Fermi gases in an optical lattice

Michael Köhl

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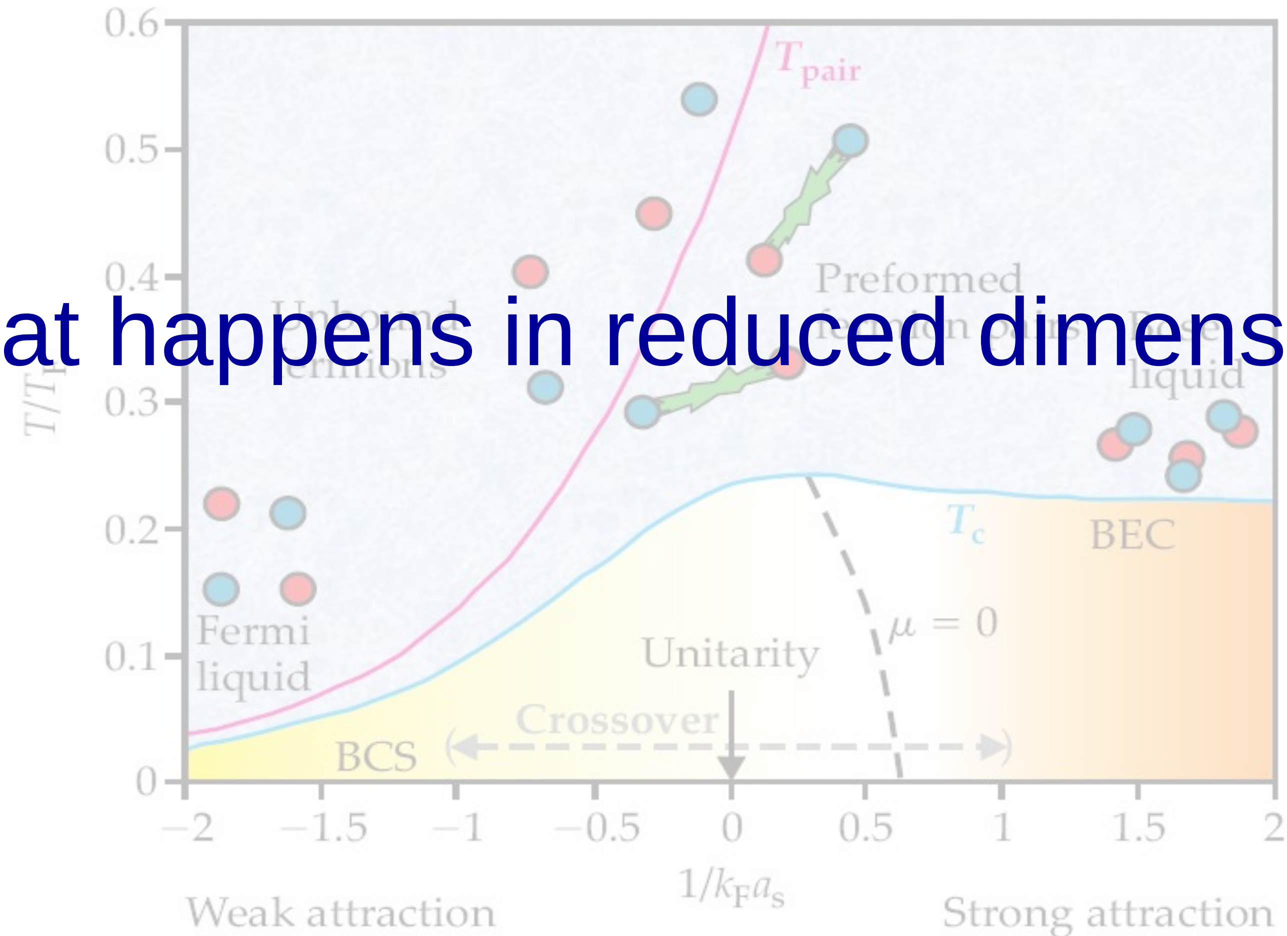
BEC-BCS crossover



What happens in reduced dimensions?

Sa de Melo, Physics Today (2008)

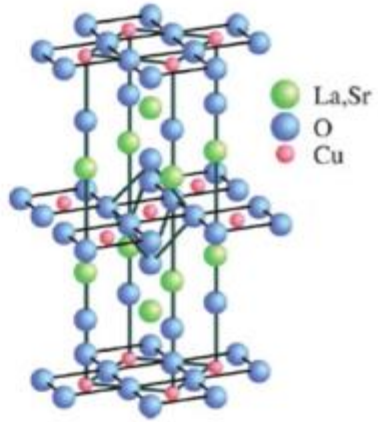
Two-dimensional Fermi gases

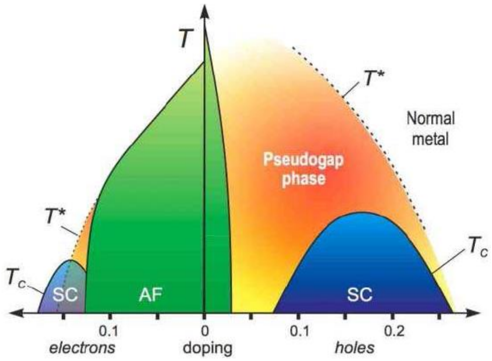
Two-dimensional gases:

“the grand challenge” of condensed matter physics

High-T_c superconductors:

- After 25 years of research still no breakthrough in understanding (nor to solve the energy crisis)
- Material is to complicated to understand even the basic mechanism

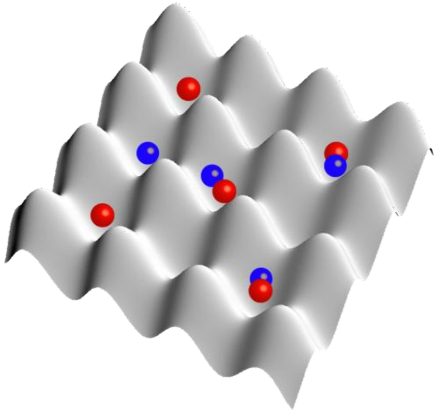




Cold atomic gases provide tuneable model system

- fermionic atoms take the role of electrons
- lattice created by standing wave laser fields

→ build quantum simulator (Feynman)



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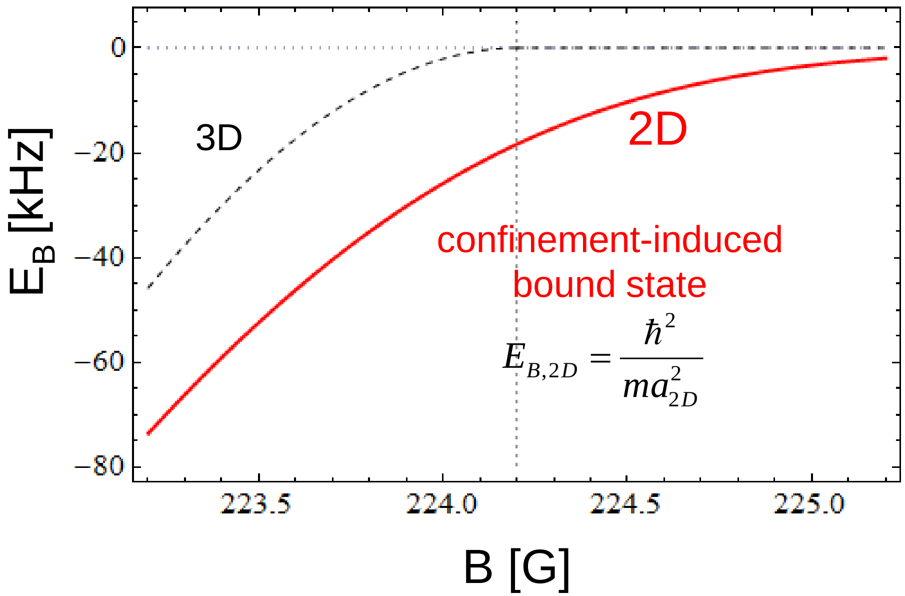
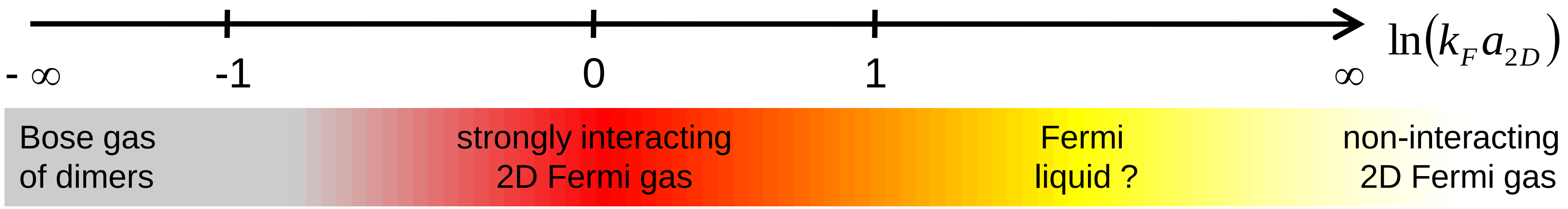
A very short theory overview for 2D



