Two-dimensional atomic Fermi gases

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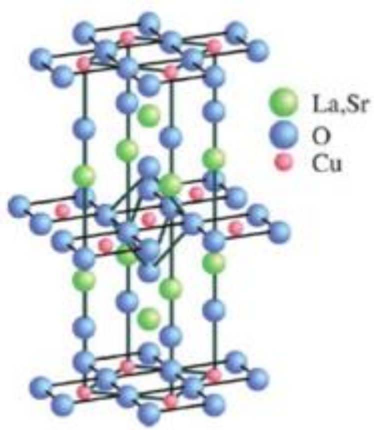
Two-dimensional Fermi gases

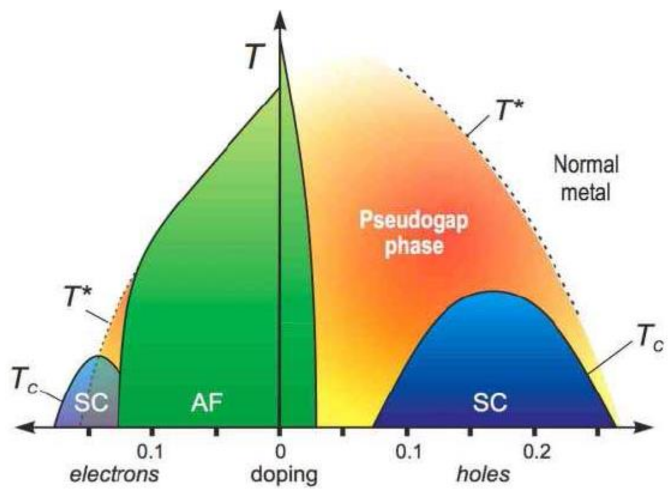
Two-dimensional gases: “the grand challenge” of condensed matter physics

High-T_c superconductors:

- After 25 years of research still many open questions

- Material is too complicated to understand even the basic mechanism





How can cold atoms help? …. Cleanliness, tunability, testing models.

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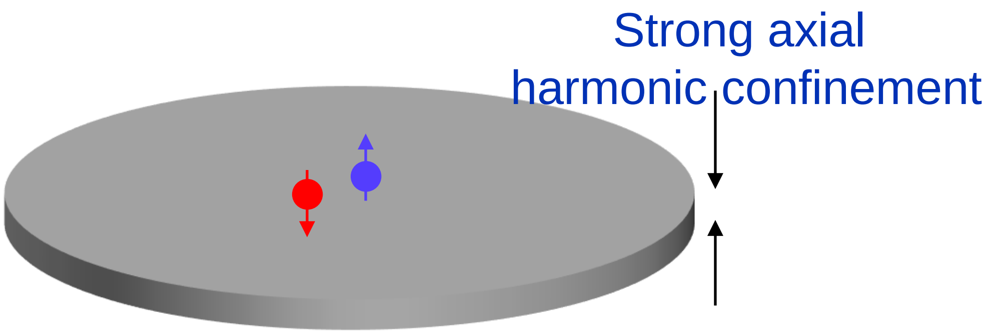
Cold atoms meets condensed matter

- Quasiparticle spectroscopy by momentum-resolved photoemission (aka ARPES)
- Spin transport and spin diffusion
- 2D Hubbard model

Quasi-2D geometry



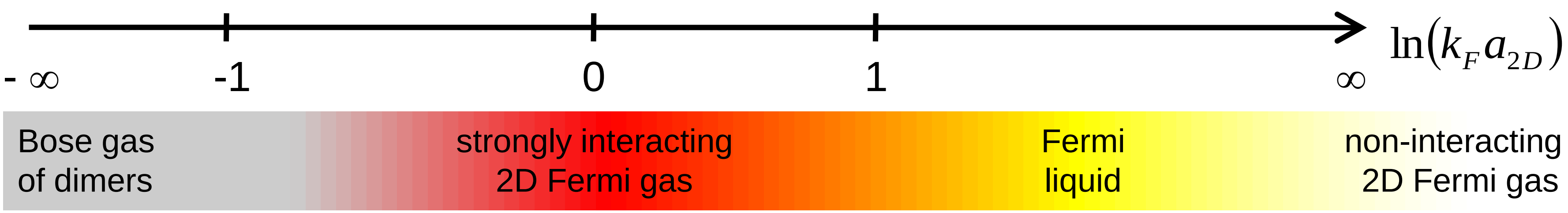
Conditions for 2D:

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

Spin ½ Fermi gas with contact interaction

Mean-field coupling constant in 2D
(Bloom 1975)

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

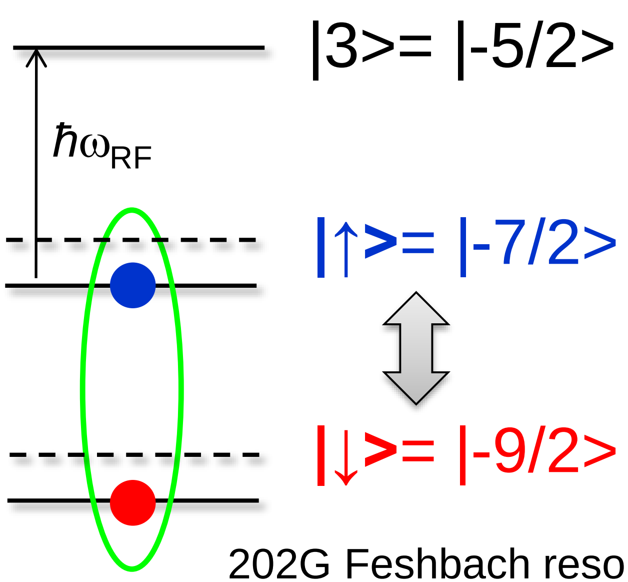


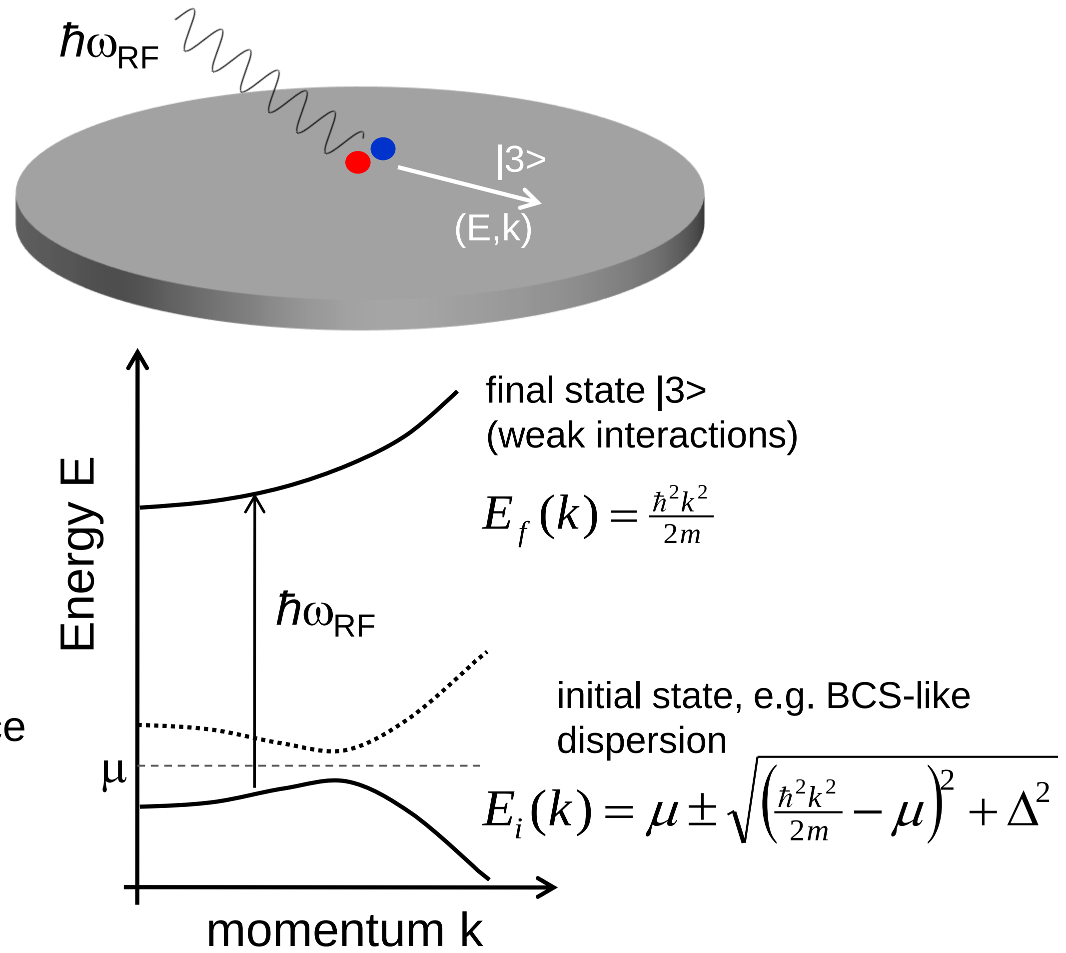
- BKT transition at $T_{BKT} \approx 0.1\ T_F$ in the strongly interacting regime
- T_{BKT} decays exponentially towards weak attractive interactions (as in 3D)

