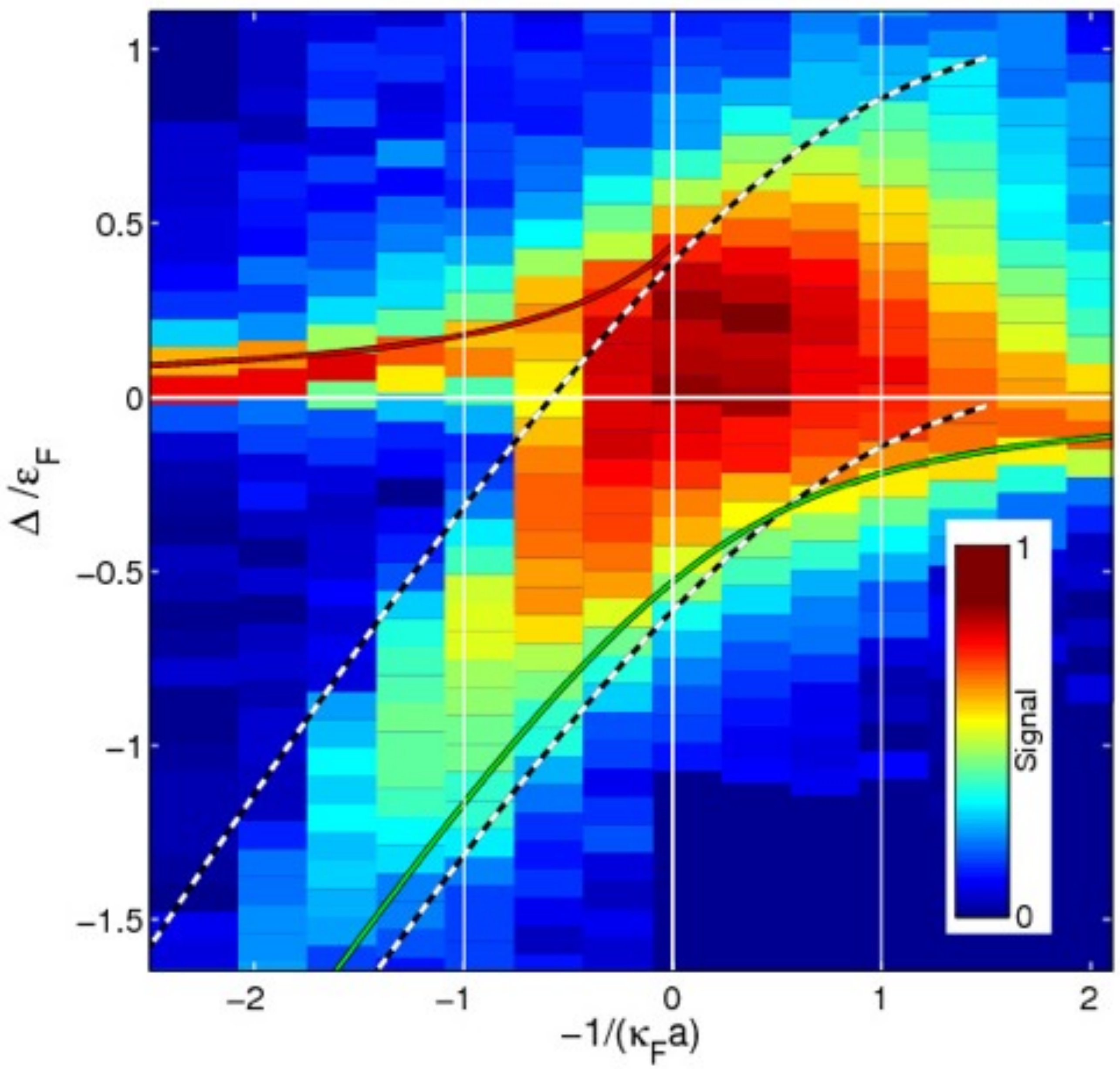
Metastability and Coherence of Polarons in a Strongly Interacting Fermi Mixture

Pietro Massignan



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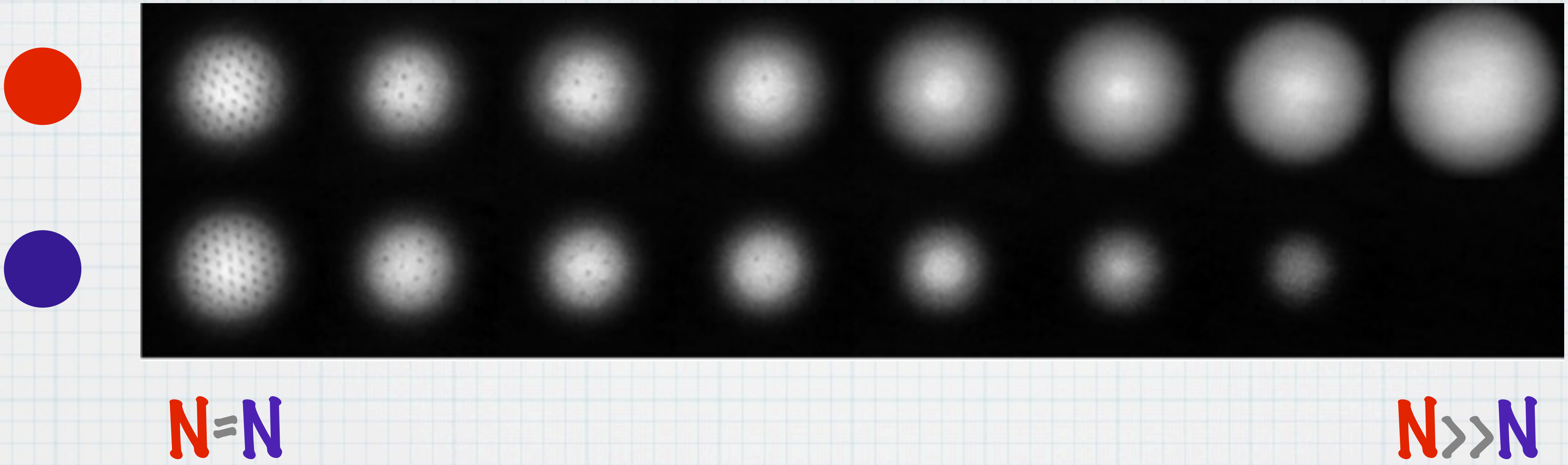
Fermi Mixtures

N=N with attractive interactions:
BEC-BCS crossover

Imbalanced Fermi mixtures

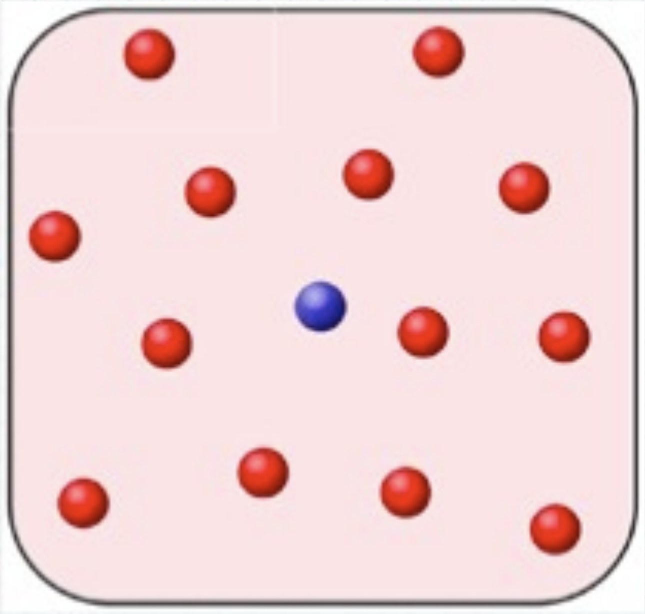


SF-normal transition

Zwierlein et al., Nature 2005

Very imbalanced Fermi mixtures

N>>1



normal Fermi liquid

Schirotzek et al., PRL 2009

Many-body systems

(from Richard Mattuck's book)

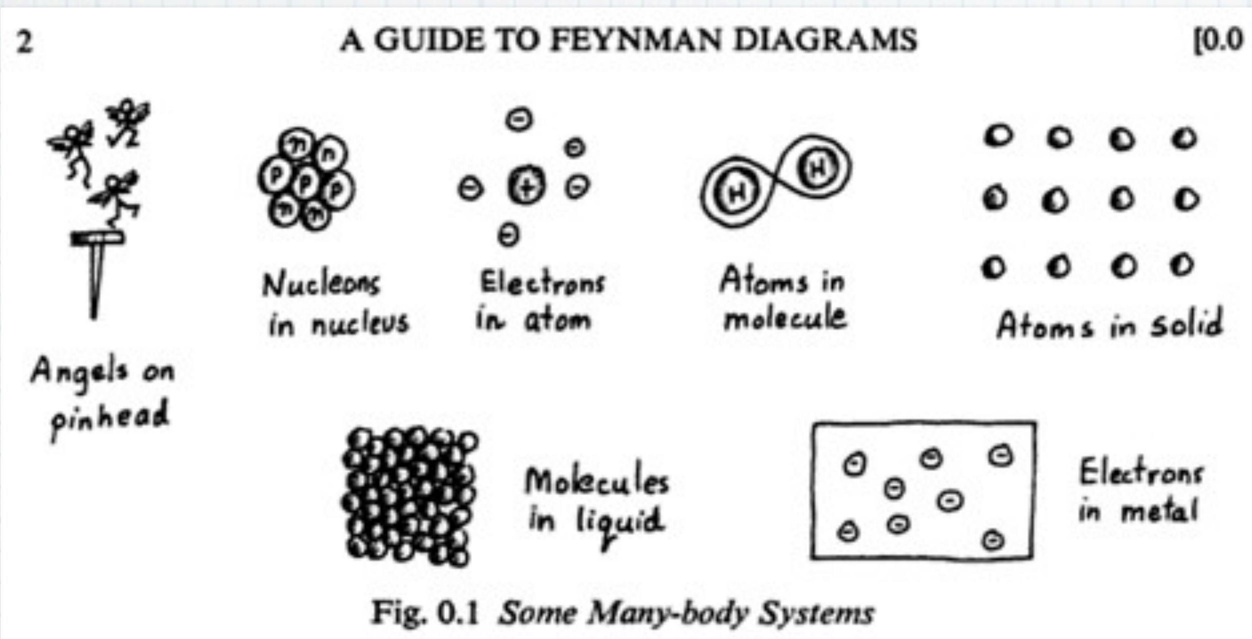
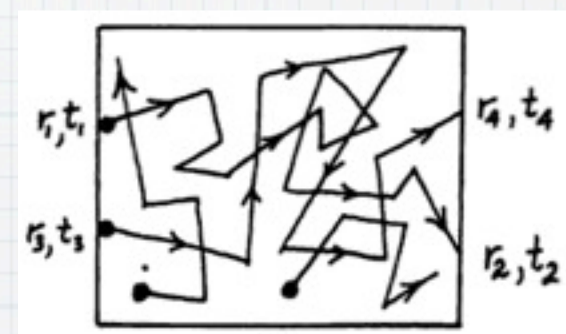
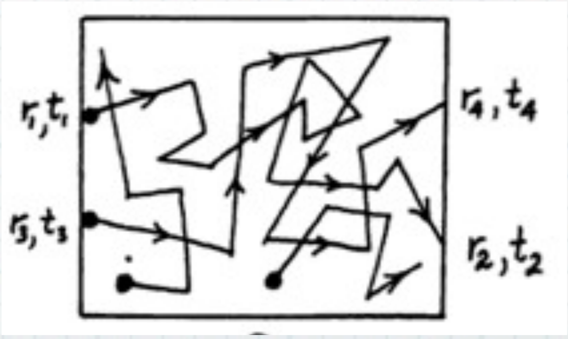