Mean-field coupling in 2D
(Bloom 1975)

$$g_{2D} = -\frac{2\pi\hbar^2}{m}\frac{1}{\ln(k_F a_{2D})}$$

$$\left(g_{3D} = \frac{4\pi\hbar^2}{m} a_{3D} \right)$$



- BKT transition at $T_{BKT} \approx 0.1\ T_F$ in the strongly interacting regime
- T_{BKT} decays exponentially towards weak attractive interactions (as in 3D)

Theory: Bloom, P.W. Anderson, Randeria, Shlyapnikov, Petrov, Devreese, Julienne, Duan, Zwerger, Giorgini, Sa de Melo, **...**

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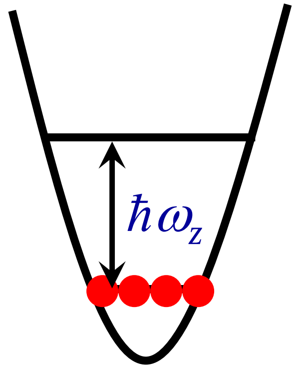
Quasi-2D geometry



<u>Conditions for 2D</u>

$$E_F\,,\,k_B T \ll \hbar\omega_z$$

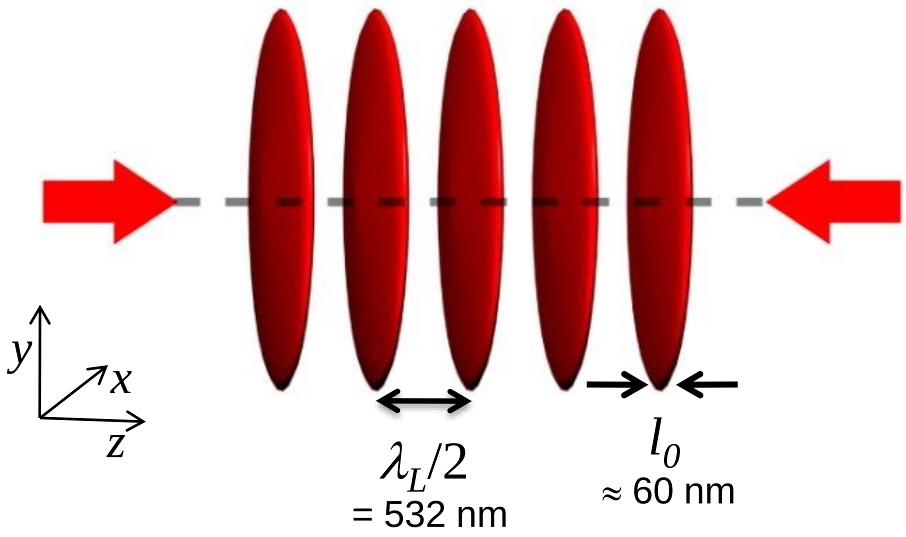
Strong axial confinement required

$E_F \approx h\times 8\,\mathrm{kHz}$

$\omega_z \approx 2\pi\times 80\,\mathrm{kHz}$

$\omega_\perp \approx 2\pi\times 130\,\mathrm{Hz}$

Optical lattice: array of 2D quantum gases



- lattice depth 83 E_{rec}
- hopping rate 0.002 Hz
- ~ 2000 Fermions per spin state
- ~ 30 "pancakes" / layers

B. Fröhlich, M. Feld, E. Vogt, M. Koschorreck, W. Zwerger, MK, PRL 106, 105301 (2011)
other 2D Fermi gases: Inguscio, Grimm, Esslinger, Jochim, Turlapov, Vale, Zwierlein

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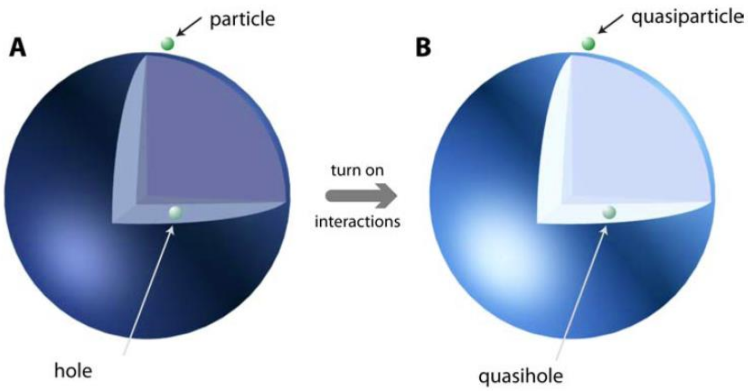
Two-dimensional Fermi gases

- Fermi liquid and pseudogap
- Increasing the polarization of a 2D Fermi gas:
  $N/2 + N/2 \rightarrow N{+}1 \rightarrow N$
- Spin dynamics

Spin-balanced Fermi liquid



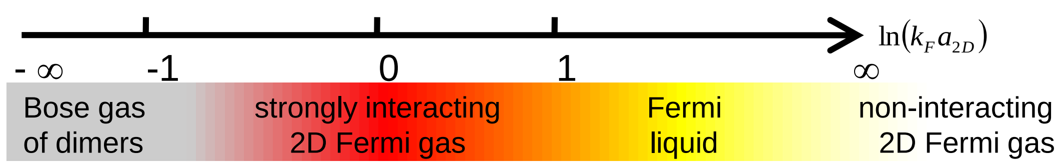
- Landau-Fermi liquid
  quasi-particles are fermionic
- finite lifetime $1/t \sim (k-k_F)^2$ (long-lived near the Fermi surface)
- effective mass: $m^*/m > 1$, depending on interaction strength

Fermi liquid:

E_F, $k_BT < \hbar\omega$ (two-dimensional)

$E_B < k_BT$ (no pairing)

$g=1/\ln(k_Fa_{2D}) < 1$ (weak interactions)



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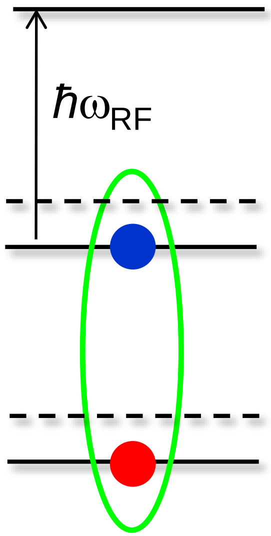
Momentum-resolved RF spectroscopy

