructed

Emergence of the Fermi Polaron

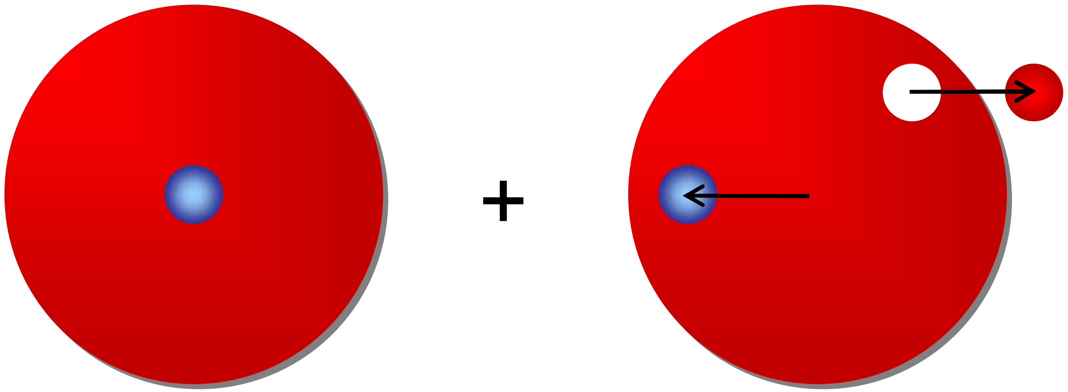


A. Schirotzek, C. Wu, A. Sommer, MWZ, PRL, to be published, arXiv/0902.3021

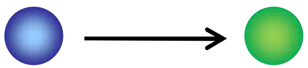
RF Spectroscopy on Polarons

Polaron = $\sqrt{Z}$ Free particle + $\sqrt{1-Z}$ scattered states

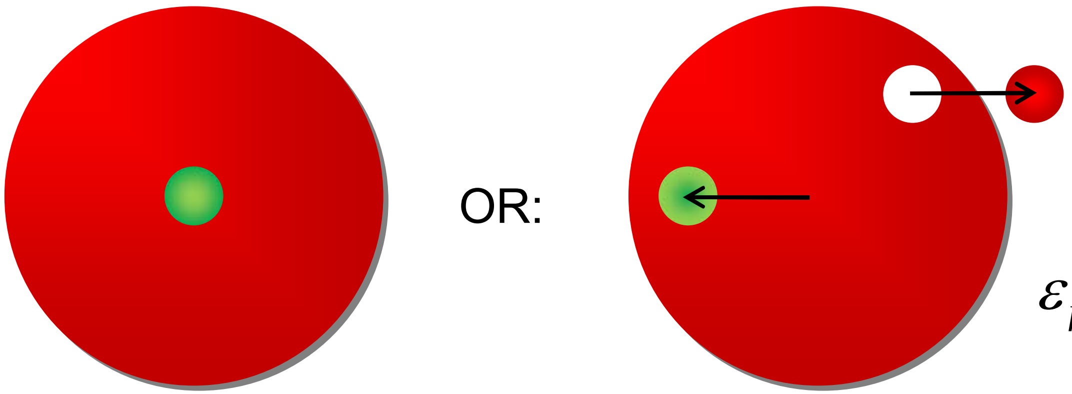
Energy $E_{\downarrow}$



Final states after RF Pulse:



Energy 0



OR:

Energy $\varepsilon_{\vec{k}} - \varepsilon_{\vec{q}} + \varepsilon_{\vec{q}-\vec{k}}$

RF Spectrum from Fermi's Golden Rule:

$$I(\omega) \propto Z\ \delta(\hbar\omega + E_{\downarrow}) + \sum_{\vec{q},\vec{k}} \left|\phi_{\vec{q}\vec{k}}\right|^2 \delta\left(\hbar\omega + E_{\downarrow} - \varepsilon_{\vec{k}} + \varepsilon_{\vec{q}} - \varepsilon_{\vec{q}-\vec{k}}\right)$$

i.e.: $$I(\omega) \propto Z\ \delta(\hbar\omega - E_{\downarrow}) + \Gamma_{incoherent}(\omega)$$

