Bad Honnef, 07 July 2015

Impurities in a Fermi sea: Decoherence and fast dynamics

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impurity physics: paradigms of condensed matter-physics

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fixed scalar impurity → orthogonality catastrophe
P.W. Anderson, *Phys. Rev. Lett.* **18**, 1049 (1967)

moving scalar impurity → heavy-impurity problem
A. Rosch, *Adv. Phys.* **48**, 295 (1999)

fixed impurity with spin → Kondo problem
J. Kondo, *Progress of Theoretical Physics* **32**, 37 (1964)

cold atoms: strongly interacting Fermi gas

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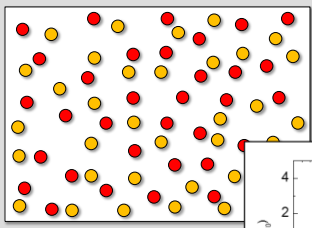
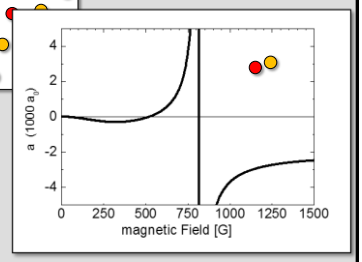


fermionic species
mixture of two spin states

Feshbach resonance



^{6}Li ^{40}K
two systems

cold atoms: superfluidity in Fermi gases

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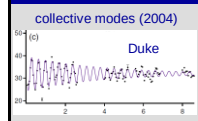
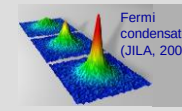
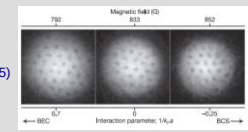
collective modes (2004)

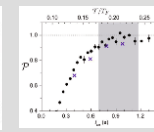




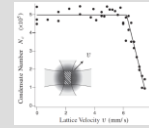
Fermi condensates (JILA, 2004)

vortices (MIT, 2005)

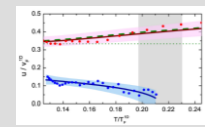




quenching of moment of inertia (Ibk, 2011)



critical velocity (MIT, 2007)



second sound (Innsbruck, 2013)

and many other fantastic experiments

much more than superfluidity

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nature of the normal state:
Fermi liquid, pseudo-gap phase, or both?

population-imbalanced Fermi gas
ground state at T=0?

new forms of superfluidity?
(FFLO state, breached pair superfluids,...)

mass-imbalanced Fermi gases
asymmetric phases, few-body effects...?

Landau's Fermi-liquid picture:
quasiparticles as building blocks for the many-body state

Fermi polarons: key experiments

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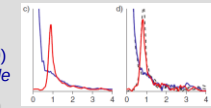
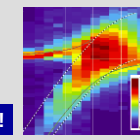
MIT 2009
Schirotzek et al., PRL 102, 230402 (2009)
Observation of Fermi polarons in a tunable Fermi liquid of ultracold atoms



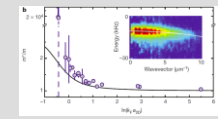
^{6}Li ↑↓

Innsbruck 2012
Kohstall et al., Nature 485, 615 (2012)
Metastability and coherence of repulsive polarons in a strongly interacting Fermi mixture



^{40}K ^{6}Li **mass imbalance !**

Cambridge 2012
Koschorrek et al., Nature 485, 619 (2012)
Attractive and repulsive Fermi polarons in two dimensions



^{40}K ↑↓

typ. expt. conditions (impurity regime)

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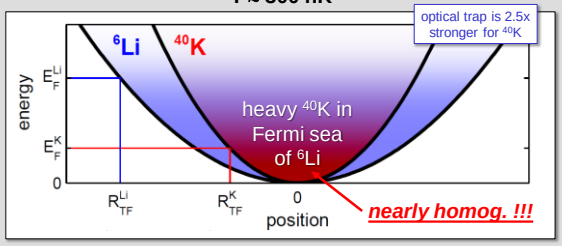
^{6}Li: N = 3.5 x 10^5 $E_F \approx 2$ μK

^{40}K: N = 2 x 10^4 E_F = 500 nK

T ≈ 300 nK



Li Fermi energy our leading energy scale!