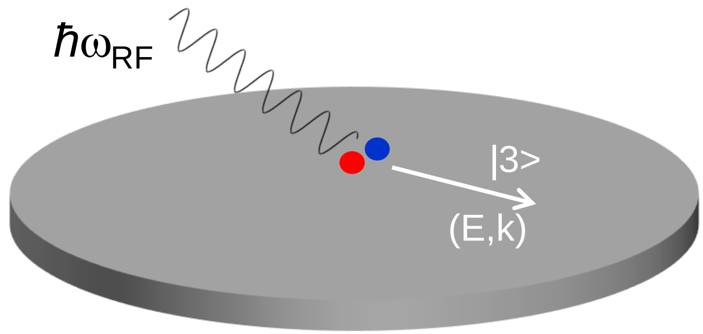


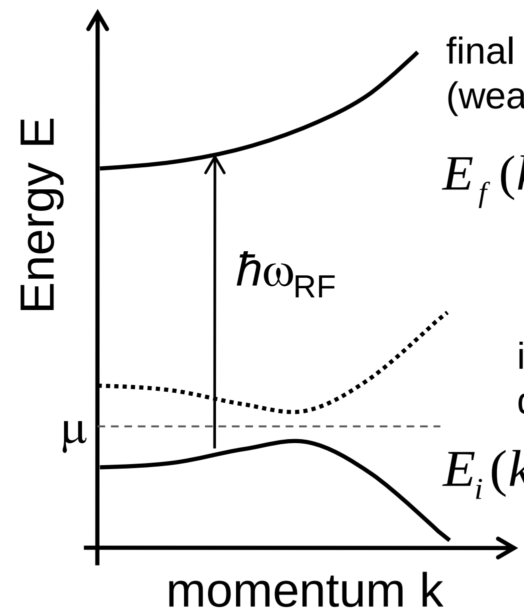
|3>= |-5/2>

|2>= |-7/2>

|1>= |-9/2>

202G FB res.





final state |3>
(weak interactions)

$$E_f(k) = \frac{\hbar^2 k^2}{2m}$$

initial state, e.g. BCS-like dispersion

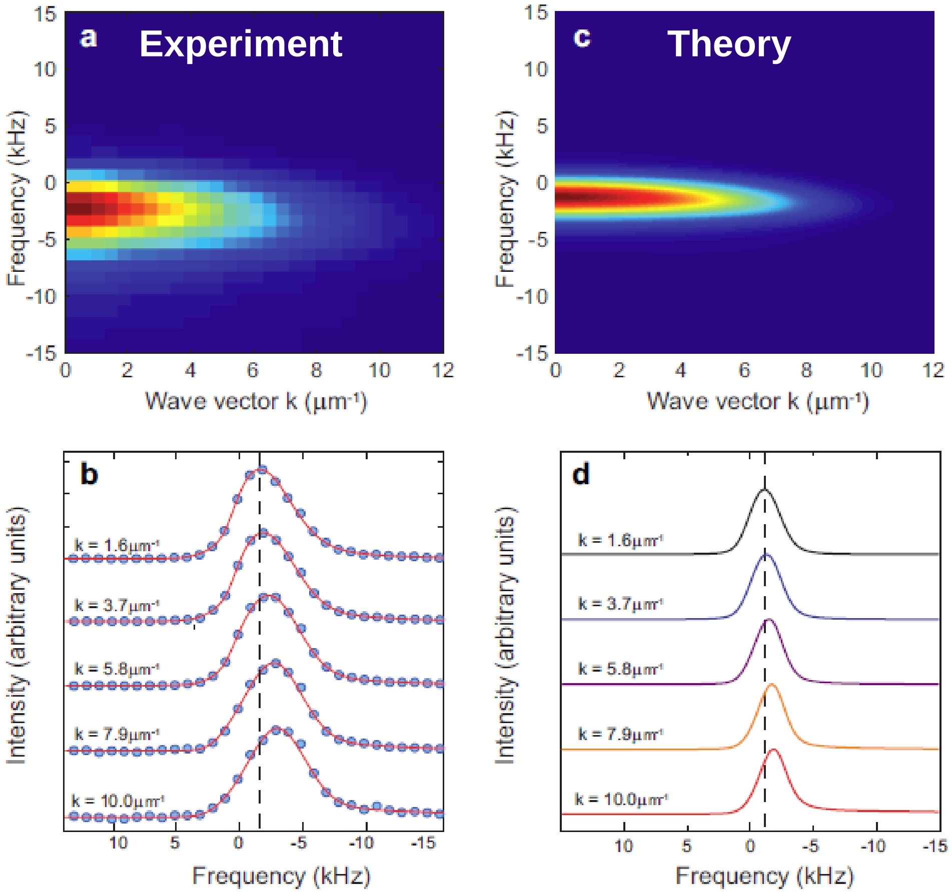
$$E_i(k) = \mu \pm \sqrt{\left(\frac{\hbar^2 k^2}{2m} - \mu\right)^2 + \Delta^2}$$

ARPES in 3D Experiment: Jin

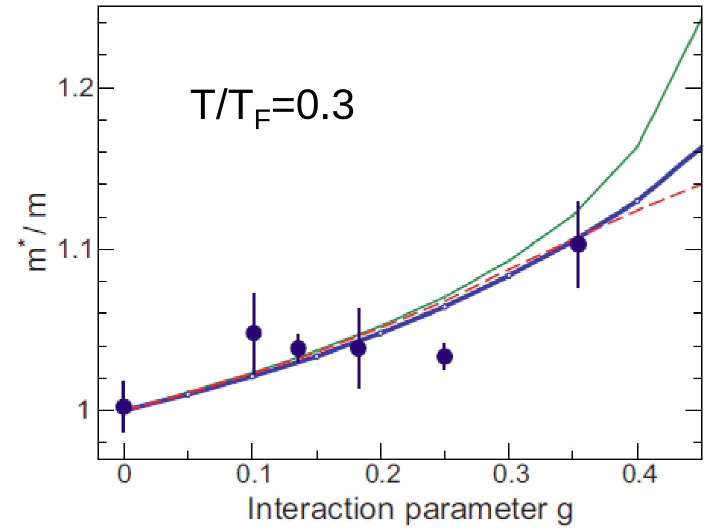
Theory: Georges, Strinati, Levin, Ohashi, Zwerger, Drummond, ...

Comparison with theory

Single-particle spectral function



Effective mass parameter



B. Fröhlich et al., Phys. Rev. Lett. 109, 130403 (2012); C. Berthod et al., 1506.00364.

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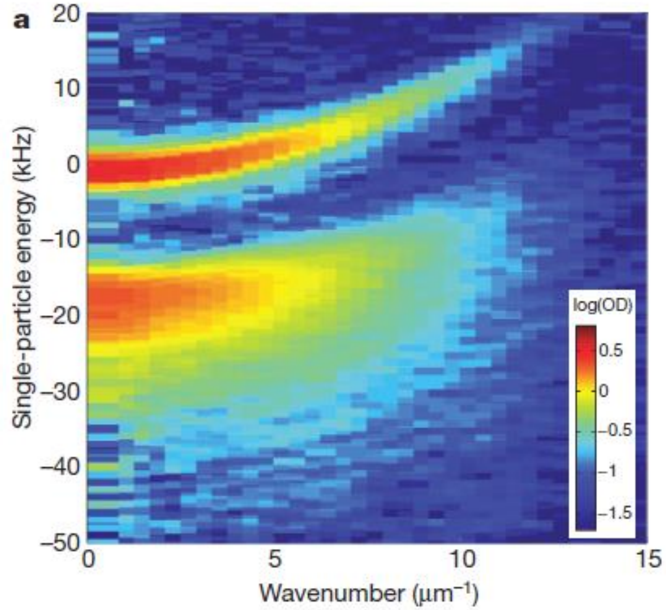
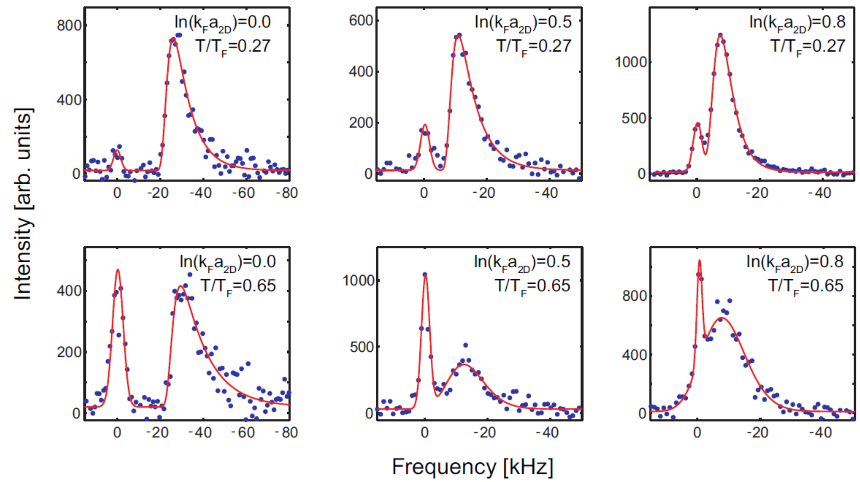
Strong interactions: Pairing pseudogap