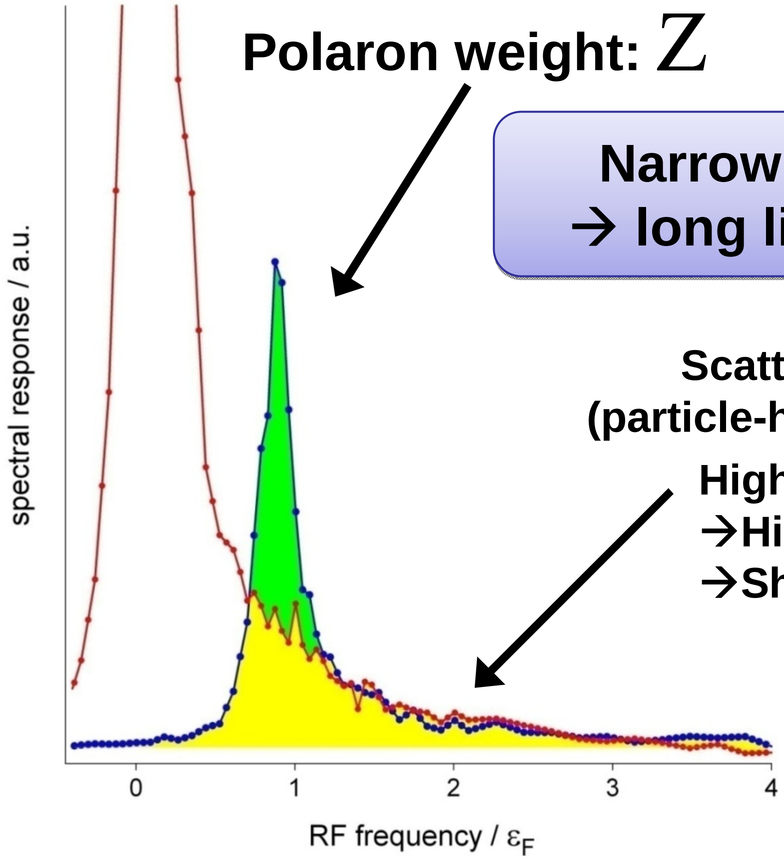
RF Spectroscopy on Polarons

Polaron = $\sqrt{Z}$ Free particle + $\sqrt{1-Z}$ scattered states

RF Spectrum: $I(\omega) \propto Z\ \delta(\hbar\omega - E_{\downarrow})\ +\ \Gamma_{incoherent}(\omega)$

Polaron weight: Z

Narrow peak
→ long lifetime



Scattered states
(particle-hole excitations)

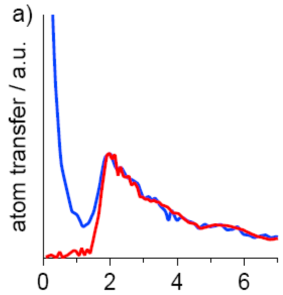
High energy
→High momentum
→Short range physics