$E_F/h \approx 40$ kHz

$1/\kappa_F \approx 3000\ a_0$

spin channels

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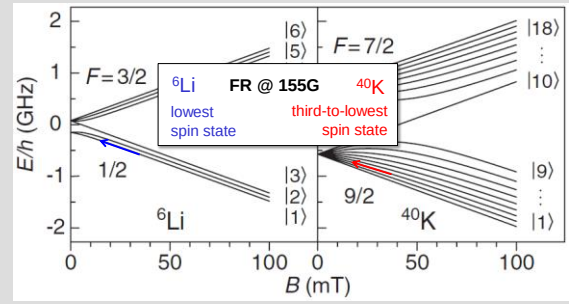

Feshbach resonance in ^{6}Li - ^{40}K

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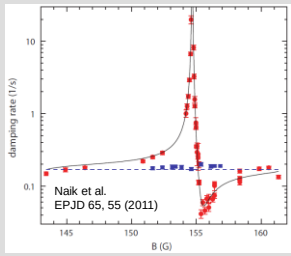

resonance parameters:

- position
  B_0 = 154.699(1) G
- width
  Δ = 0.880 G
- background scatt. length
  a_{bg} = 63.0 a_0
- differential magnetic moment
  δμ = 2.35(2) MHz/G

→ resonance length (Petrov)
R* = 2650(25) a_0

resonance is *closed-channel dominated* (two-body physics)

and has intermediate character in the many-body sense

κ_F R* ≈ 1

impurity in a Fermi sea

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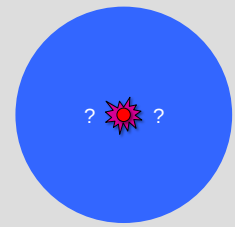

weak ($k_F|a|$<<1): simple mean-field description

stronger: *quasiparticle* (polaron)
à la Landau Fermi liquid theory

strong ($k_F|a|$ > 1): polaron or molecule?

Innsbruck FeLiKx team (2011)

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*Metastability and coherence of **repulsive polarons** in a strongly interacting Fermi mixture*
C. Kohstall et al., Nature **485**, 615 (2012)

energy diagram (T=0)

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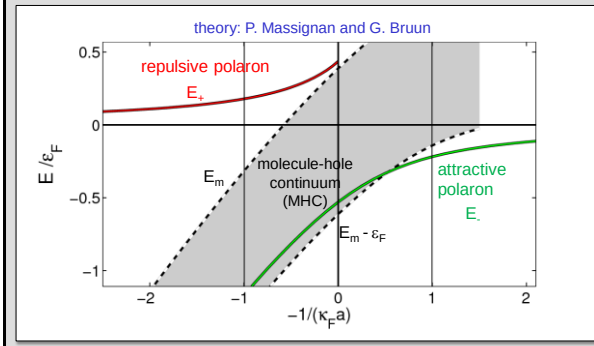

radio-frequency spectroscopy

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K in non-interacting spin state

K in (strongly) interacting spin state

radio-frequency

NB: different from standard rf probing !

spectral response

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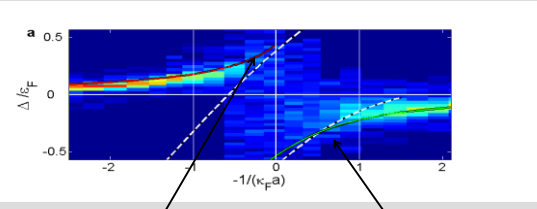
1 ms π-pulse (w/o interaction)



repulsive polaron observed up to $-1/\kappa_F a = -0.3$

polaron-molecule transition $-1/\kappa_F a = 0.6$

spectral response (strong rf)

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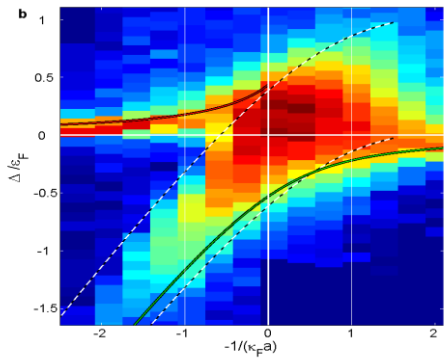

spectral response: what do we understand?