Single-particle spectral function

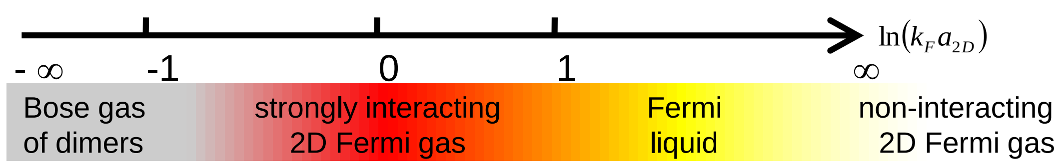




E_F, $k_BT < \hbar\omega$ (two-dimensional)

$E_B > k_BT$ (pairing)

$g=1/\ln(k_Fa_{2D}) > 1$ (strong interactions)



M. Feld et al., Nature 480, 75 (2011)

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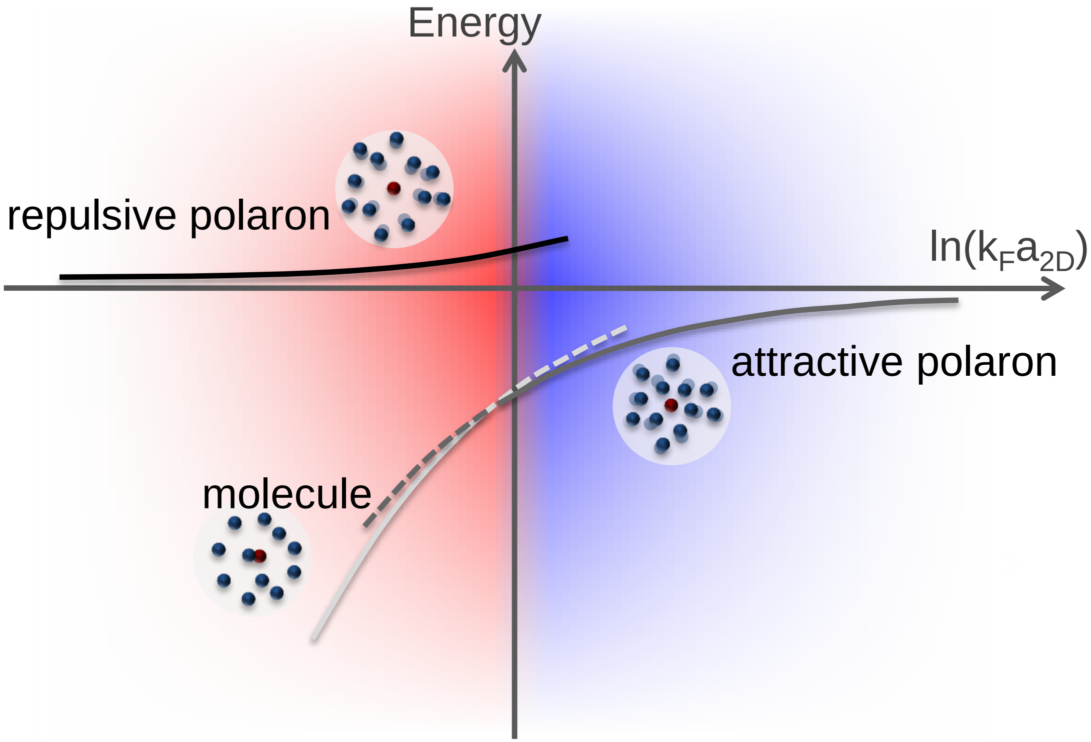
Strongly imbalanced Fermi gases in 2D

The "N+1" problem: one |↓> impurity in a large |↑> Fermi sea

$$|P\rangle = \alpha_0 c^\dagger_{0\downarrow}|N\rangle + \frac{1}{\Omega}\sum_{\mathbf{k},\mathbf{q}} \alpha_{\mathbf{kq}} c^\dagger_{\mathbf{q-k}\downarrow} c^\dagger_{\mathbf{k}\uparrow} c_{\mathbf{q}\uparrow}|N\rangle,$$

- Mobile impurity interacting with a Fermi sea of atoms
- Tunable interactions
- Polaron properties determine phase diagram of imbalanced Fermi mixtures



3D Theory: Bruun, Bulgac, Chevy, Giorgini, Lobo, Prokofiev, Stringari, Svistunov, ...
3D Experiment: Zwierlein, Salomon, Grimm, Jochim
2D Theory: Bruun, Demler, Enss, Parish, Pethick, Recati, ...