Theory: Bloom, P.W. Anderson, Randeria, Shlyapnikov, Devreese, Julienne, Duan, Zwerger, Giorgini, Sa de Melo, **...**
Experiment: B. Fröhlich et al., PRL 106, 105301 (2011), Inguscio, Grimm, Esslinger, Jochim, Moritz, Turlapov, Vale, Zwierlein

Quasiparticle spectroscopy

Momentum-resolved RF spectroscopy





ARPES in 3D Experiment: Jin

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

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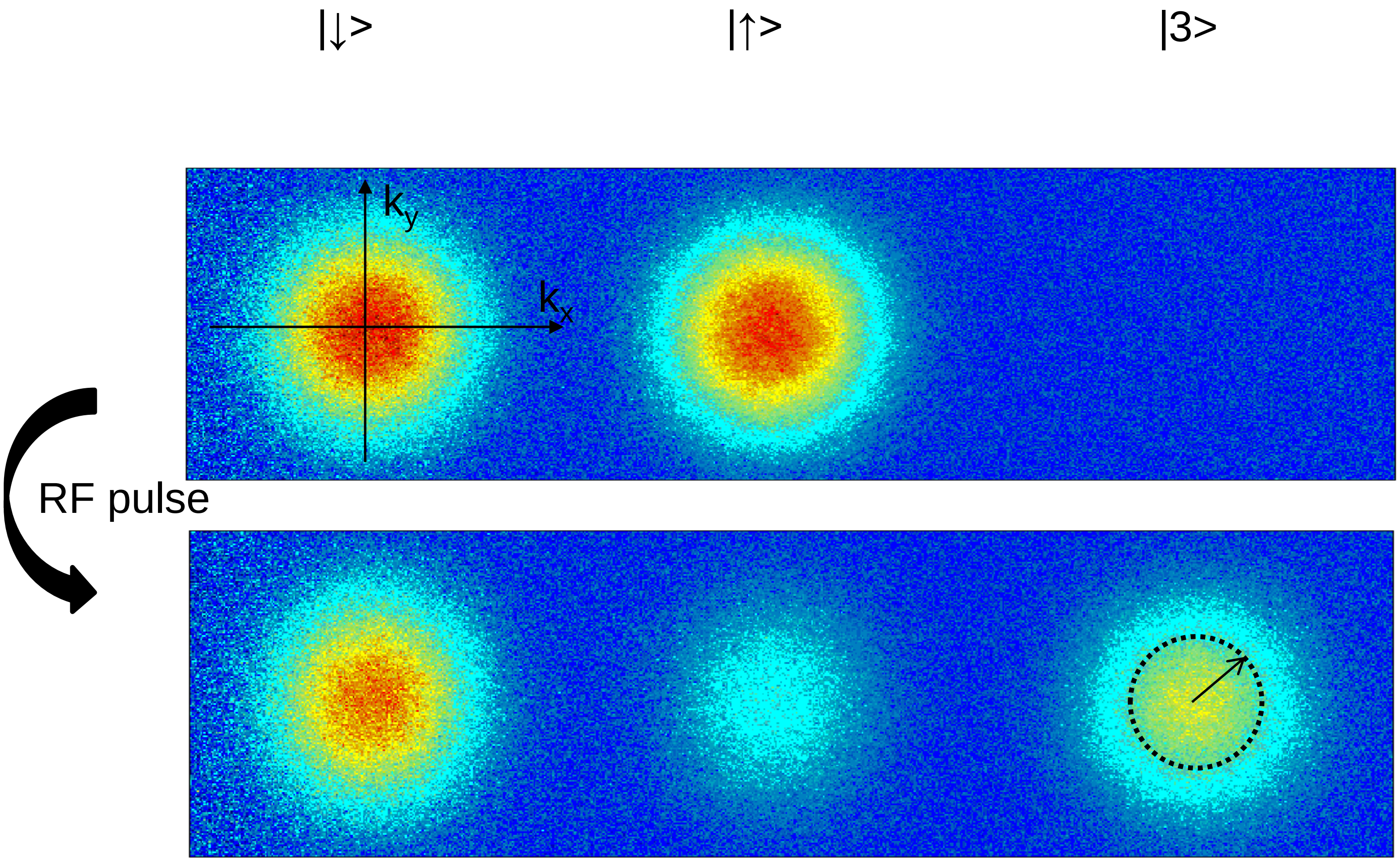
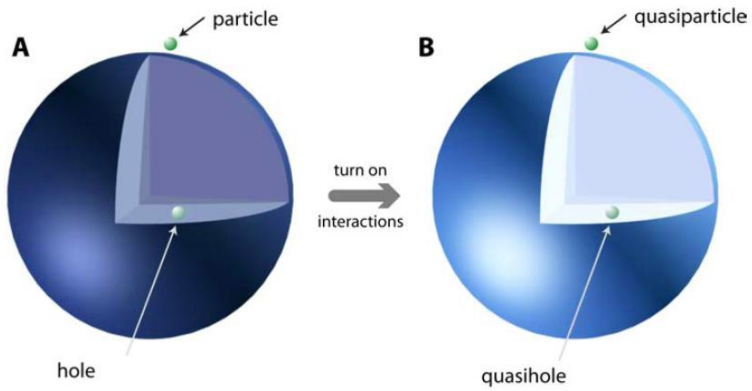
Experimental realization



$$k = \sqrt{k_x^2 + k_y^2}$$

Spin-balanced Fermi liquid



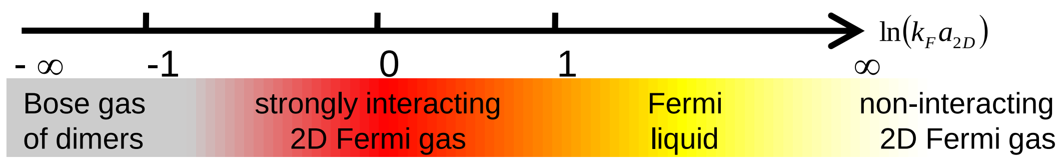
- Landau-Fermi liquid
  quasi-particles are fermionic
- finite lifetime $1/t \sim (k-k_F)^2$ (long-lived near the Fermi surface)
- effective mass: $m^*/m > 1$, depending on interaction strength