Fig. 0.1 *Some Many-body Systems*

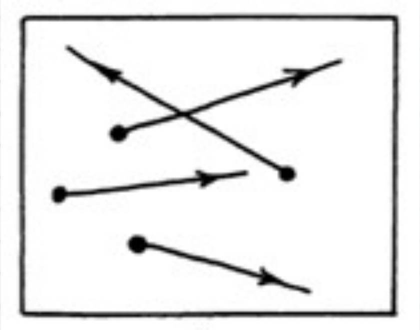


Quasi-Particles

Landau's idea:
who cares about real particles?



Of importance are the excitations,
which behave
as quasi-particles!



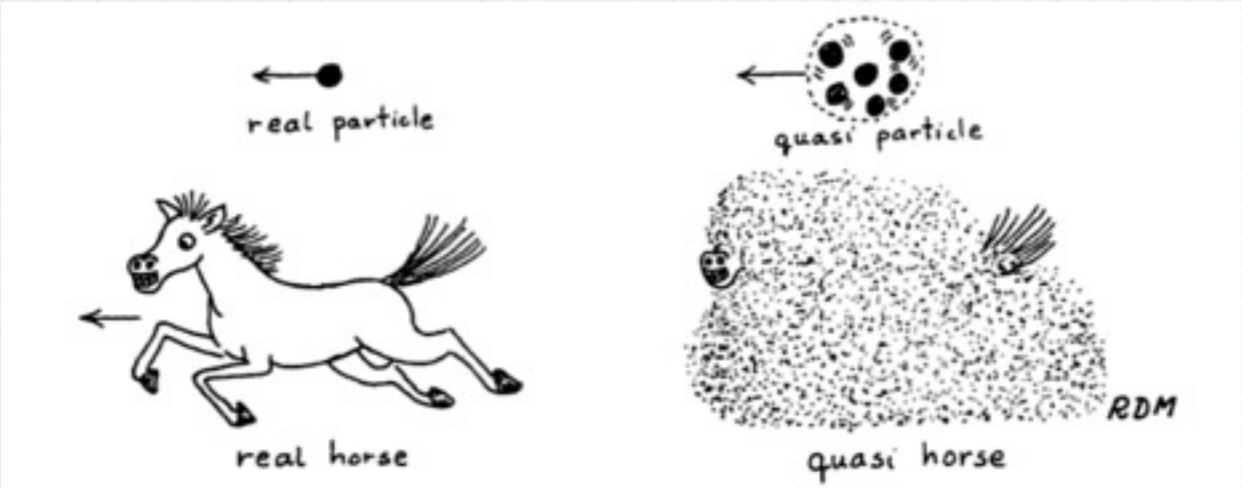


Fig. 0.4 *Quasi Particle Concept*

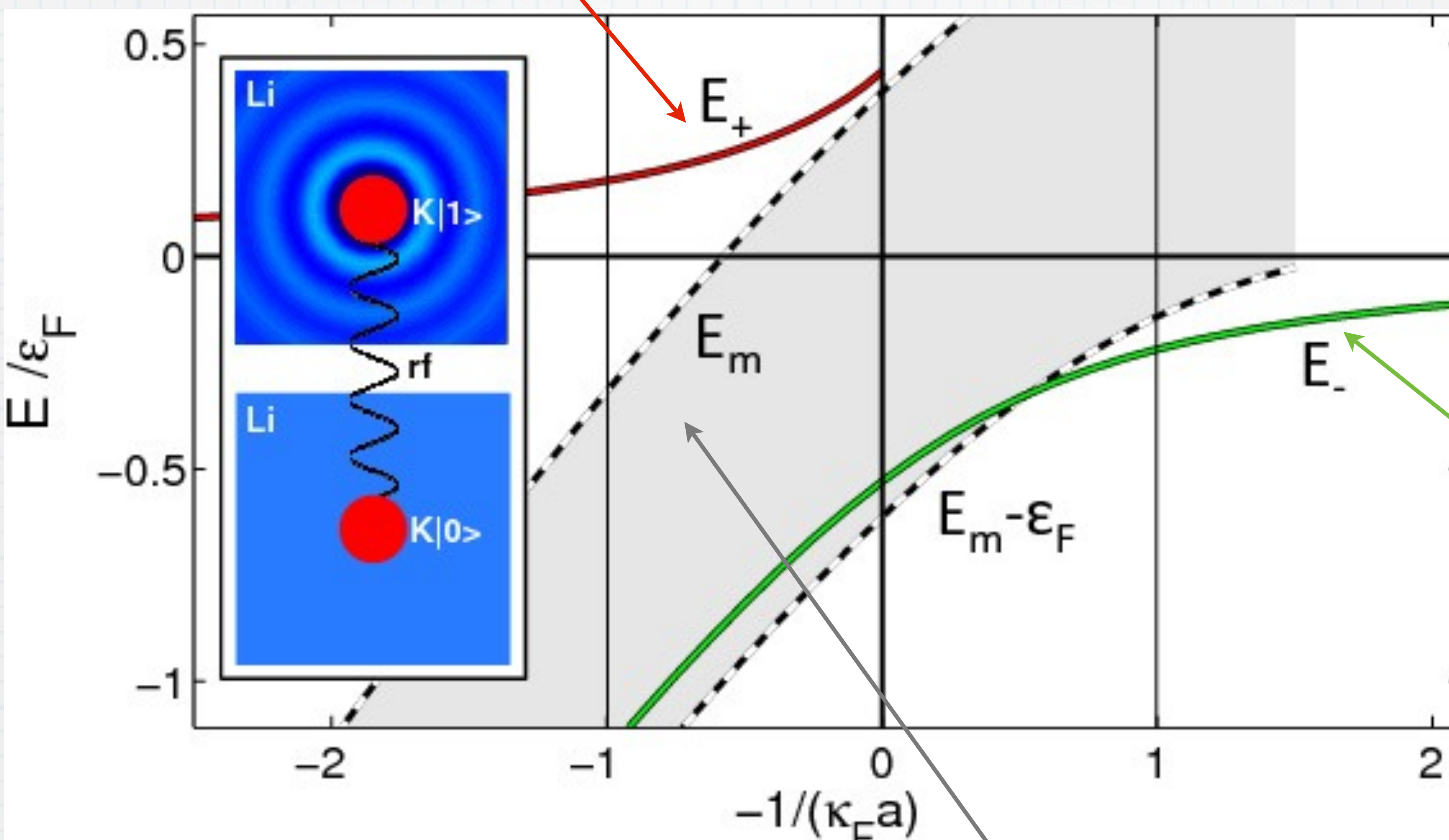
a QP is a "free particle" with:
@ renormalized mass
@ chemical potential
@ shielded interactions
@ q. numbers (charge, spin, ...)
@ lifetime

The polaron problem

new quantum toy!
a gas with strong repulsive interactions

(intrinsically metastable, due to the existence of weakly-bound lower-lying states)