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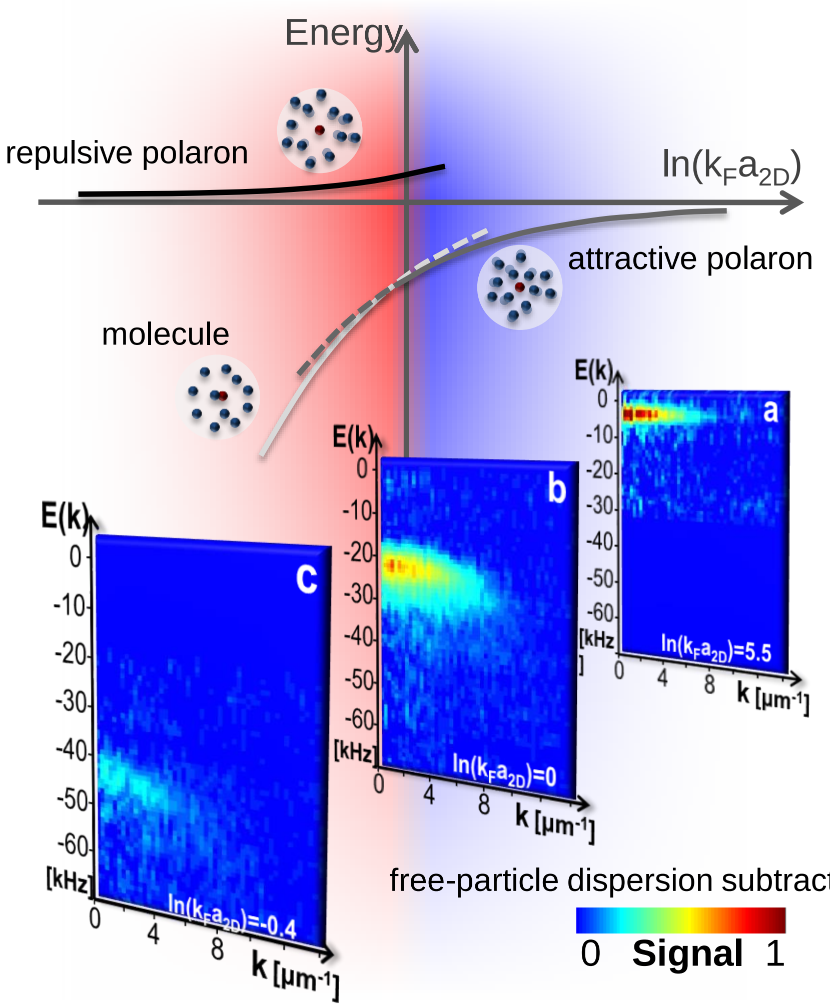
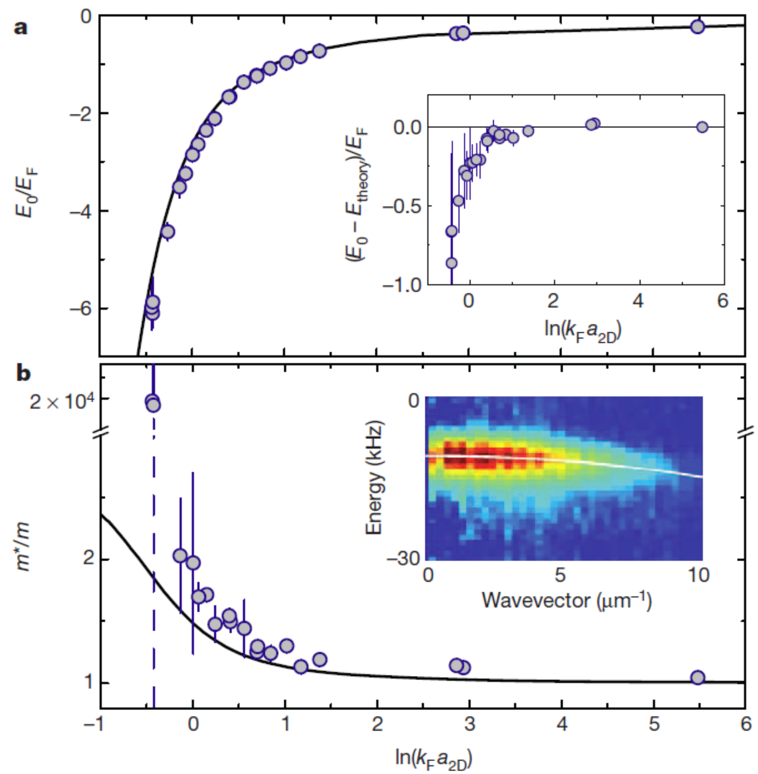
Characterizing the attractive polaron





Theory from: R. Schmidt, T. Enss,
V. Pietilä, E. Demler, PRA 85, 021602 (2012)

M. Koschorreck et al., Nature 485, 619 (2012)

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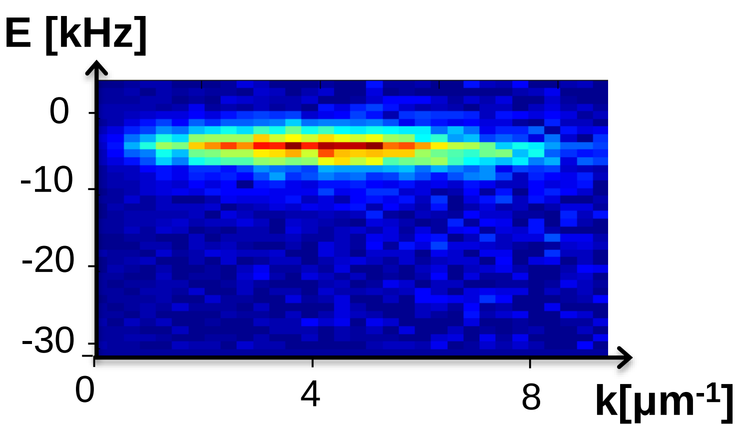
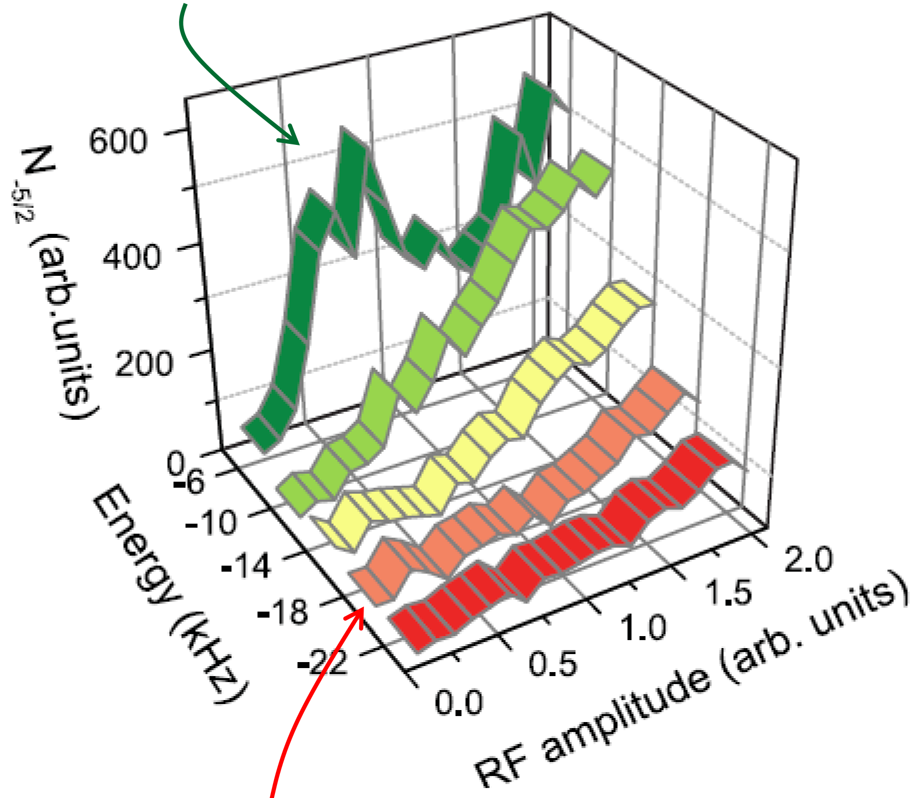
Coherence of the polaron