<u>Fermi liquid:</u>

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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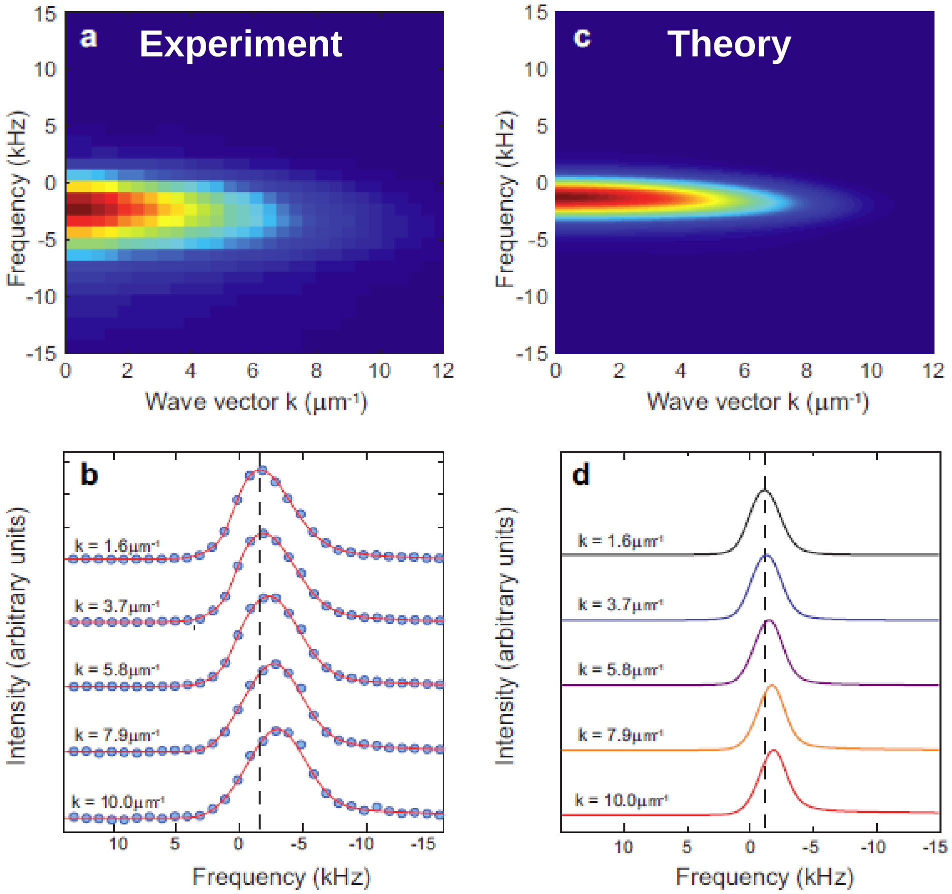
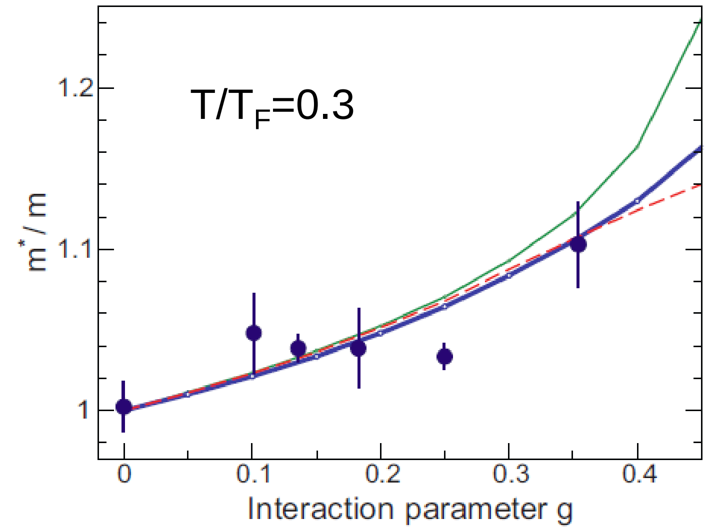
Comparison with theory