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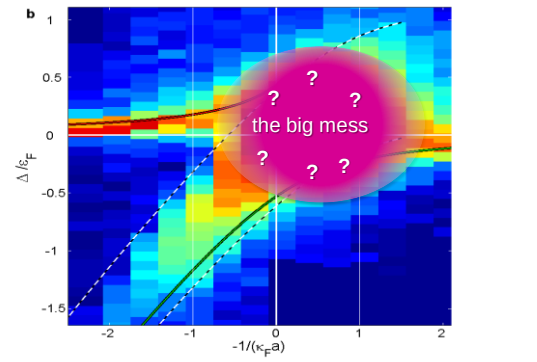

idea for time-domain impurity spectroscopy

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PHYSICAL REVIEW X 2, 041020 (2012)

Time-Dependent Impurity in Ultracold Fermions: Orthogonality Catastrophe and Beyond

Michael Knap,[1,2] Aditya Shashi,[3] Yusuke Nishida,[4] Adilet Imambekov,[3] Dmitry A. Abanin,[2] and Eugene Demler[2]

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[2]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

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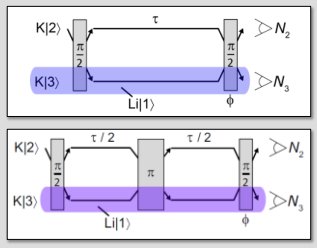
(Received 2 July 2012; published 27 December 2012)

Ramsey

spin echo



atom interferometer (with non-int. state as phase reference)

FeLiKx group + theory collaborators

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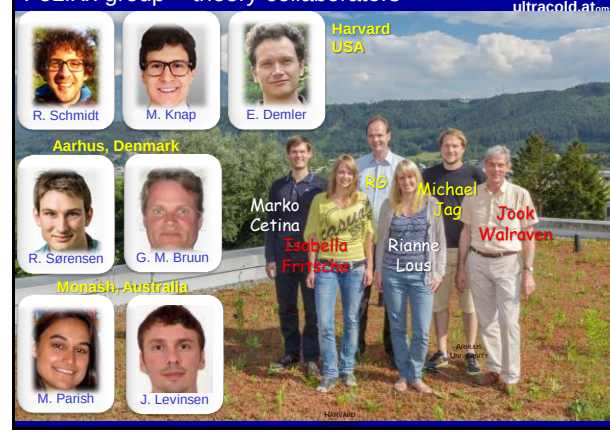

interferometer fringes

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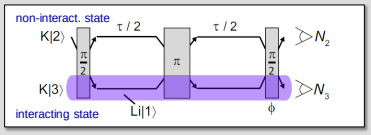
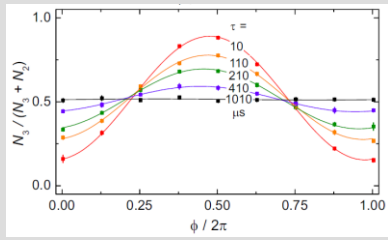


Cetina et al., arXiv:1505.00738



loss of coherence

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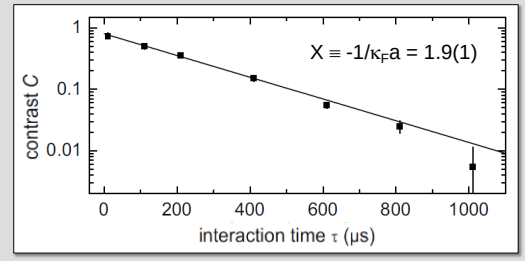
moderate interaction strength



fits to a simple exponential decay

Cetina et al., arXiv:1505.00738

how to measure very fast dynamics on resonance?

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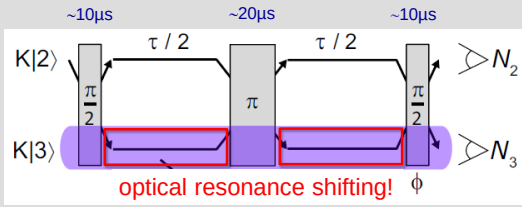
problem: decoherence too fast for rf pulses



apply rf-pulses somewhat away from resonance ($1/\kappa_F|a| \approx 2$)

optical resonance shifting

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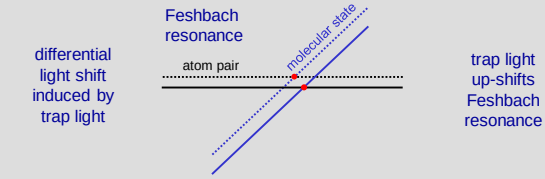
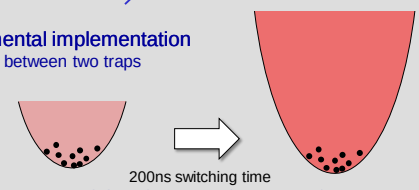