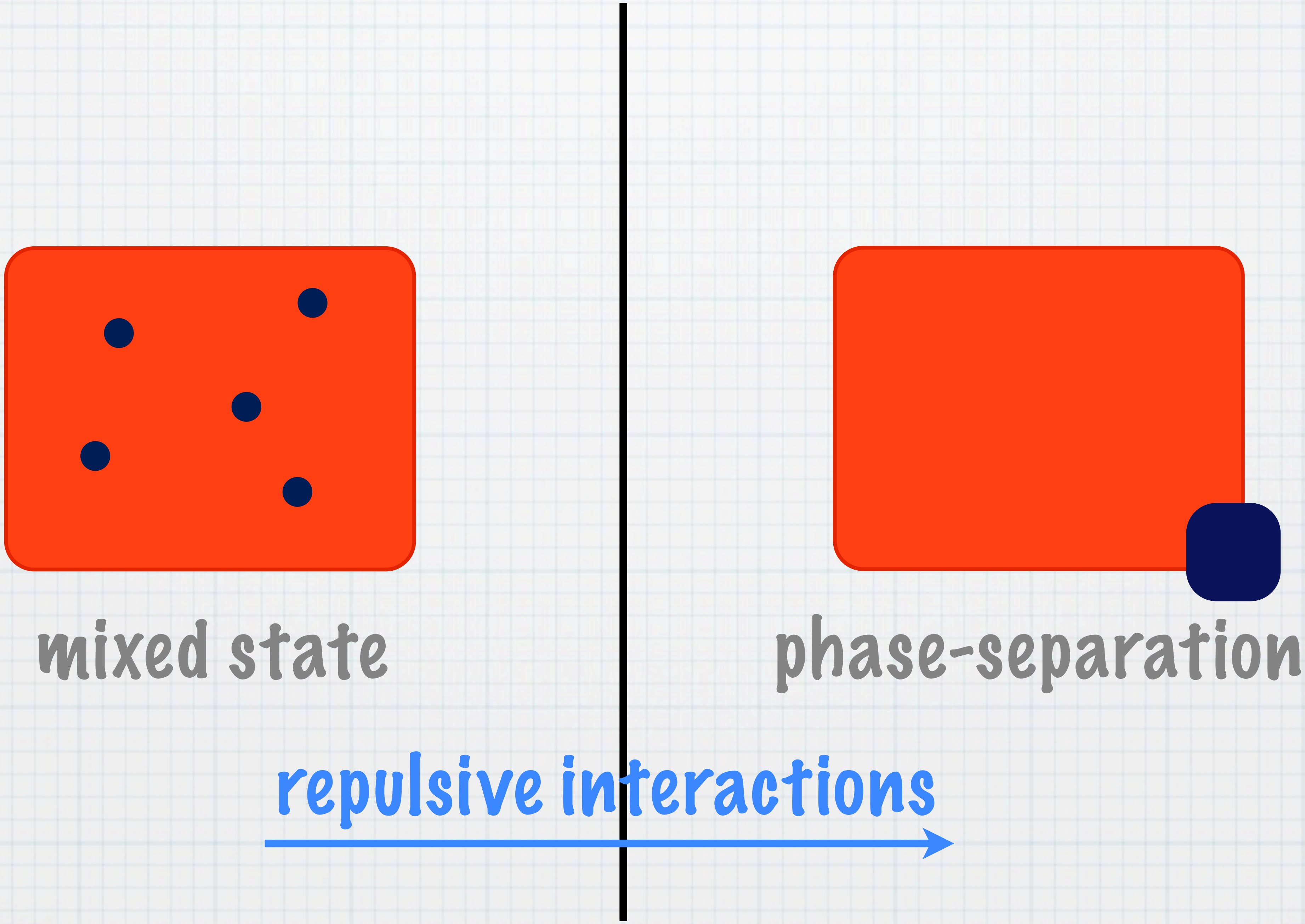
repulsive polaron



attractive polaron

molecule-hole continuum

Itinerant FerroMagnetism



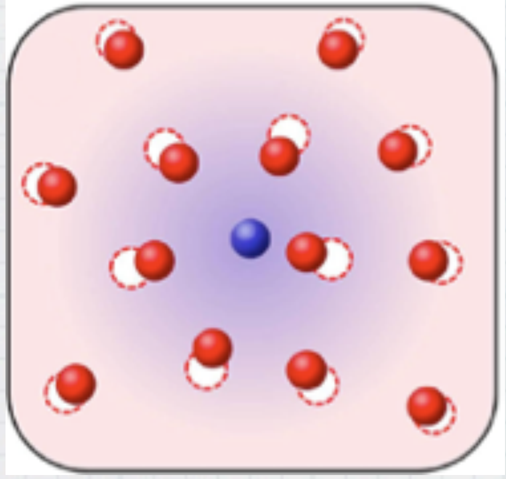
Polaron: variational Ansatz

the ↓ impurity

$$|\psi_{\mathbf{p}}\rangle = \phi_0 c^\dagger_{\mathbf{p}\downarrow} |FS_N\rangle + \sum_{q<k_F}^{k>k_F} \phi_{\mathbf{qk}} c^\dagger_{\mathbf{p+q-k}\downarrow} c^\dagger_{\mathbf{k}\uparrow} c_{\mathbf{q}\uparrow} |FS_N\rangle$$

non-interacting ↑ Fermi sea

Particle-Hole dressing



Very good agreement with QMC results for $\mu_\downarrow$ and m*

This variational Ansatz has a diagrammatic equivalent:
the forward scattering, or ladder, approximation.

universal attractive case considered by:
Chevy, Combescot, Recati, Lobo, ...

Perform analytic continuation to complex energies
to look at the repulsive polaron

repulsive case considered by:
Zhai, Pilati&Giorgini, PM & Bruun

Dressed Molecules

$$H = \sum_{\mathbf{p}} \left[\xi_{\mathbf{p},\uparrow} u^\dagger_{\mathbf{p}} u_{\mathbf{p}} + \xi_{\mathbf{p},\downarrow} d^\dagger_{\mathbf{p}} d_{\mathbf{p}} + (\xi_{\mathbf{p},M} + \nu_0)\, b^\dagger_{\mathbf{p}} b_{\mathbf{p}}\right] + \frac{g_0}{V} \sum_{\mathbf{p},\mathbf{p}'} \left(b^\dagger_{\mathbf{p}} u_{\mathbf{p}'} d_{\mathbf{p}-\mathbf{p}'} + h.c.\right)$$

the ↑↓ molecule   the ↓ impurity

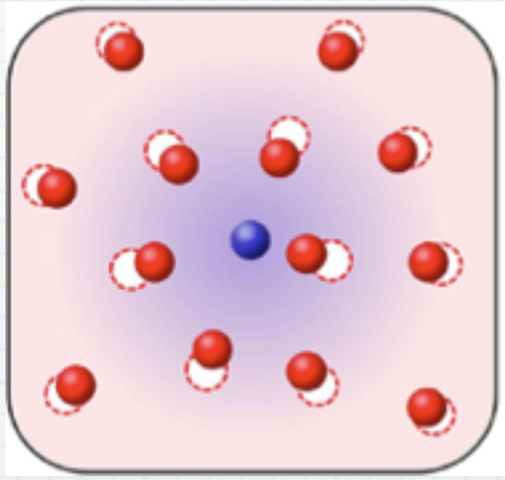
$$|\Phi_{\mathbf{p}=0}\rangle = \left(\beta^{(0)}_0 b^\dagger_0 + \sum_k \beta^{(1)}_{\mathbf{k}} d^\dagger_{-\mathbf{k}} u^\dagger_{\mathbf{k}} + \sum_{\mathbf{k},\mathbf{q}} \beta^{(2)}_{\mathbf{k},\mathbf{q}} b^\dagger_{\mathbf{q}-\mathbf{k}} u^\dagger_{\mathbf{k}} u_{\mathbf{q}} + \sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} \beta^{(3)}_{\mathbf{k},\mathbf{k}',\mathbf{q}} d^\dagger_{\mathbf{q}-\mathbf{k}-\mathbf{k}'} u^\dagger_{\mathbf{k}'} u^\dagger_{\mathbf{k}} u_{\mathbf{q}}\right) |FS_{N-1}\rangle.$$

Particle-Hole dressing

non-interacting ↑ Fermi sea

universal case considered by:
Punk&Dumitrescu&Zwerger, Mora&Chevy, Combescot&Giraud&Leyronas (2009)
Mathy,&Parish&Huse (2010)

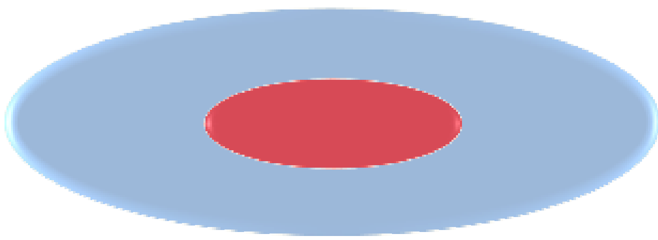
Theorists like it easy

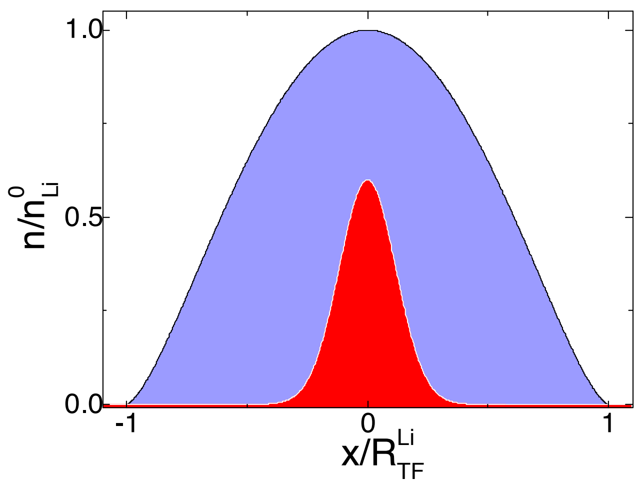


but what's "under the hood"?

Experimental conditions & Interaction control

Starting point: small sample of ^{40}K atoms + degenerate ^{6}Li Fermi gas in thermal equilibrium & weakly interacting (a_{bg}~65 a_0), trapped in an optical potential





Exp. parameters	
$\vec{\nu}_{Li}$ (Hz)	(690,690,85)
$\vec{\nu}_{K}$ (Hz)	(425,425,52)
T(nK)	290
N_{Li}	3.5 x 10^5
N_K	2 x 10^4
T/T_F^{Li}	0.14
T/T_F^{K}	0.6

Relevant energy & length scales: averaging Li local Fermi energy over K distribution	
ε_F^{Li}	h X 37 (2) kHz
κ_F^{Li}	(2850 a0)$^{-1}$

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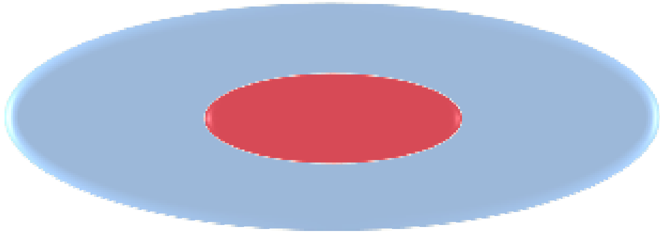