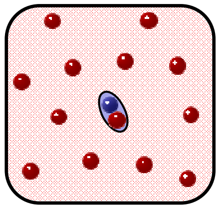
Spectrum @ 690 G

Quasiparticle residue vs interaction strength

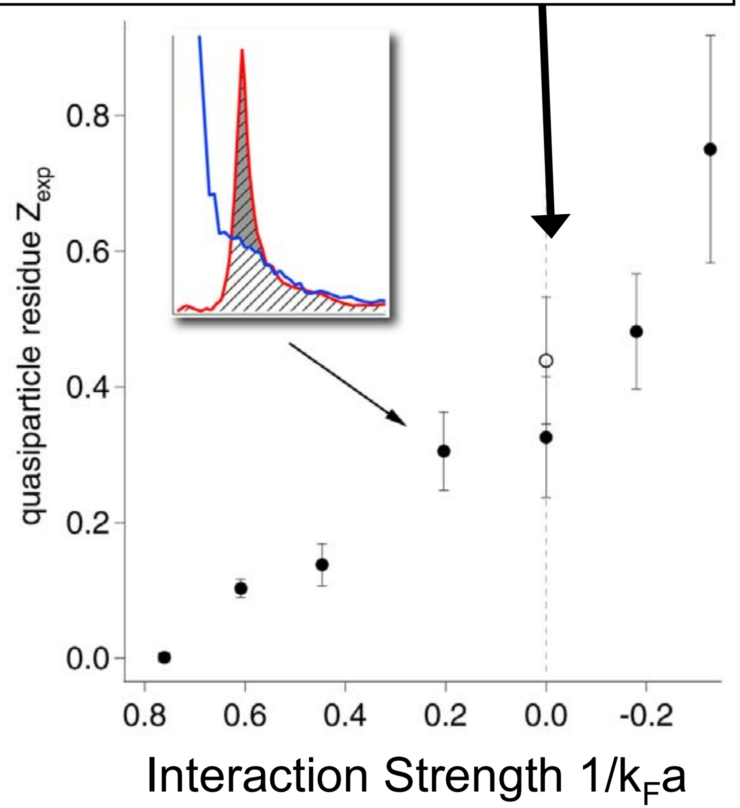
Polaron weight 40% on resonance

S. Pilati, S. Giorgini, PRL 100, 030401

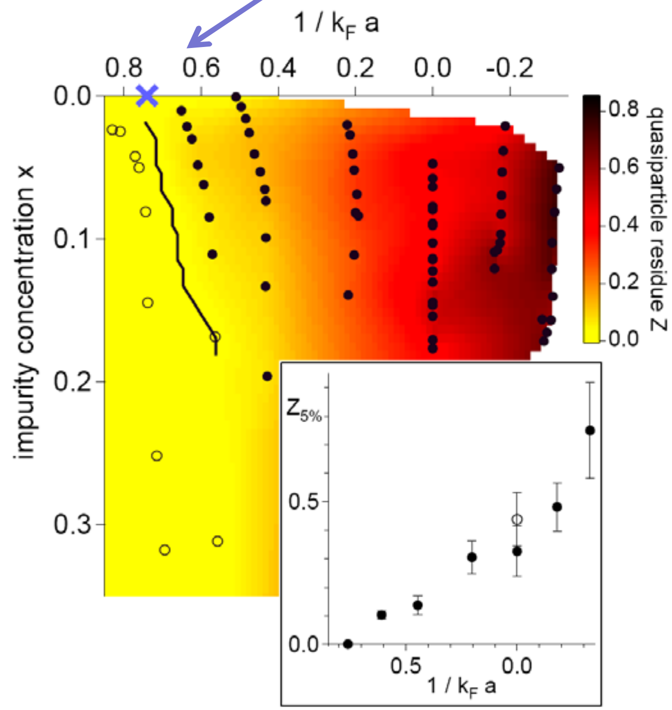


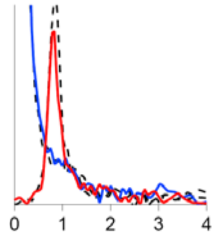


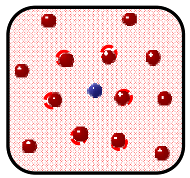
Molecular limit



- ● |1> majority
- ○ |3> majority