experimental implementation
switching between two traps



200ns switching time
switch equiv. to 40mG (up to 100mG)

loss of coherence

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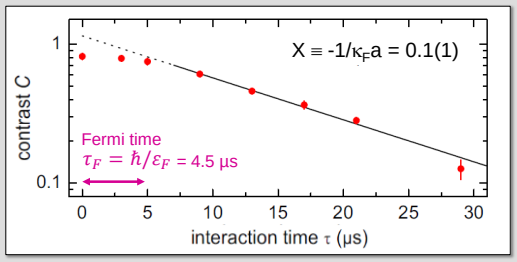
on resonance



initial quantum evolution

fits to exponential decay after ~1.5 τ_F

Cetina et al., arXiv:1505.00738

decoherence rate

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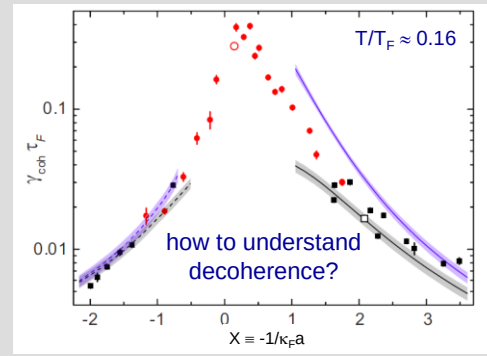
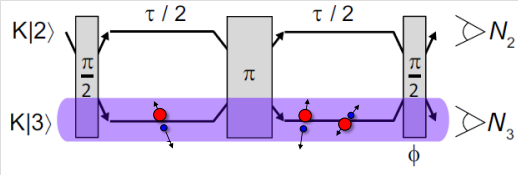
Cetina et al., arXiv:1505.00738



elastic scattering

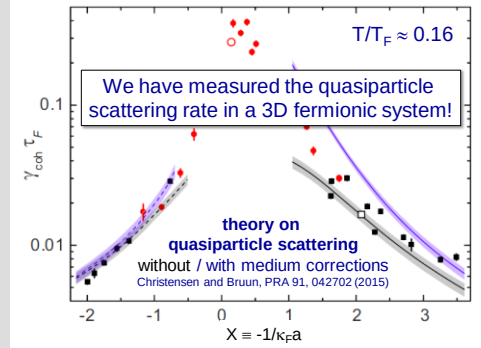


elastic scattering provides "which way" information
→ loss of fringe visibility

Greenberger, Yasin (1988); Englert (1996)