Single-particle spectral function



Effective mass parameter



B. Fröhlich et al., Phys. Rev. Lett. 109, 130403 (2012)

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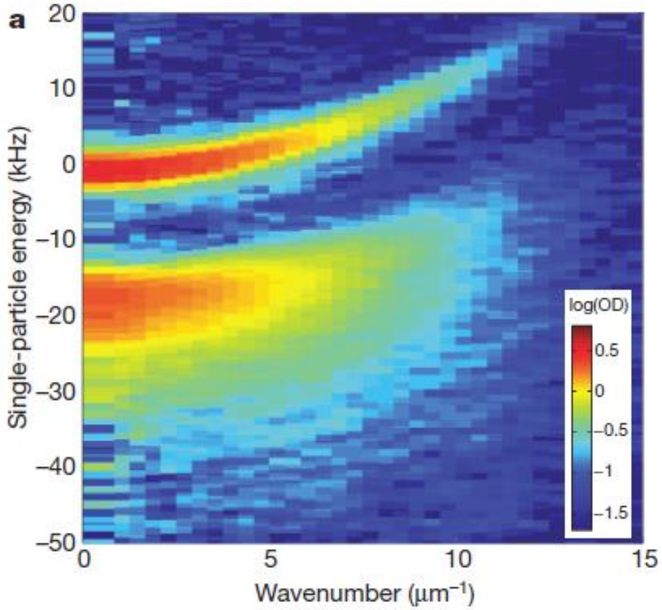
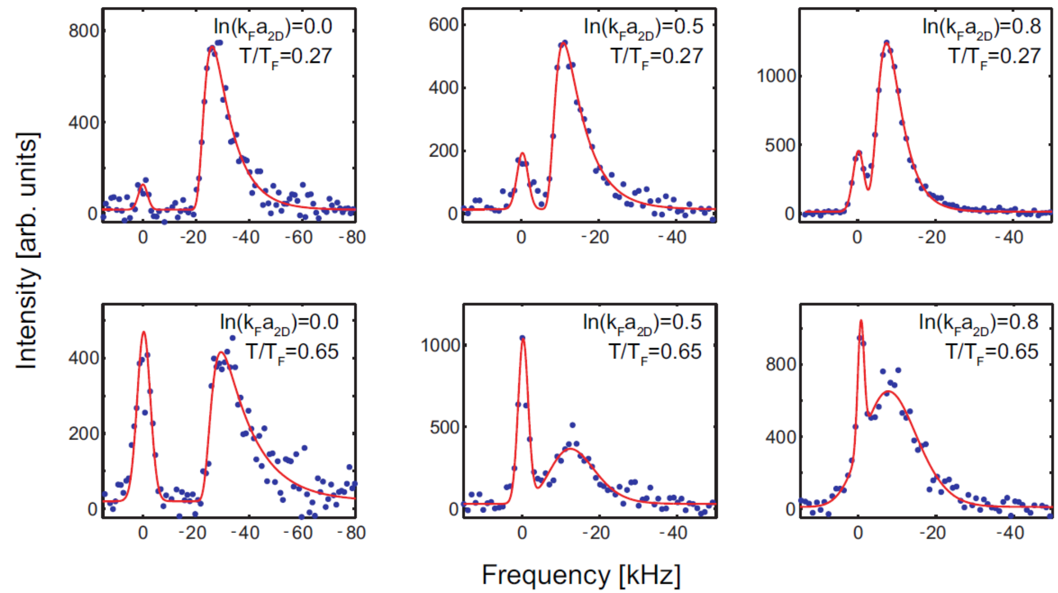
Strong interactions: Pairing pseudogap