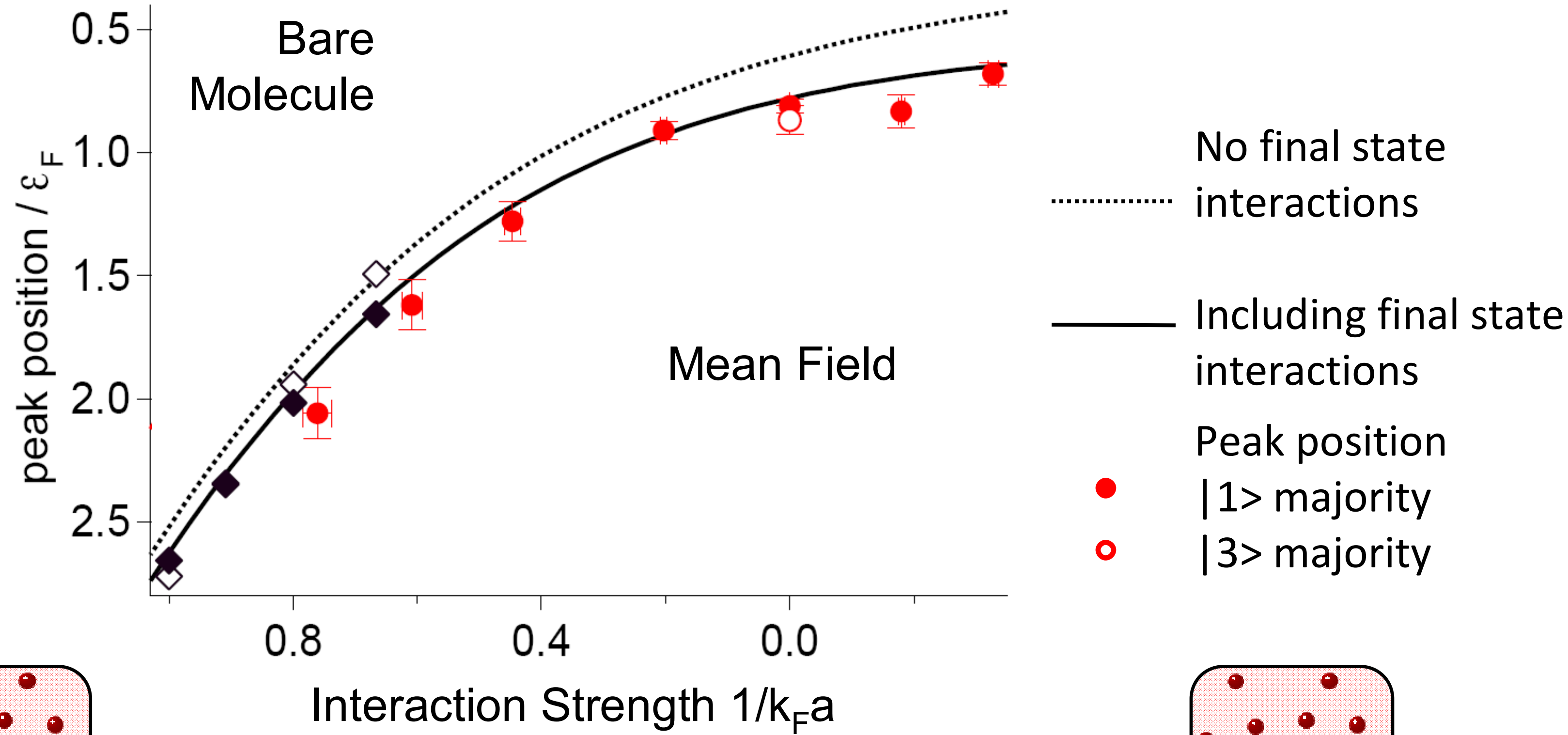


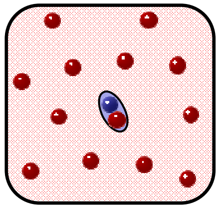


Mean Field limit

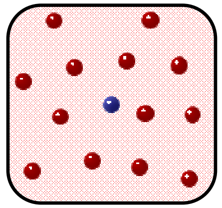
- **Polarons transition to molecules for a critical interaction strength: 0.76**
- **Transition between Spin ½-Polarons and Spin 0-Polarons**
- **Breakdown of a Fermi liquid**
- **Coincides with critical strength for always having a BEC**