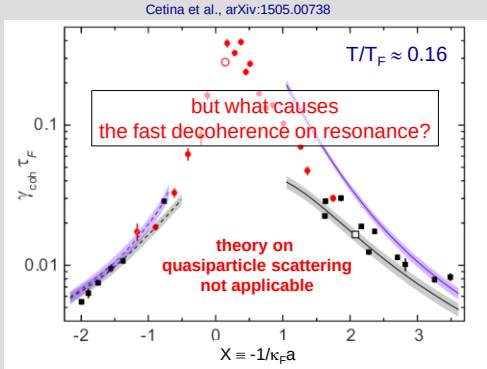
decoherence rate

Cetina et al., arXiv:1505.00738

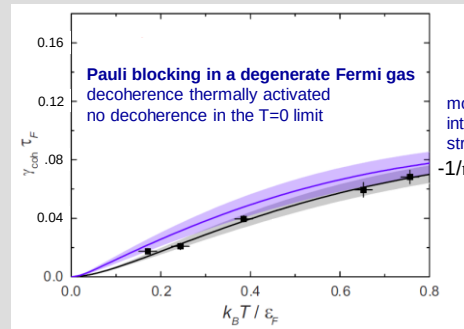


decoherence rate

Cetina et al., arXiv:1505.00738

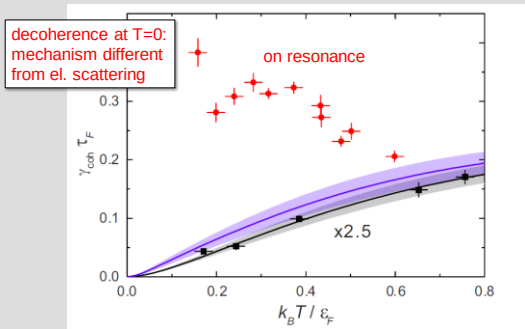


temperature dependence



Cetina et al., arXiv:1505.00738

temperature dependence



Cetina et al., arXiv:1505.00738

Fermi time: relevant time scale

$\tau_F = \hbar/\varepsilon_F$

ultracold Fermi gas
(E_F = 1.7 μK)
4.5 μs

traditional
condensed-matter system
(E_F = 5 eV)
130 as

we can observe the time dynamics
of excitations deep in the Fermi sea!

experiments on fast quantum dynamics

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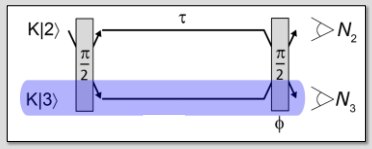
what happens on a very fast time scale?

$\tau_F = \hbar/\varepsilon_F$ = 4.5 μs

dynamics of quasiparticle formation (“birth of a polaron”) ?

Ramsey interferometer



optical control of interaction

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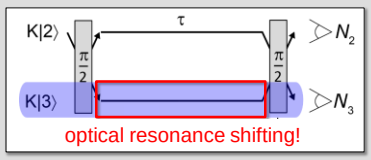
Ramsey interferometer



interaction parameter
$X \equiv -1/\kappa_F a$

during rf pulses: $|X_0| \approx 5$
between rf pulses: $|X| < 1$

birth of a polaron (what we would expect)

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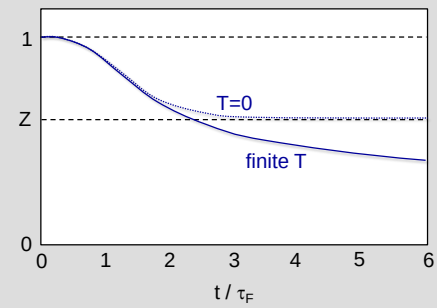
not on resonance, but not too far away



polaronic regime

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theory Chevy ansatz, experimental data, **functional det. theory**

X = -0.23
(X_0 = -3.9)

unpublished data

X = +0.86
(X_0 = 5.8)

remarkable match

on-resonance regime

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X = +0.08
(X_0 = 4.8)

unpublished data

Chevy ansatz

functional det.
expt. data

Chevy ansatz vs. functional determinants

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Chevy ansatz

- single particle-hole excitations only (no decay into molecular excitations)
- zero-temperature theory
- describes finite mass ratio

functional determinants

- multiple particle-hole excitations (no decay into molecular excitations)
- finite-temperature theory
- restricted to infinitely heavy impurity (*under our conditions problem fixed by R* correction*)

interacting impurities: what we have learned

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conventional rf spectroscopy (frequency domain) 2012

- energies of attractive and repulsive quasiparticle branch
- lifetime of (metastable) repulsive polaron
- determination of quasiparticle residue via Rabi oscillations

time domain spectroscopy 2015

- quasiparticle scattering rate
- ultrafast decoherence on resonance
- "birth of a polaron": dynamics of quasiparticle formation
- ultrafast dynamics on resonance: observation of beating

observation of Anderson's orthogonality catastrophe ?

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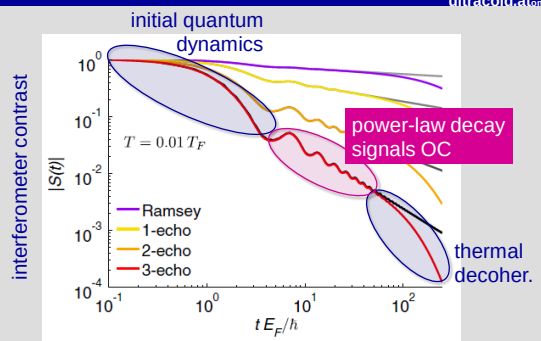

Knap et al., PRX 2, 04020 (2012)

future experiments

ultrafast impurity dynamics cntn'd

interactions between impurities

- high concentration
- fermions vs. bosons

impurities pinned in a species-specific lattice

- immobile and infinite mass
- long-range vs. short-range interactions

FWF Der Wissenschaftsfonds. SFB FoQuS Foundations and Applications of Quantum Science