Rabi oscillations between polaron and free particle



Incoherent transfer: rate ~ amplitude

M. Koschorreck et al., Nature 485, 619 (2012)

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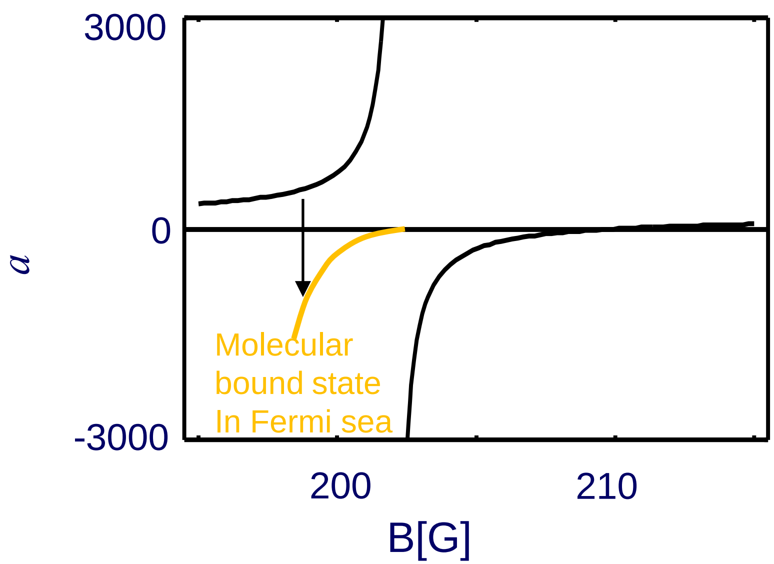
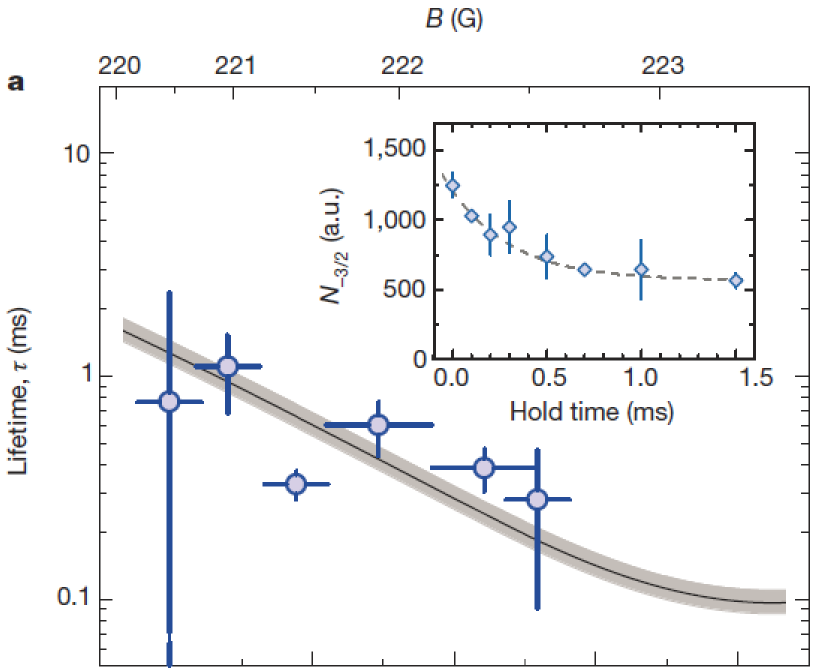
Repulsive polarons





For strong interactions: lifetime ~ $1/E_{Fermi}$

- similar to broad Feshbach resonance in 3D (Ketterle group)
- narrow Feshbach resonance could be advantageous (Grimm group)

M. Koschorreck et al., Nature 485, 619 (2012)

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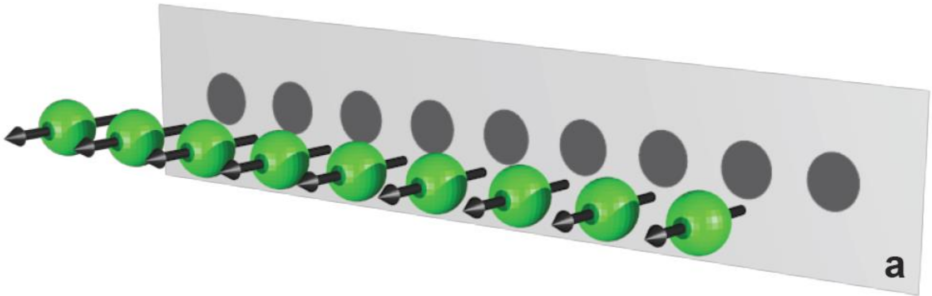
Spin dynamics

Spin dynamics

transversely
polarized
Fermi gas



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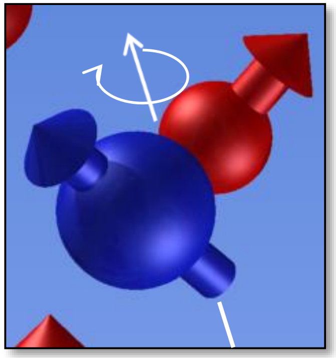
Spin-spin interaction

Spin exchange / Spin-rotation



Strength determined by interaction constant

$$g_{2D} = -\frac{2\pi\hbar^2}{m}\frac{1}{\ln(k_F a_{2D})}$$

Many-body effects in Fermi liquid
(Leggett-Rice effect)

Spin relaxation

e.g. spin-orbit coupling breaks symmetry underlying spin conservation

Usually absent in cold atom systems

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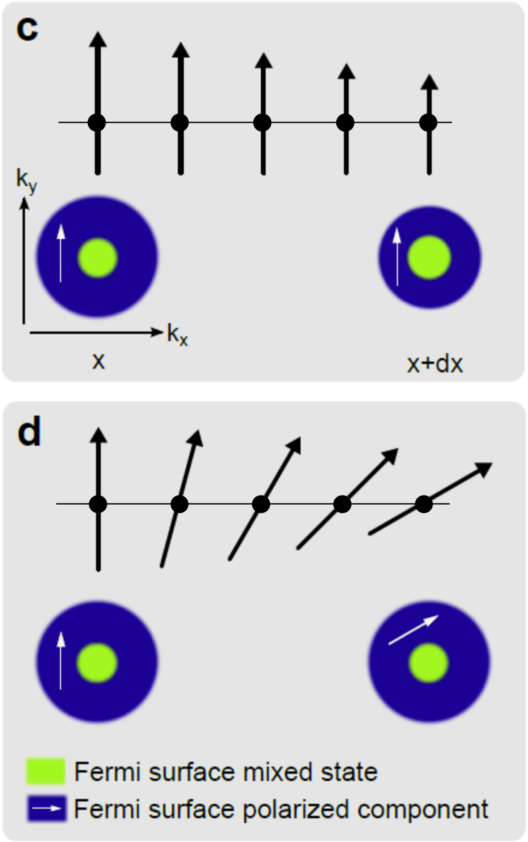
Longitudinal vs. transverse diffusion

Spin currents are driven by a gradient of the magnetization $\vec{M}(\vec{r},t) = M(\vec{r},t)\,\vec{p}(\vec{r},t)$

Longitudinal: Gradient of **magnitude**

$$\nabla \vec{M} = \vec{p}\nabla M + M\nabla\vec{p}$$

Transverse: Gradient of **orientation**



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For strong interaction: Spin diffusion

Diffusion equation $$\frac{\partial \vec{M}(x,t)}{\partial t} = D\nabla^2 \vec{M}(x,t)$$

Spin diffusion constant

$$D = v l_{mfp} = \frac{v}{n\sigma}$$

Fermi gas at unitarity:

$$\left.\begin{array}{l} v = \hbar k_F / m \\ n \approx k_F^2 \\ \sigma = \dfrac{1}{k_F} \end{array}\right\} \quad D \approx \frac{\hbar}{m}$$

Quantum limit of diffusivity

Semiconductor nanostructures $D \approx 10^2 \frac{\hbar}{m}$ Weber et al., Nature (2005)

3D Fermi gases at unitarity $D \approx 6 \frac{\hbar}{m}$ Zwierlein group, Nature (2011)

$D \approx \frac{\hbar}{m}$ Thywissen group, Science (2013)