Polaron Energy vs Interaction Strength





Molecular limit

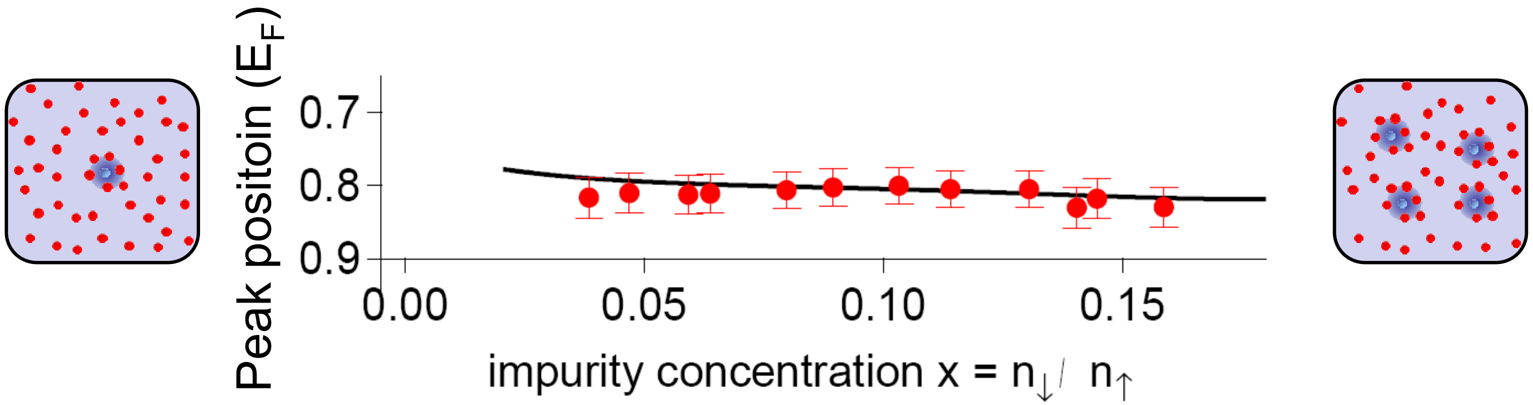


Mean Field limit

Diagrammatic Monte-Carlo: N. Prokof'ev and B.V. Svistunov, PRL 99, 250201 (2007)
N. V. Prokof'ev and B. V. Svistunov, PRB 77, 125101 (2008)
Variational approach/T-Matrix: F. Chevy PRA **74**, 063628 (2006), R. Combescot et al., PRL 98, 180402 (2007), R. Combescot and S. Giraud, PRL 101, 050404 (2008)

Building a Fermi liquid from the bottom up

- Polarons are **weakly interacting** despite resonant interactions:



- → Represent the quasi-particles in *Landau's Fermi liquid* description

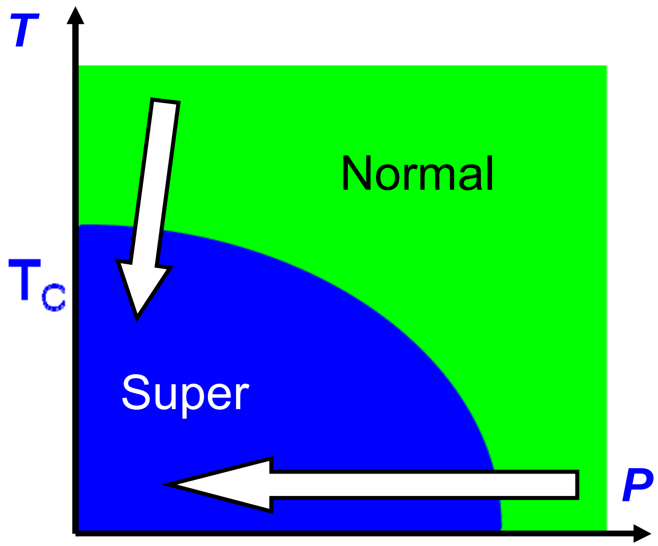
Build a Fermi liquid from the bottom up by adding polarons

To 1st order, it is a non-interacting Fermi gas of polarons, with renormalized mass.