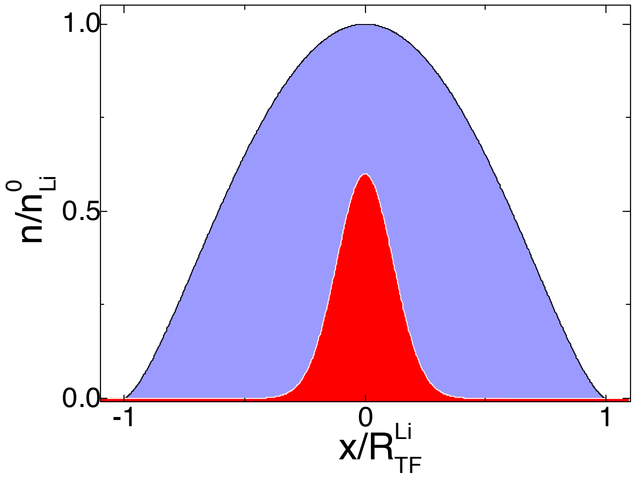

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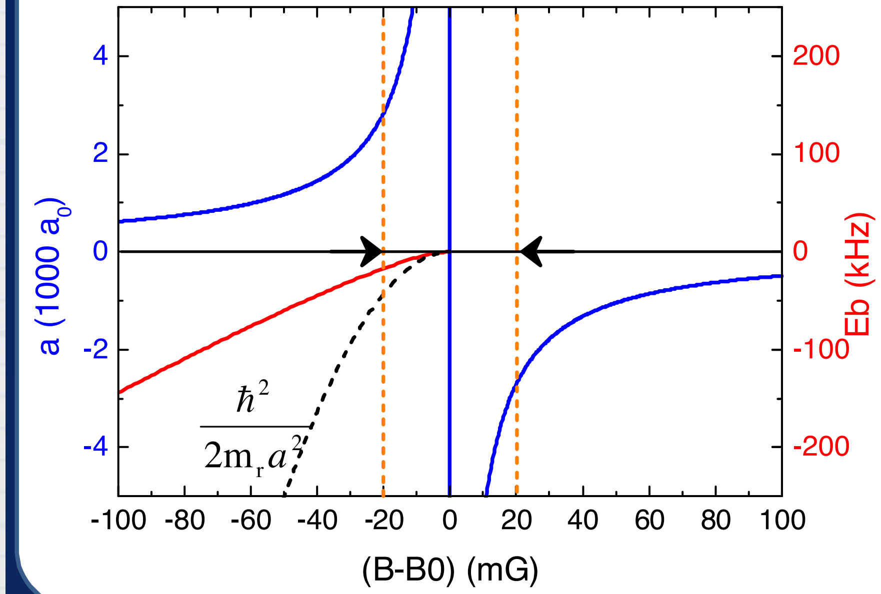
Interspecies interaction controlled via a magnetic Feshbach resonance occurring between ^{6}Li lowest spin state and ^{40}K third-to-lowest spin state



a_{bg}	63.0 a_0
Δ	0.880 G
B_0	154.719(2) G
R*	2710 a_0

Narrow & decaying feature!
Challenging both for theo. & exp.

$$R^* = \frac{\hbar^2}{2\,m_r\,a_{bg}\,\Delta\,\delta\mu} \approx 1/\kappa_F^{Li}$$

- Effects from CC contributions important
- 2 mG stability available for fine tuning of interaction

Narrow Feshbach Resonances

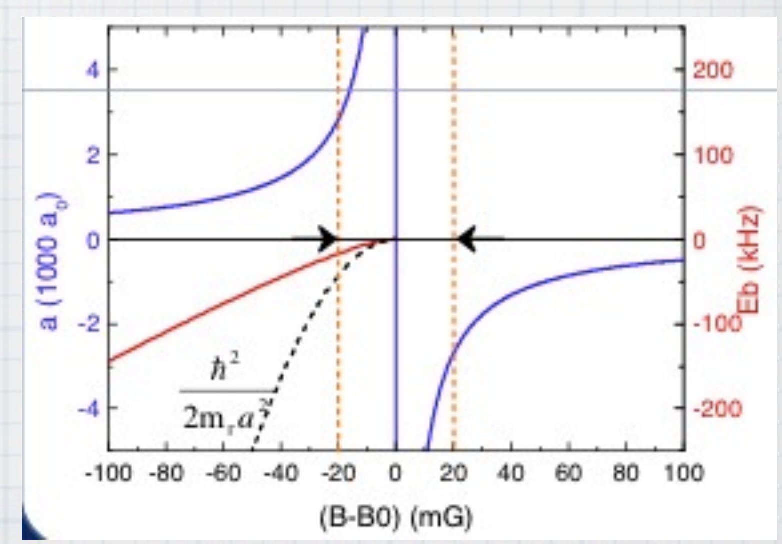
Scattering amplitude: $f = -\left[a^{-1} + ik + R^* k^2 + \dots\right]^{-1}$

Molecule energy: $E_M = -\frac{\hbar^2}{2m_r(a_*)^2}$ with $a^* = \frac{2R^*}{\sqrt{1+4R^*/a}-1}$

$a \gg R^* : \quad a^* \sim a$

$a \ll R^* : \quad a^* \sim \sqrt{aR^*}$

a FR is broad if $R^* \ll R_{VdW}$ or $k_F R^* \ll 1$

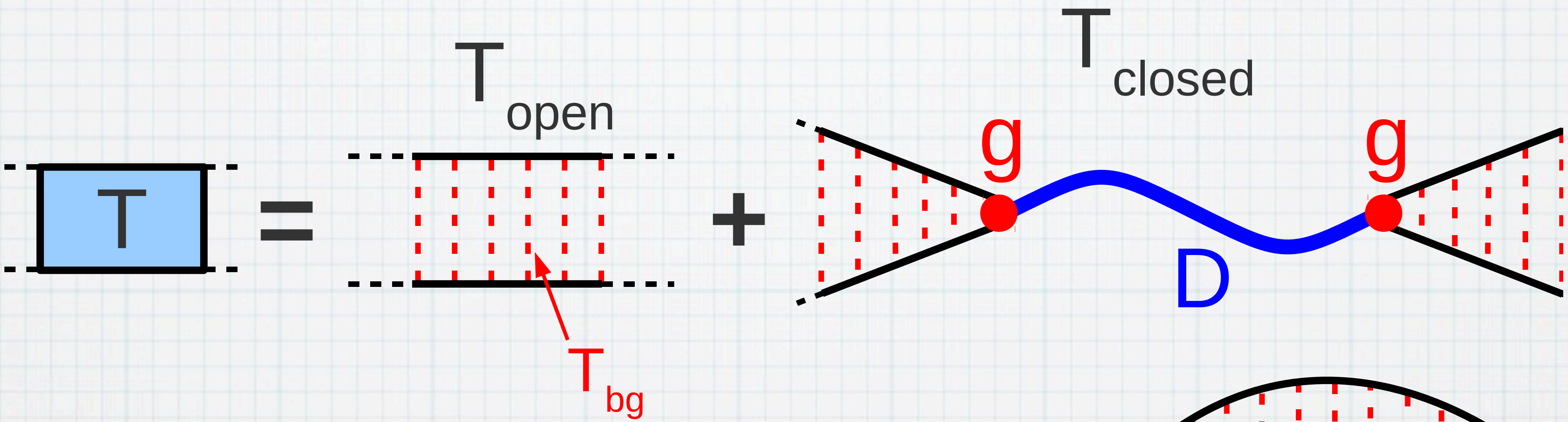


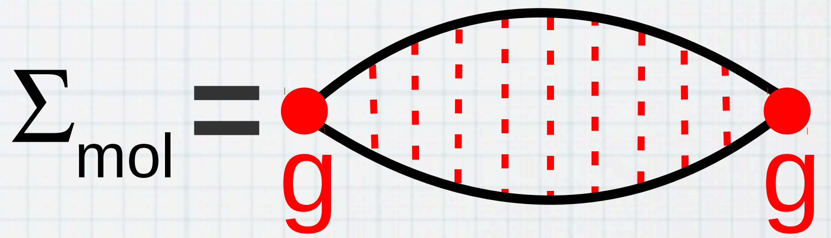
Most heteronuclear FR are narrow.

Many-body description of narrow FR

Bruun, Jackson & Kolomeitsev, PRA 2005
PM & Stoof, PRA 2008
PM, arXiv:1112.1029

$T = T_{open} + T_{closed}$





$$T = -\frac{2\pi\hbar^2}{m_r} f \quad \text{with} \quad f = -\left\{\left[a_{\rm bg}\left(1 - \frac{\Delta B}{B - B_0 - E_{\rm CM}/\delta\mu}\right)\right]^{-1} - \frac{2\pi\hbar^2}{m_r}\Pi(\mathbf{p}, E_{\rm CM})\right\}^{-1}$$

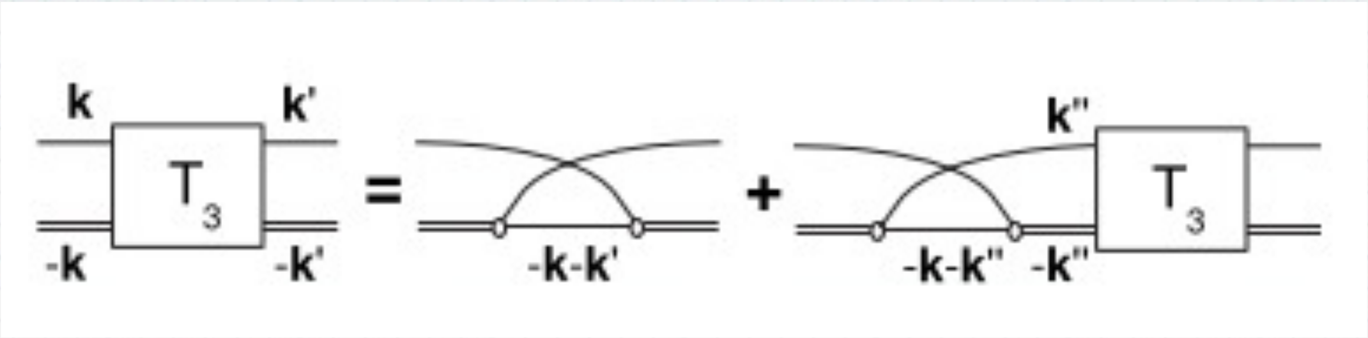
low energy expansion:

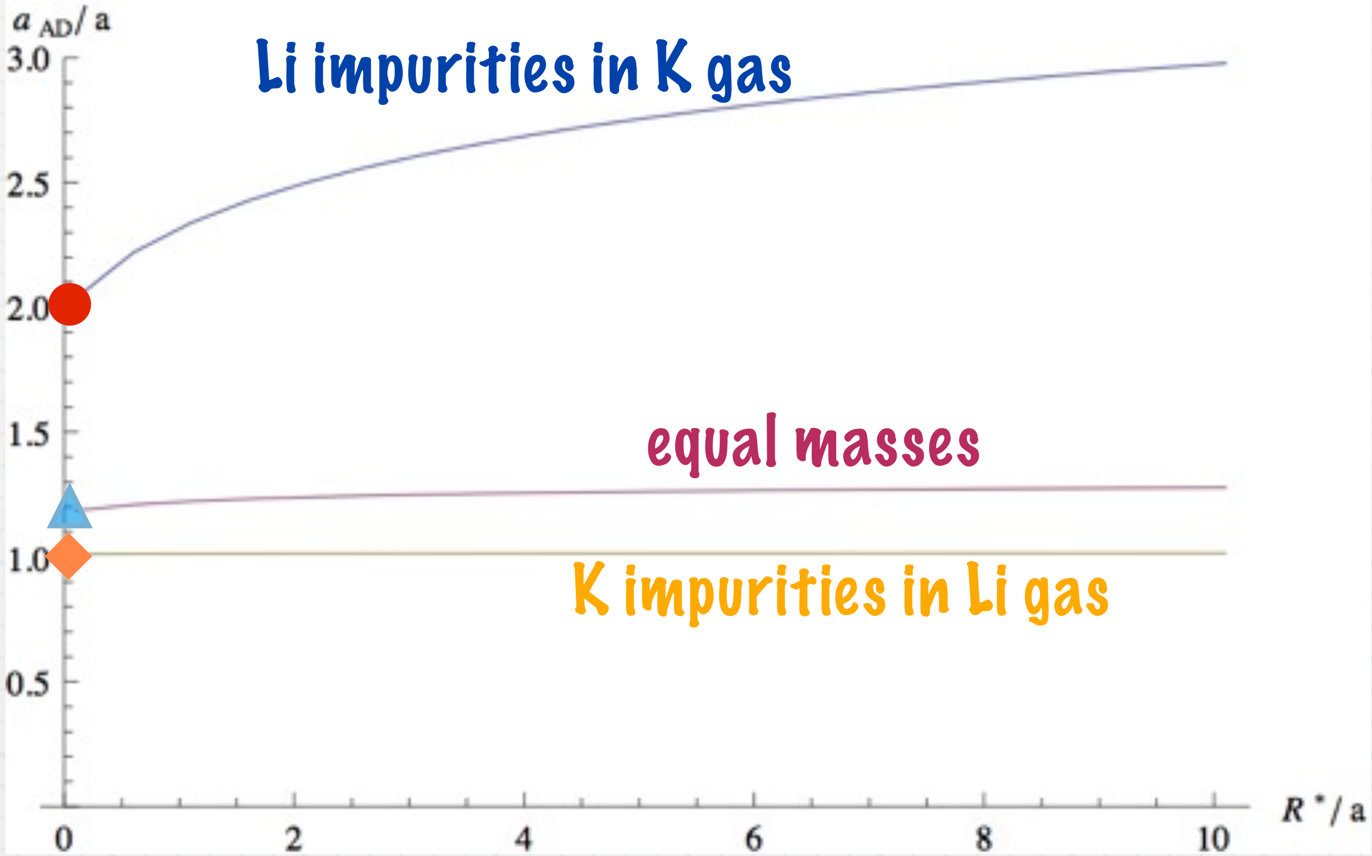
$$a^*(B) = a_{\rm bg}\left(1 - \frac{\Delta B}{B - B_0}\right)$$

$$R^*(B) = \frac{\hbar^2 \Delta B}{2 m_r a_{\rm bg}(B - B_0 - \Delta B)^2 \delta\mu}$$

$$f_{\rm vac} = -\left[a^{-1} + ik + R^* k^2 + \ldots\right]^{-1}$$

WarmUp: Atom-Dimer scattering





Range of FR

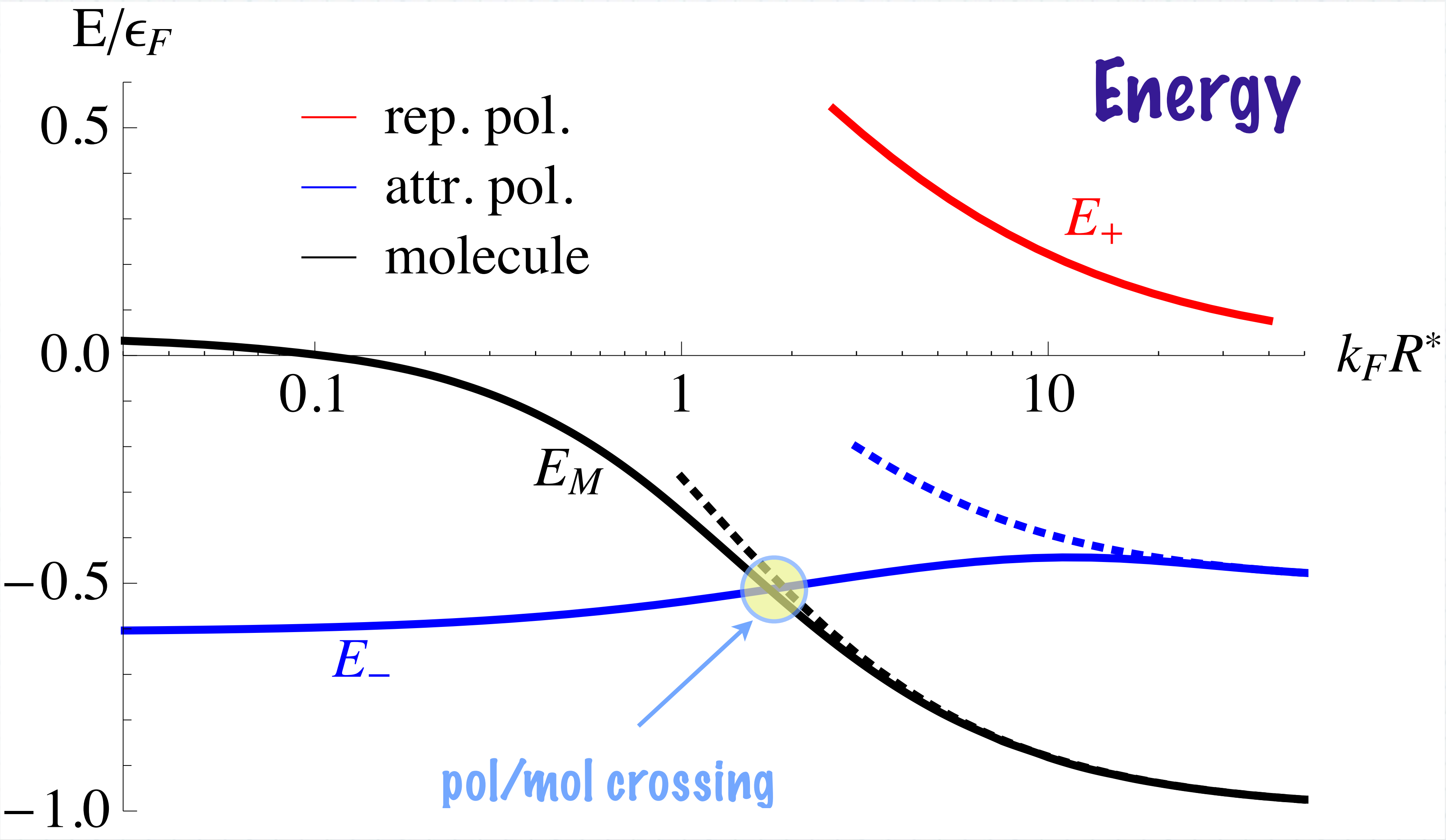
agrees with real-space calculation (Petrov, PRA 2003; Petrov&Levinsen, arXiv: 1101.5979)

"Narrow" pols & mols

PM, arXiv:1112.1029

$(k_F a)^{-1}=0$ [at resonance]

equal masses



repulsive pol.

attractive pol.

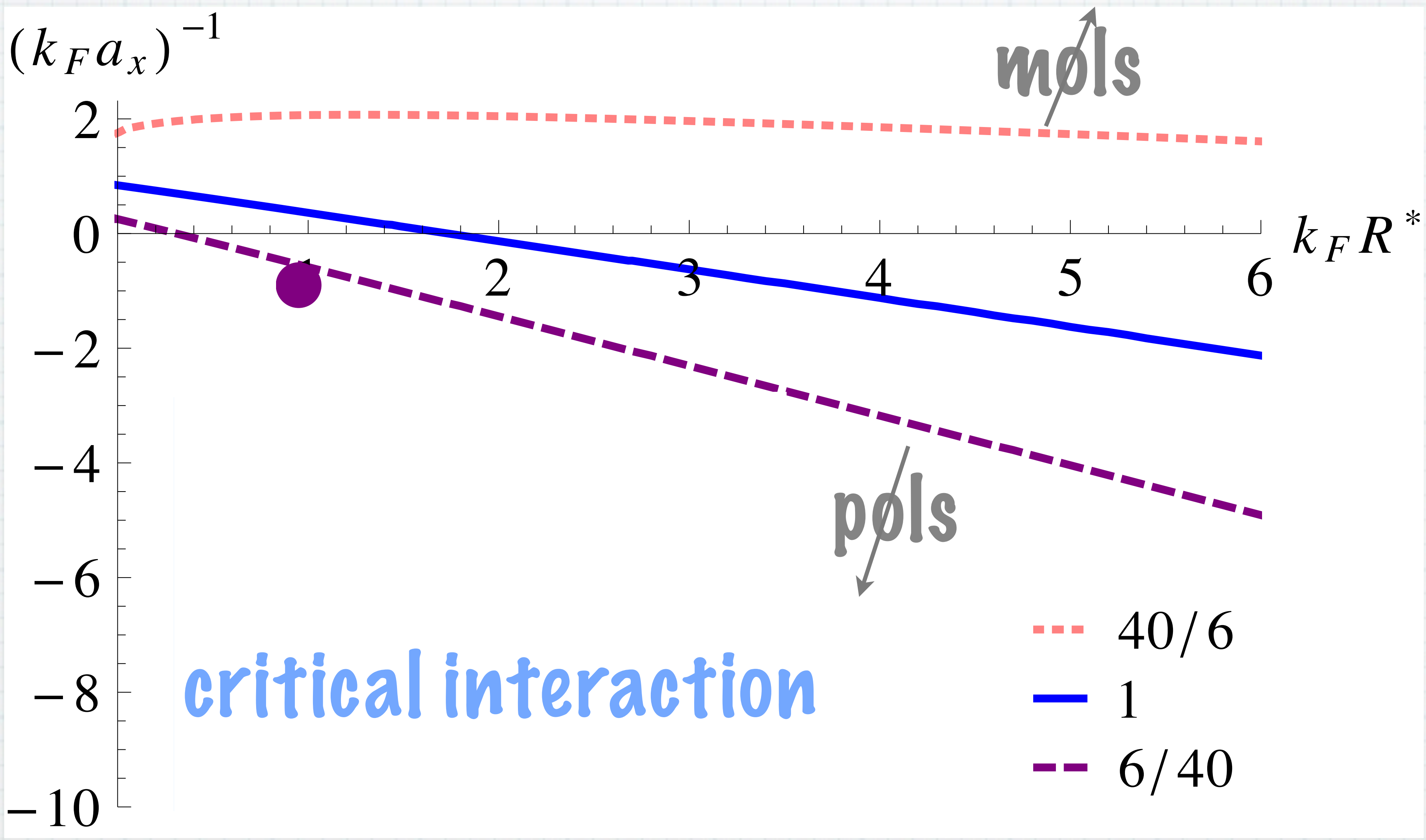
molecule

analytic result in the narrow limit:

$$E_{\rm M}^{\rm Th} = -\epsilon_F \left[1 - \frac{m_\uparrow}{m_r}\frac{2-\pi(k_F a)^{-1}}{2+\pi k_F R^*}\right].$$