Theory: Leggett & Rice, Bruun, Levin, Enss, Lewenstein, Laloe, …

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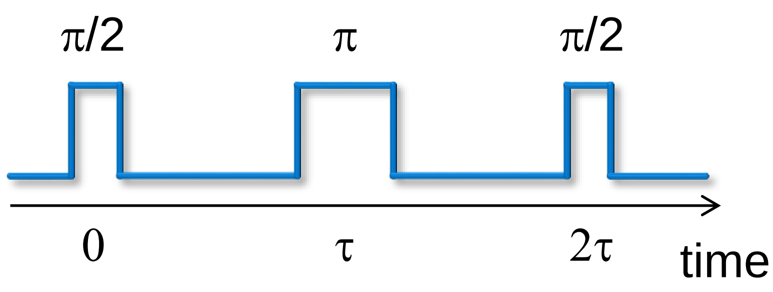
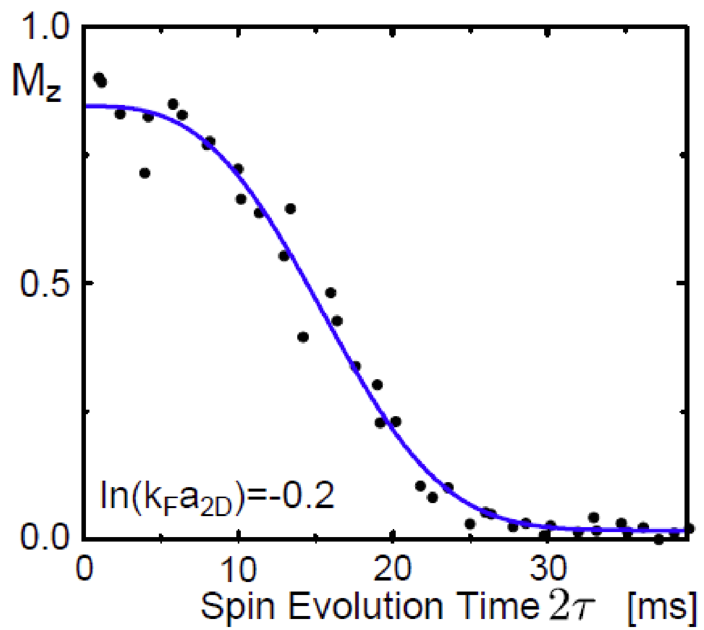
Spin-echo technique





Eliminates effect of magnetic field gradient

$$M_z(\tau) = \exp\left[-\tfrac{2}{3}\mathcal{D}_\perp(\delta\gamma B')^2\tau^3\right].$$

characteristic exponent

Theory: Hahn, Purcell, Leggett, Mullin, Dobbs, Lhuillier, Laloe, ...
Experiment in 3He: Osheroff

M. Koschorreck et al., Nature Physics 9, 405 (2013).

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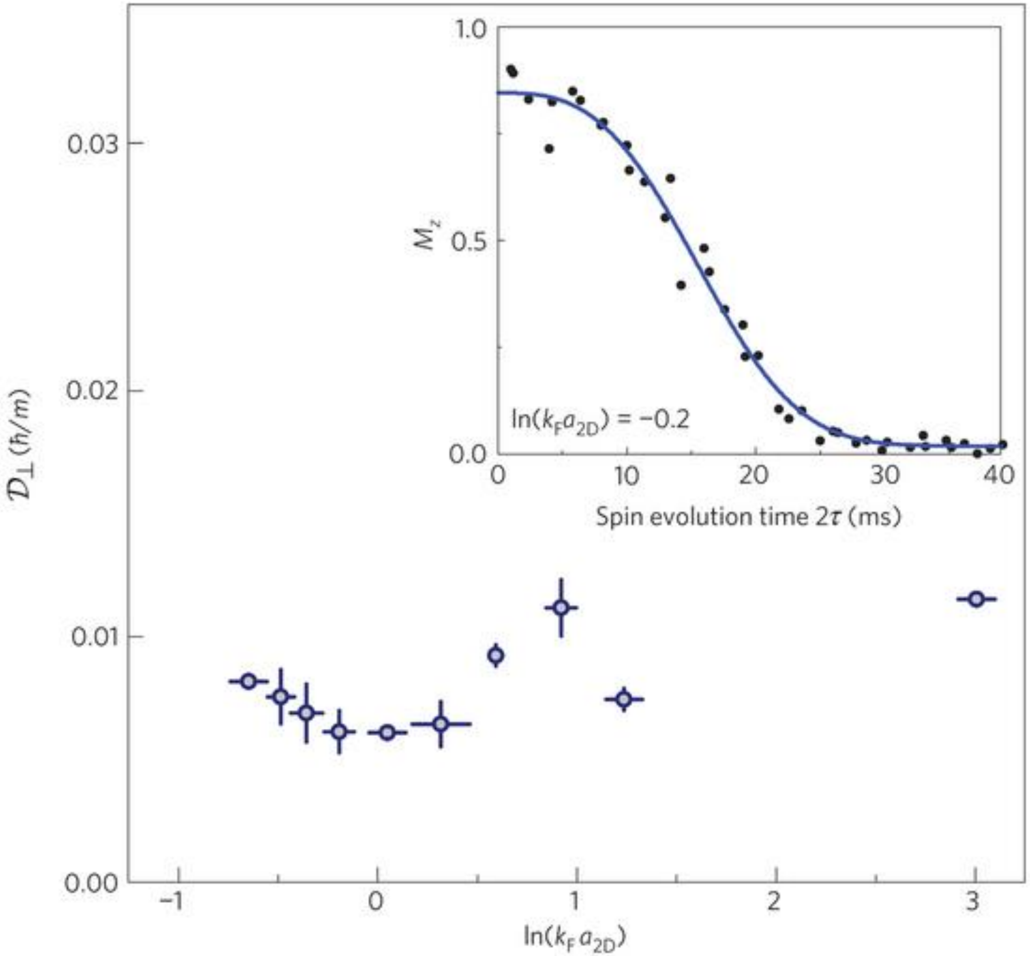
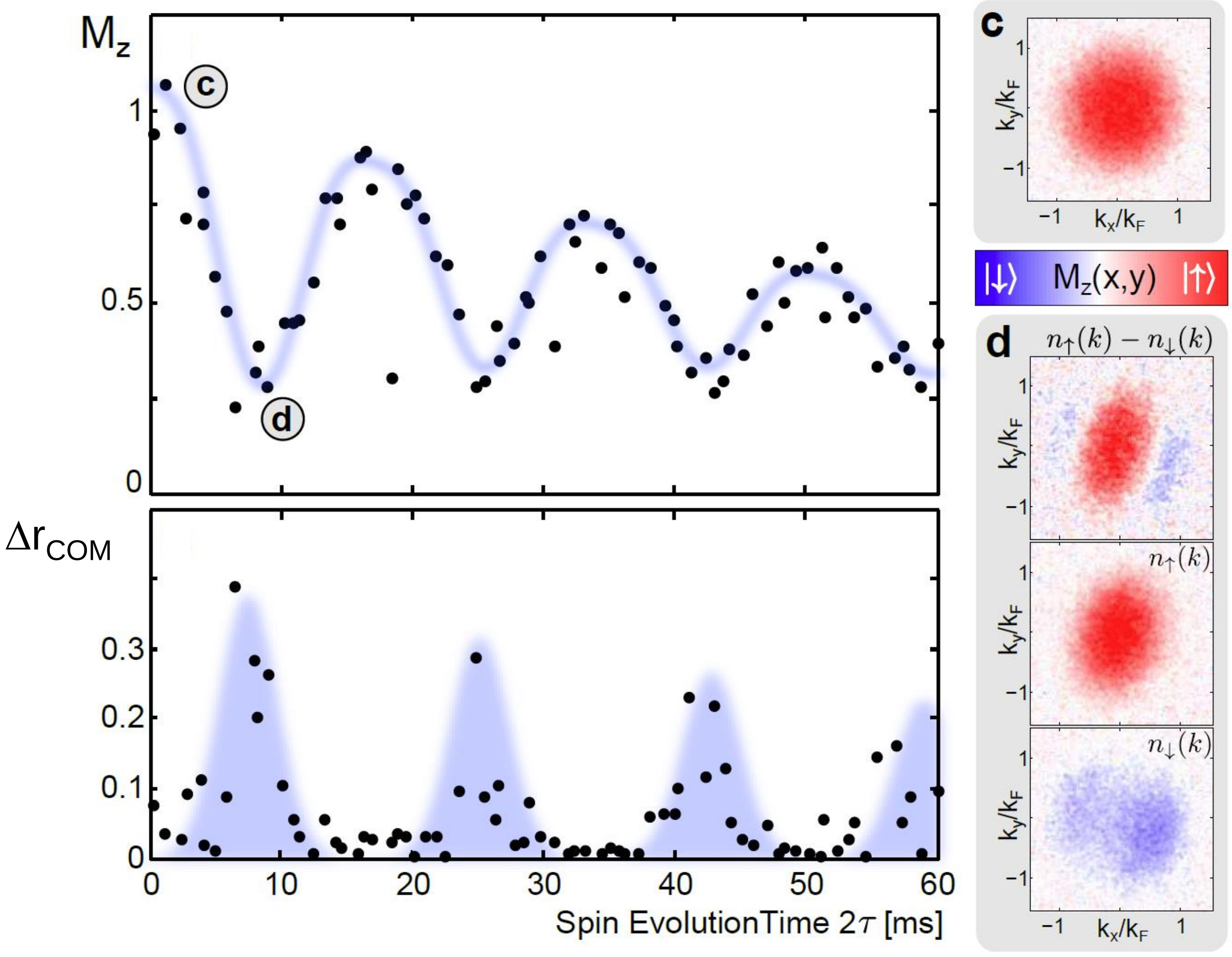
Spin diffusion in the strongly interacting regime