$m^* \sim 1.2\, m$ on resonance

- Raises question on the nature of the gas above T_C
- What condenses really at T_C?

Condensation of polaron pairs

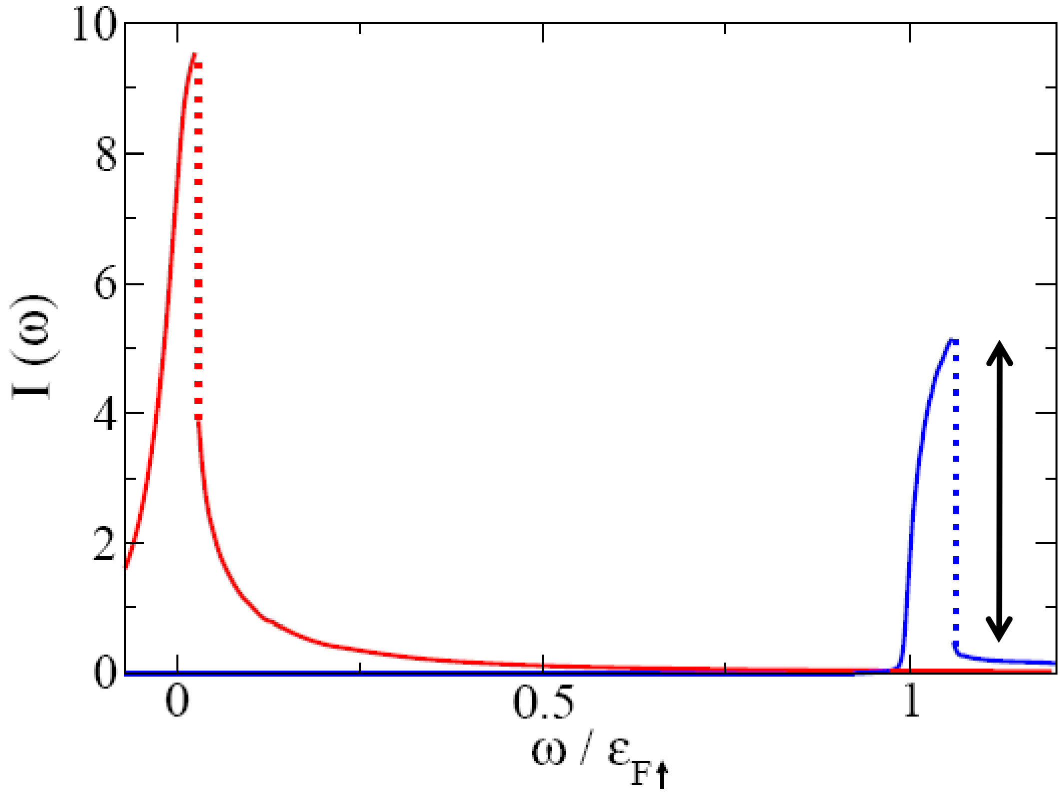


Ideal Spectra for this Fermi Liquid

Initial state: Fermi sea of polarons with effective mass m^*

Final state: Free Fermi gas with bare mass m

$$\varepsilon^*_{\vec{k}} = \frac{\hbar^2 k^2}{2m^*} \rightarrow \varepsilon_{\vec{k}} = \frac{\hbar^2 k^2}{2m} > \varepsilon^*_{\vec{k}} \qquad \lambda = 1 - \frac{m}{m^*_\downarrow}$$



Shape of the spectrum:

$$I_\downarrow(\omega) \propto \frac{Z_\downarrow}{\lambda^{3/2}} \rho\left(\omega + \left|E_\downarrow\right|\right)$$