Pol/Mol crossing at a narrow FR

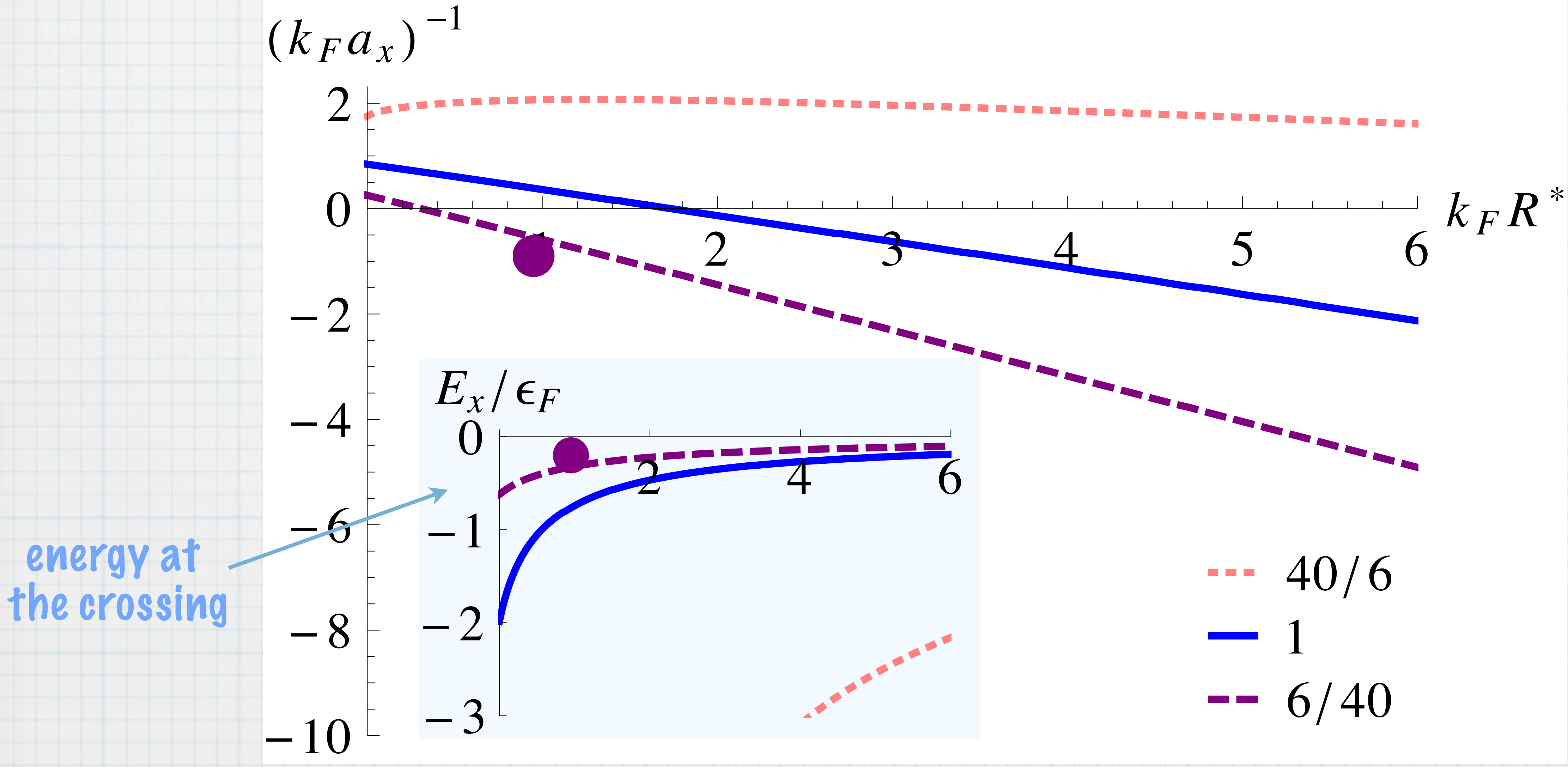
PM, arXiv:1112.1029



for impurity/gas mass ratios: 6/40, 1, 40/6

Pol/Mol crossing at a narrow FR

PM, arXiv:1112.1029

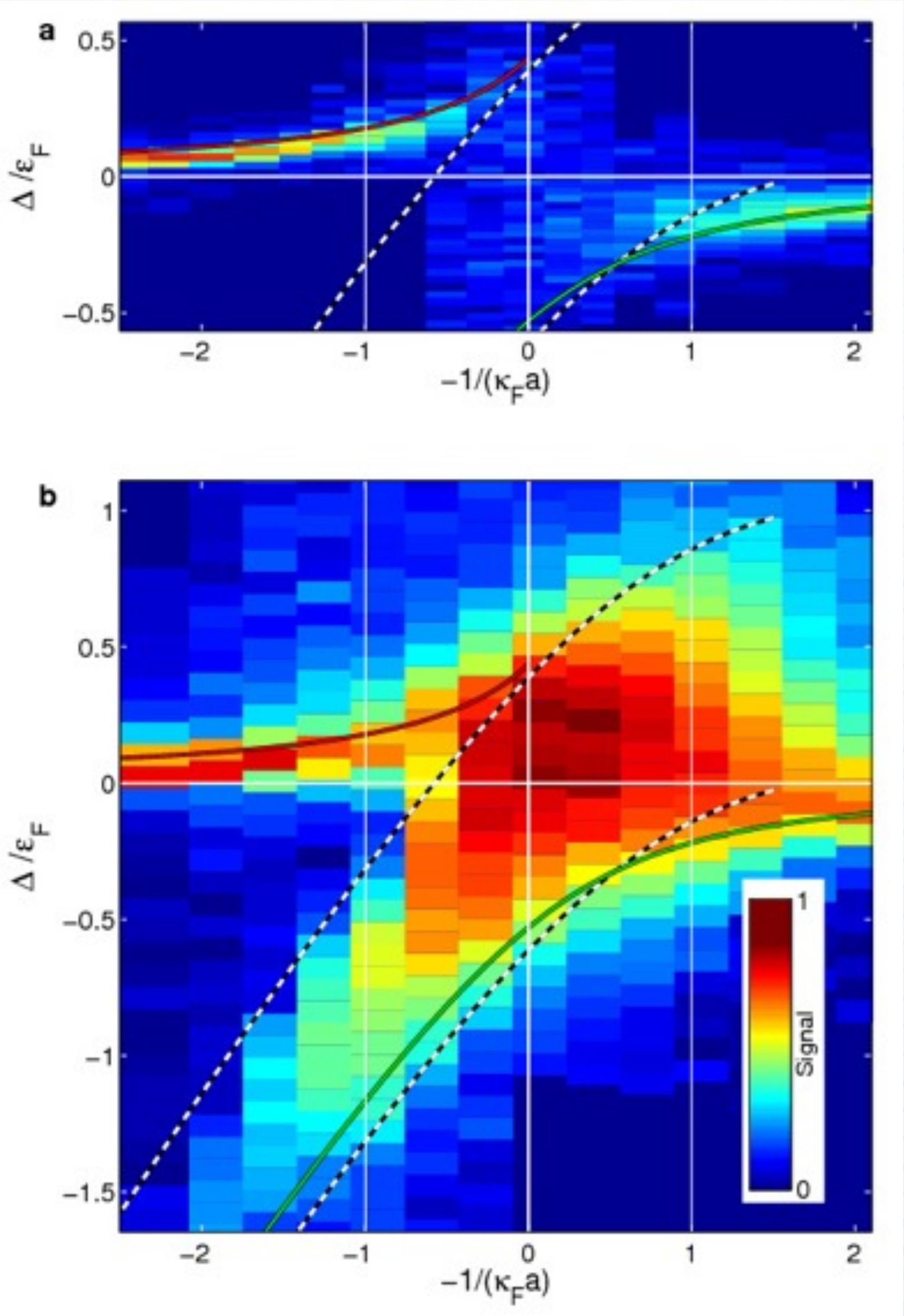


for impurity/gas mass ratios: 6/40, 1, 40/6

RF spectroscopy

repulsive polarons exist
as well-defined quasiparticles
even in the strongly-interacting regime

low power RF:



high power RF:

high power is needed to
couple to the MH continuum,
due to a small FC overlap

— repulsive pol.

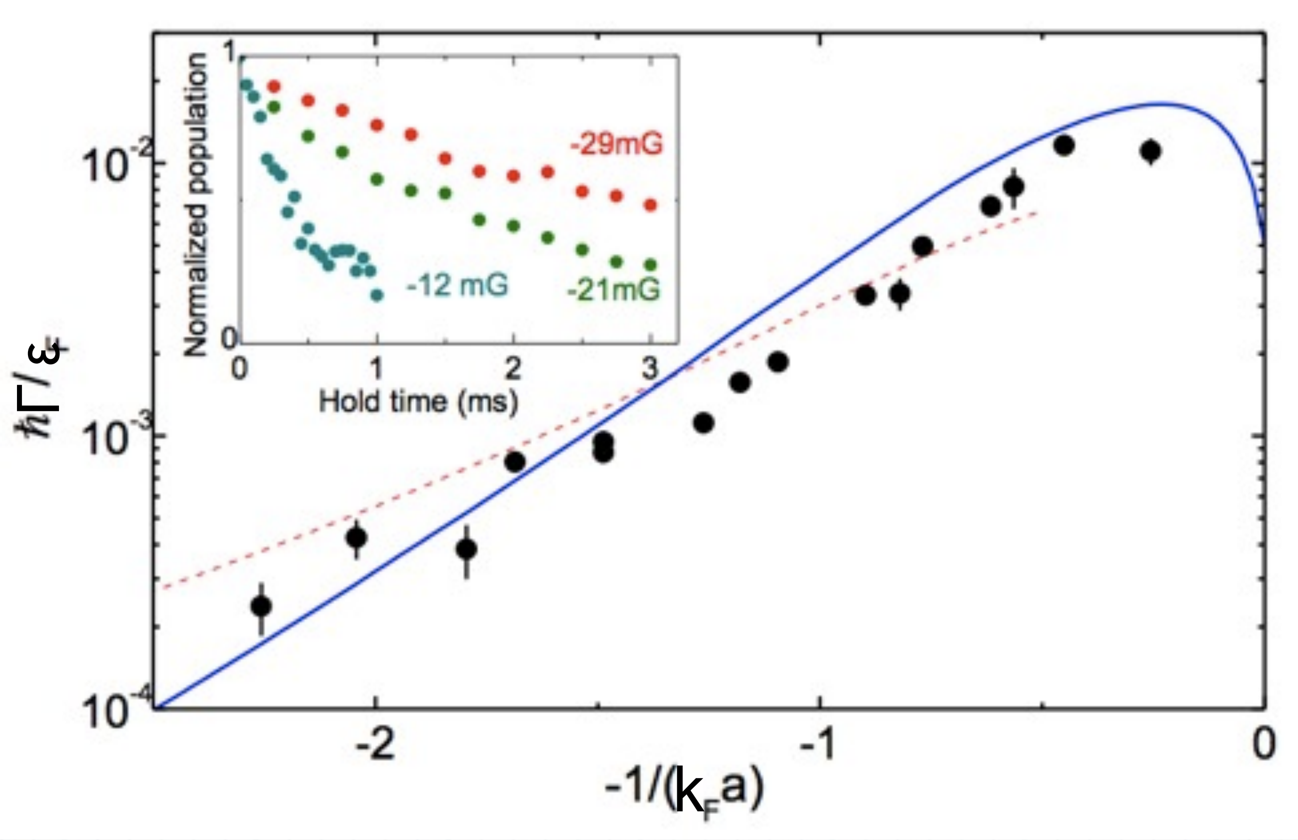
— attractive pol.