Smallest spin diffusion constant ever measured: 0.007(1) ħ/m.

M. Koschorreck et al., Nature Physics 9, 405 (2013).

Weakly interacting regime: spin oscillations



M. Koschorreck et al., Nature Physics 9, 405 (2013).

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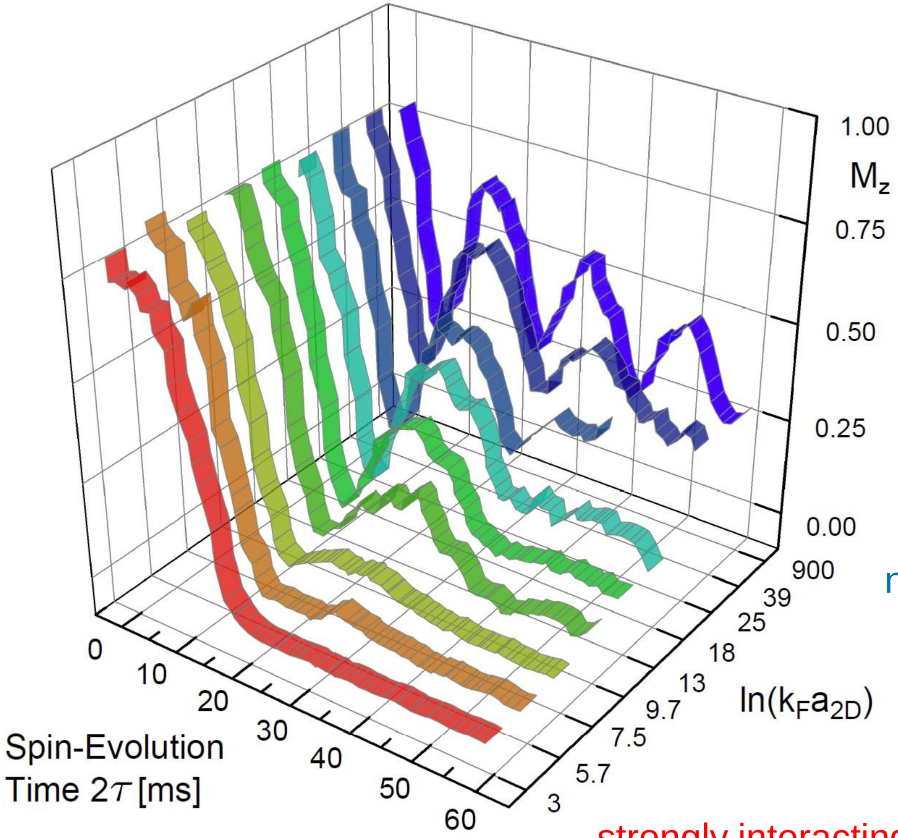
Damping and frequency shift



non-interacting

strongly interacting

M. Koschorreck et al., Nature Physics 9, 405 (2013).

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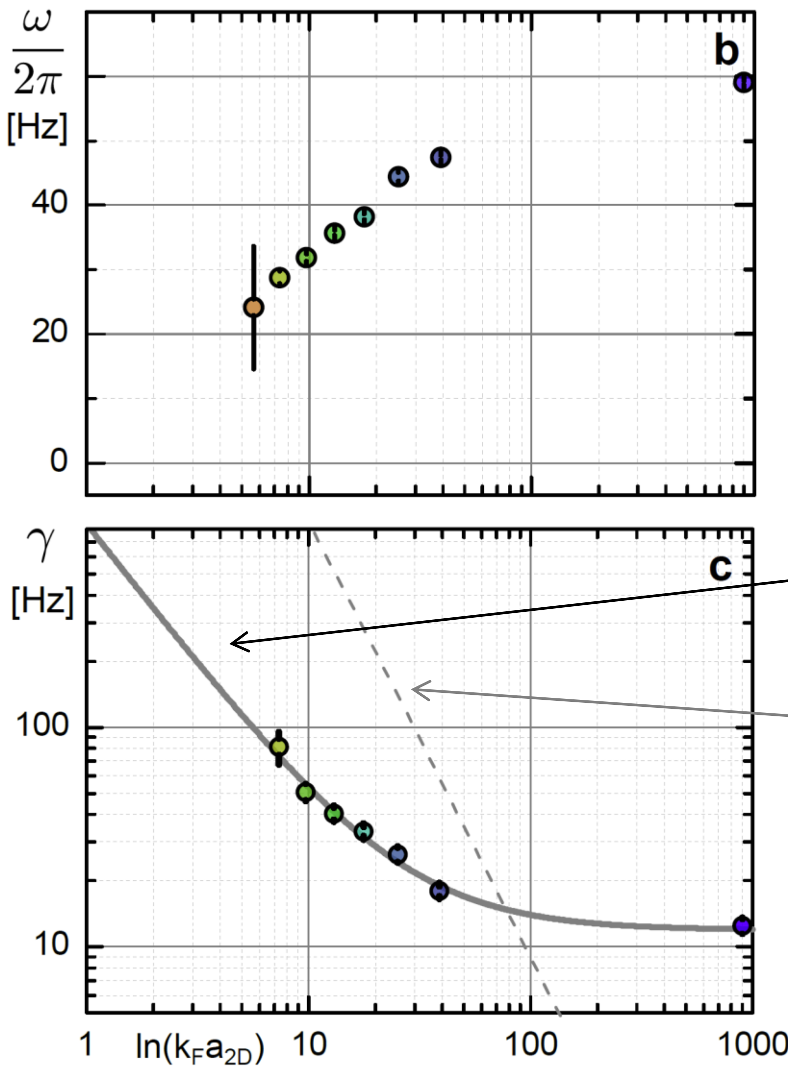
Damping and frequency shift



strongly interacting

non-interacting

M. Koschorreck et al., Nature Physics 9, 405 (2013).

Mode softening

Spin-dipole mode becomes overdamped in the strongly interacting regime [Stringari et al., PRA 2000].

Measured damping rate scales as $\sim 1/\ln(k_F a_{2D})$

Scattering rate $\sim 1/\ln(k_F a_{2D})^2$

Ramsey-dephasing rate: $\gamma_{Ramsey} \approx 1600$ Hz

Summary

Measurement of single-particle spectral function to observe

- Fermi liquid
- Pseudogap
- Polarons

Spin diffusion with $D \sim 0.01\ \hbar/m$

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Thanks

Lab tours tomorrow afternoon possible.
If you are interested, please contact me.

Fermi gases — L. Miller, D. Pertot, E. Cocchi, J. Drewes, J. Chan, F. Brennecke
A. Behrle, T. Harrison, K. Gao

Trapped ions — H.-M. Meyer, T. Ballance, R. Maiwald, M. Link

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