Jump of the spectrum at

$$\hbar\omega = \left|E_\downarrow\right| + \varepsilon_{k_F} - \frac{m}{m^*_\downarrow} \varepsilon_{k_F}$$

Size of the jump:

$$\frac{Z_\downarrow}{\lambda^{3/2}} \rho\left(\varepsilon_{F\downarrow}\right)$$

W. Schneider, V. B. Shenoy, M. Randeria, preprint cond-mat 0903:3006

also suppl. Info. in: A. Schirotzek, C. Wu, A. Sommer, MWZ, PRL, to be published, arXiv/0902.3021

Conclusion & Outlook

- **Observation of Fermi Polarons in a Fermi liquid with tunable interactions**
- **Benchmark test for many-body theories**

The hydrogen atom of diagrammatic Monte-Carlo calculations – B. Svistunov

- **Next: Measure *m**, collisional properties,** **Bruun et al., PRL 100, 240406 (2008)**

Outlines a new strategy to study strongly interacting systems:

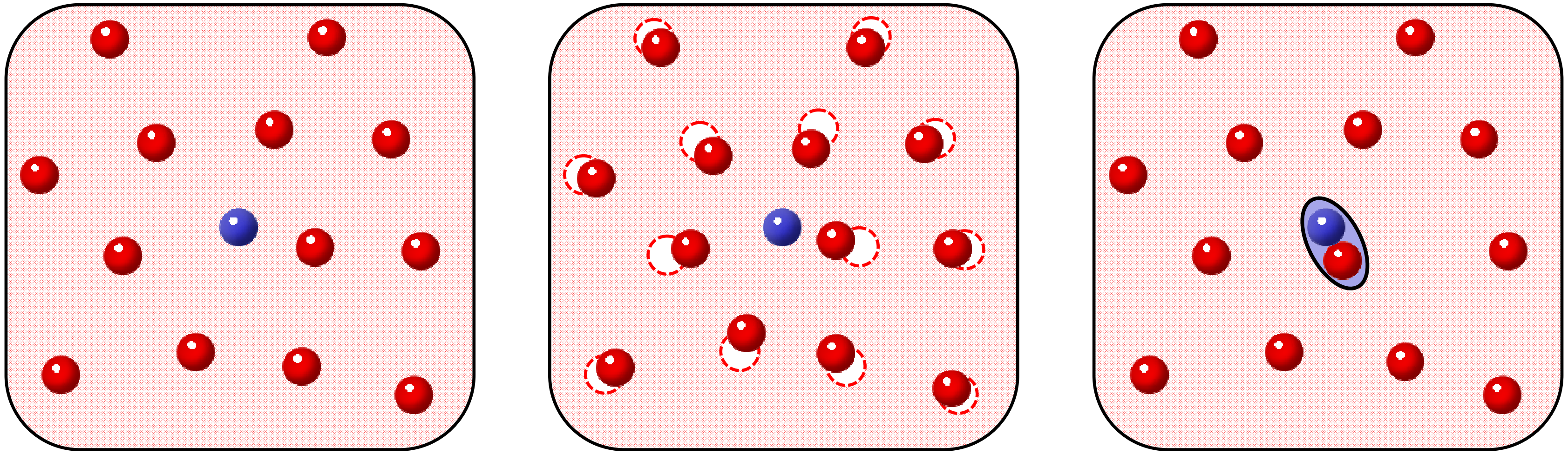
Explore the limit of few impurities

Wavefunction, effective parameters, renormalized interactions

→First understand the N+1 limit before addressing N+M-body physics

→Related problems: impurity with mass $M \gg m$ (^{40}K in ^{6}Li + optical lattice)

immobile impurity: Anderson's orthogonality catastrophe



The team

BEC 1:
Andre Schirotzek
Ariel Sommer

Fermi 1:
Cheng-Hsun Wu
Ibon Santiago
Dr. Peyman Ahmadi

Undergraduates:
Sara Campbell
Caroline Figgatt
Jacob Sharpe
Kevin Fischer