- - - molecule+hole continuum

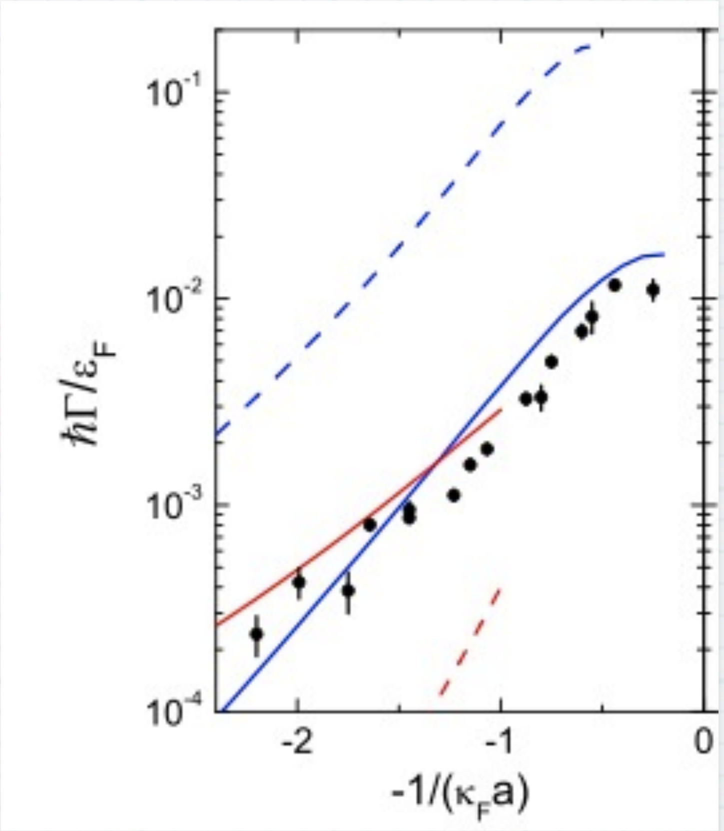
$k_F R^* \simeq 1$

C. Kohstall, M. Zaccanti, M. Jag, A. Trenkwalder, PM, G. Bruun, F. Schreck & R. Grimm, arXiv:1112.0020.

Decay of repulsive polarons



exp. data
vs. theory for
Pol+ → Pol- and Pol+ → Mol



narrow vs. broad:
substantial lifetime increase!

Rabi oscillations

$$\hat{R} \propto \Omega_0 \sum_{\mathbf{q}} (\hat{a}^\dagger_{1\mathbf{q}} \hat{a}_{0\mathbf{q}} + h.c.)$$

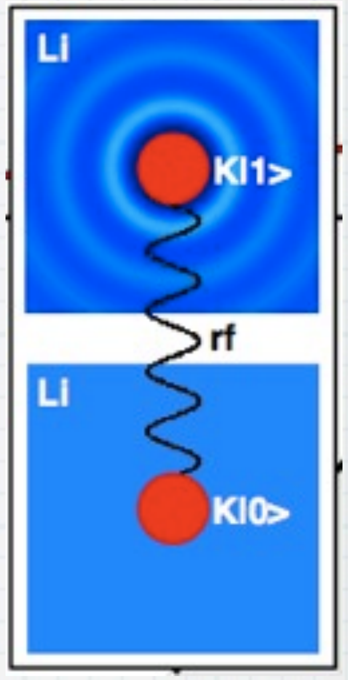
$$|I\rangle = \hat{a}^\dagger_{0\mathbf{q}=0} |\mathrm{FS}\rangle$$

$$|F\rangle = \sqrt{Z} \hat{a}^\dagger_{1\mathbf{q}=0} |\mathrm{FS}\rangle + \sum_{p<\hbar\kappa_F<q} \phi_{\mathbf{q},\mathbf{p}} \hat{a}^\dagger_{1\mathbf{p}-\mathbf{q}} \hat{b}^\dagger_{\mathbf{q}} \hat{b}_{\mathbf{p}} |\mathrm{FS}\rangle + \ldots$$

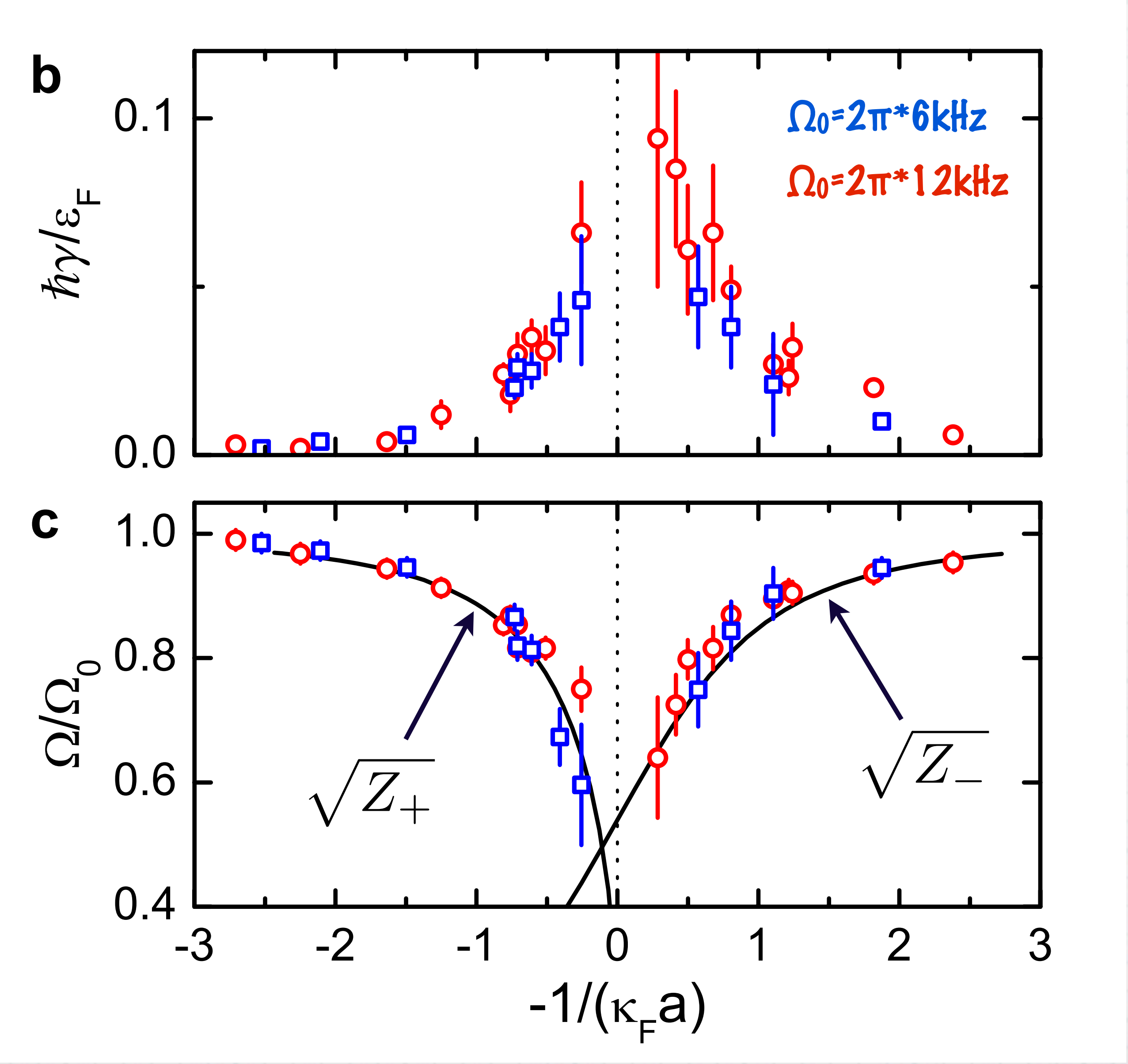
$$\langle F|\hat{R}|I\rangle = \sqrt{Z}\Omega_0$$

regime of very high RF power,
well beyond linear response regime:
fast oscillations, and quasiparticle decay
may be ignored

collision-induced decoherence
is the main damping mechanism



Rabi frequency
as a measure of
polaron residues



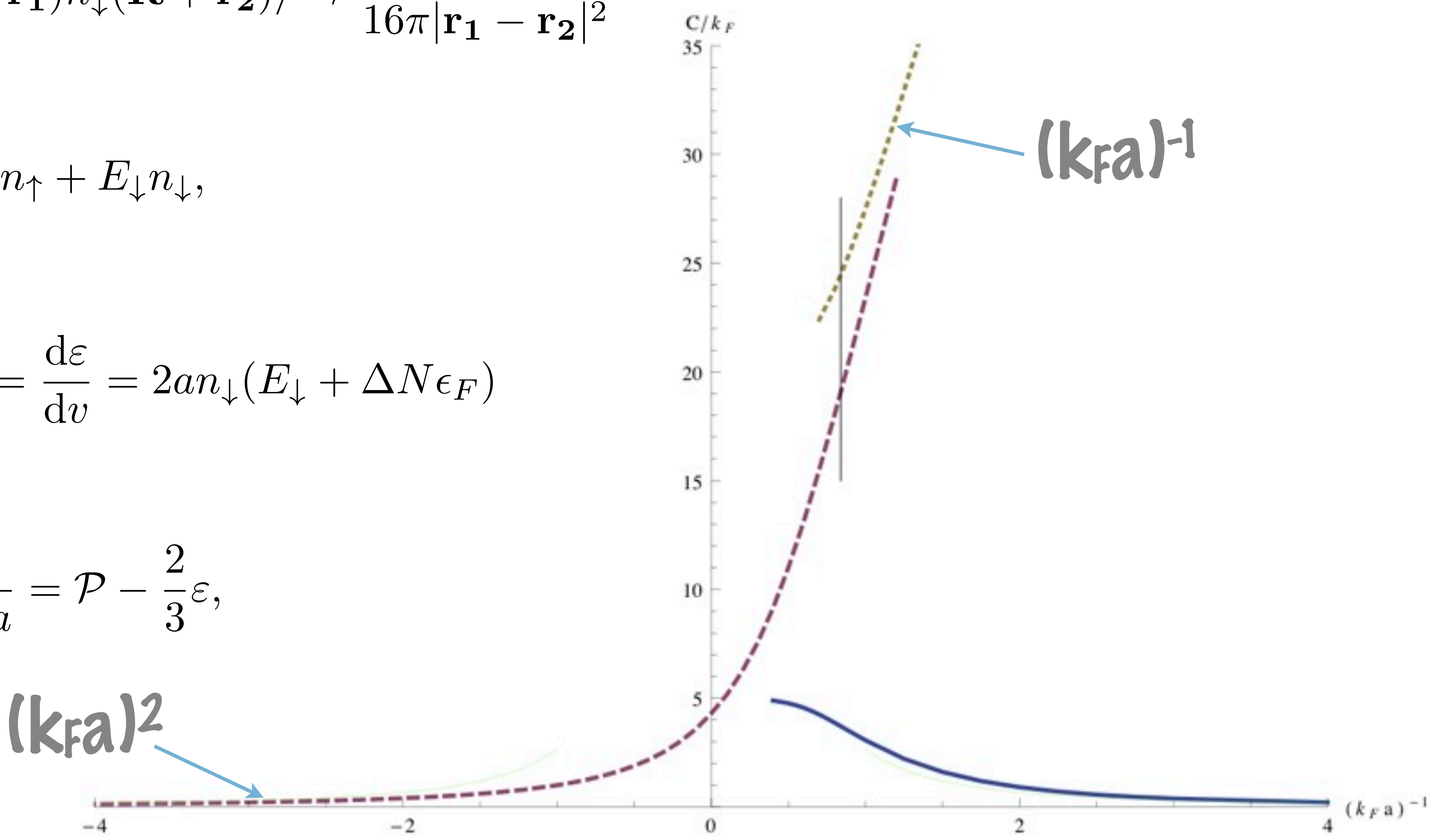
Tan's contact density C

$$\langle n_\uparrow(\mathbf{R}+\mathbf{r_1}) n_\downarrow(\mathbf{R}+\mathbf{r_2})\rangle \rightarrow \frac{\mathcal{C}\, n_\downarrow}{16\pi|\mathbf{r_1}-\mathbf{r_2}|^2}$$

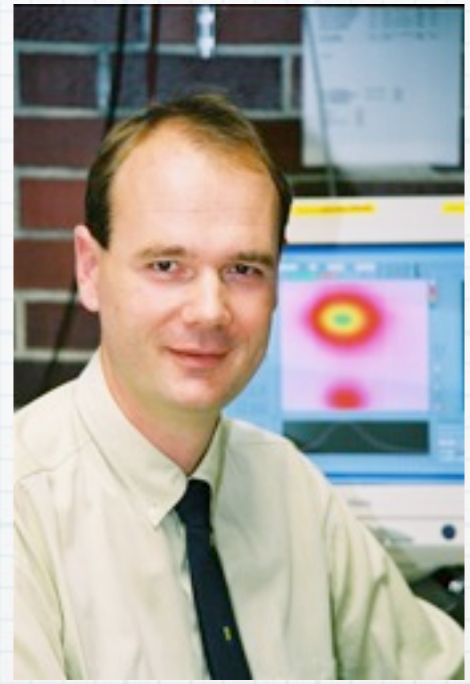
$$\varepsilon = \frac{3}{5}\epsilon_F n_\uparrow + E_\downarrow n_\downarrow,$$

$$-\frac{\mathcal{C}}{8\pi m_r} = \frac{\mathrm{d}\varepsilon}{\mathrm{d}v} = 2a n_\downarrow (E_\downarrow + \Delta N \epsilon_F)$$

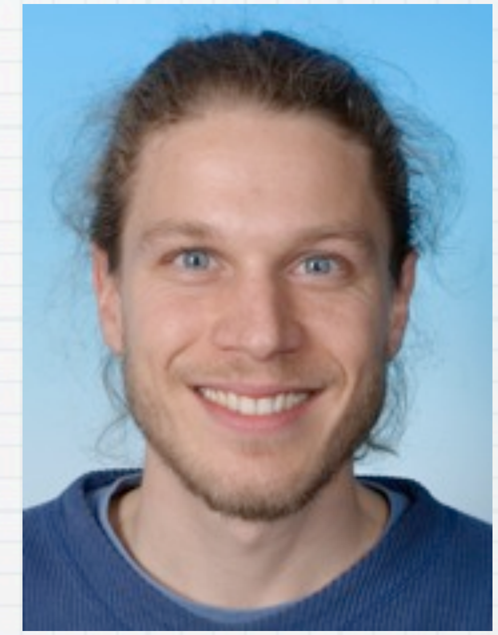
$$\frac{\mathcal{C}}{24\pi m_r a} = \mathcal{P} - \frac{2}{3}\varepsilon,$$



in collaboration with:

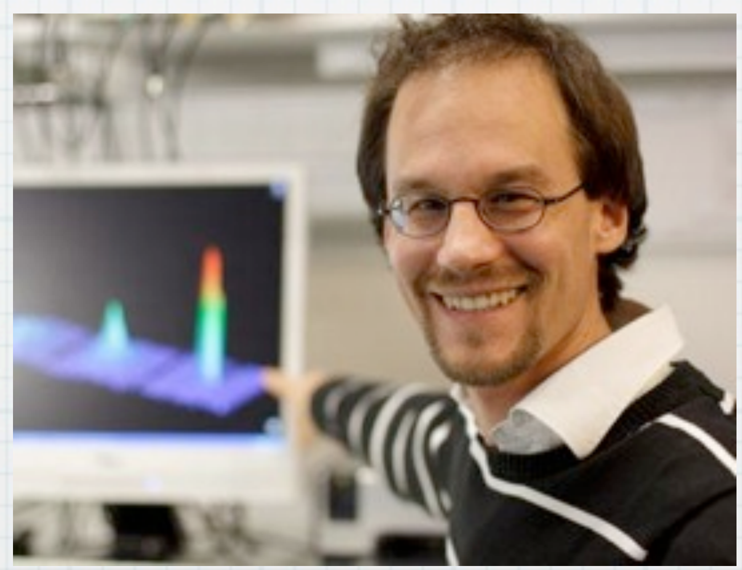


Rudi Grimm

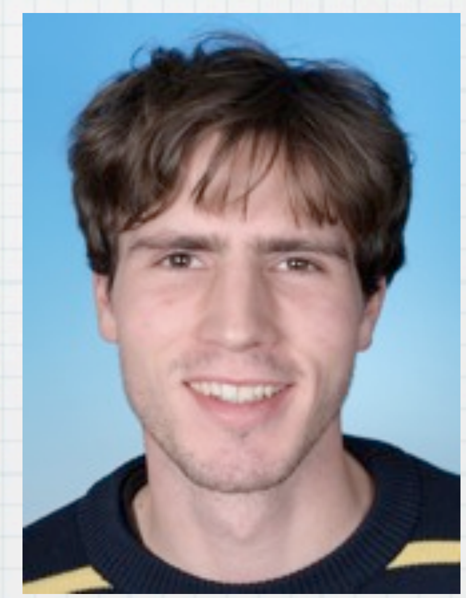


Matteo Zaccanti

Georg Bruun



Florian Schreck



Christoph Kohstall

M. Jag & A. Trenkwalder

Conclusions

- A new strongly interacting quantum state: the repulsive polaron
  - energy, residue, lifetime, m^*, ΔN, contact
- Many-body physics at narrow Feshbach resonances
  - perturbative expansion possible!
  - polaron/molecule crossing and quasiparticle properties vs. width of the resonance
- A large effective range yields a substantial lifetime increase: interesting perspectives for studying novel phenomena in metastable systems with strong repulsive interactions

I) G. Bruun and PM, Phys. Rev. Lett. **105**, 020403 (2010)
II) K. Sadeghzadeh, G. Bruun, C. Lobo, PM, and A. Recati, New J. of Phys. **13**, 055011 (2011)
III) PM and G. Bruun, Eur. Phys. J. D **65**, 83 (2011)
IV) C. Kohstall, M. Zaccanti, M. Jag, A. Trenkwalder, PM, G. Bruun, F. Schreck and R. Grimm, arXiv:1112.0020
V) PM, arXiv:1112.1029

Residue and eff. mass

(at resonance)

QuasiParticle energies

$k_F R^* = 0$

$k_F R^* = 5$

Residue and eff. mass

(through the crossover)

$k_F R^* = 0$

$k_F R^* = 5$

of particles in the dressing cloud

$$\delta\mu_\uparrow = \frac{\partial^2\varepsilon}{\partial n_\uparrow \partial n_\downarrow} + \frac{\partial^2\varepsilon}{(\partial n_\uparrow)^2}\Delta N = 0$$

$$\Delta N = -\left(\frac{\partial\mu_\downarrow}{\partial n_\uparrow}\right)_{n_\downarrow} \Big/ \left(\frac{\partial\mu_\uparrow}{\partial n_\uparrow}\right)_{n_\downarrow} \approx -\left(\frac{\partial\mu_\downarrow}{\partial\epsilon_F}\right)_{n_\downarrow}$$

weak coupling: $\Delta N = -\frac{2}{\pi}k_F a - \frac{4}{\pi^2}(k_F a)^2 + \ldots$