Single-particle spectral function

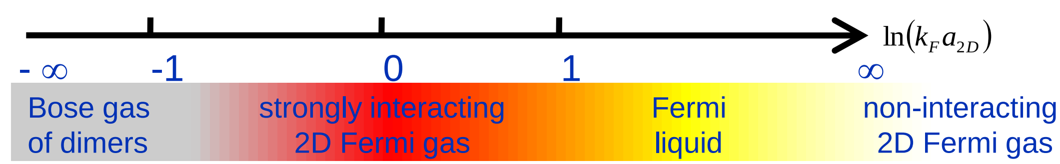




E_F, $k_B T < \hbar\omega$ (two-dimensional)

$E_B > k_B T$ (pairing)

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



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

Observation of polaron quasiparticles: M. Koschorreck et al., Nature 485, 619 (2012)

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Spin transport

Spin diffusion

Spin diffusion $D = \frac{v}{n\sigma}$

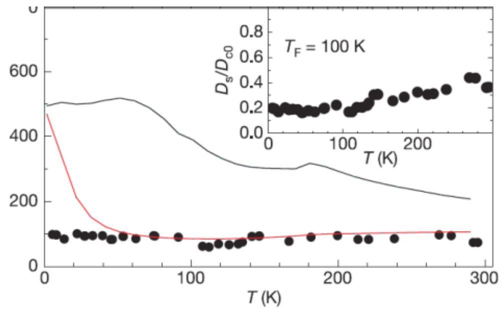
Fermi gas at unitarity:

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

Quantum limit of diffusivity

Semiconductor nanostructures

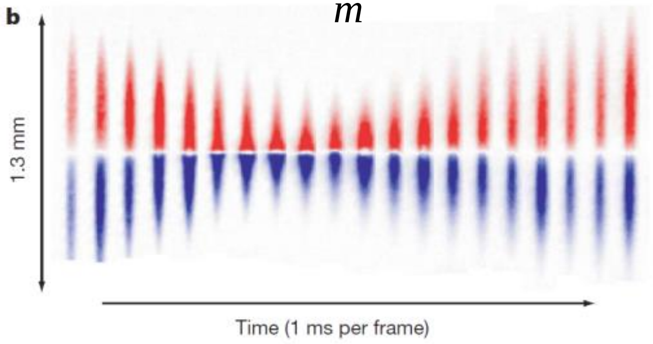
$$D \approx 10^2 \frac{\hbar}{m}$$



Weber et al., Nature (2005)

3D Fermi gases at unitarity

$$D \approx 6.3 \frac{\hbar}{m}$$



Zwierlein group, Nature (2011)

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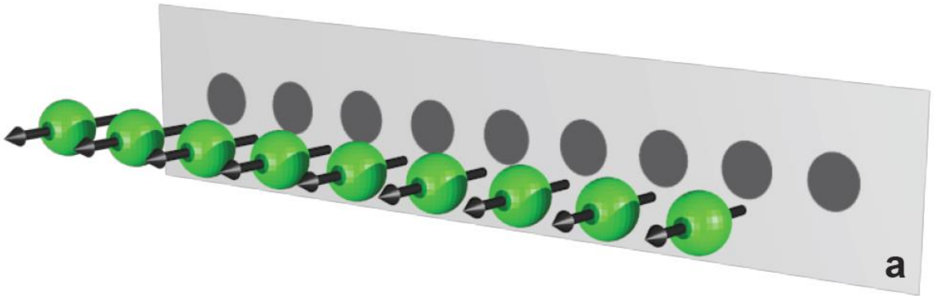
Spin dynamics

transversely
polarized
Fermi gas



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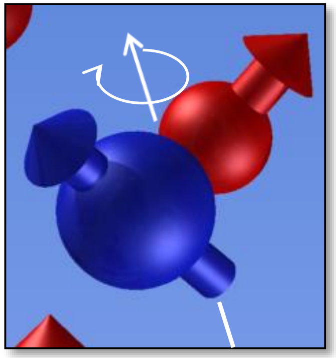
Spin-spin interaction

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

absent in cold atom systems

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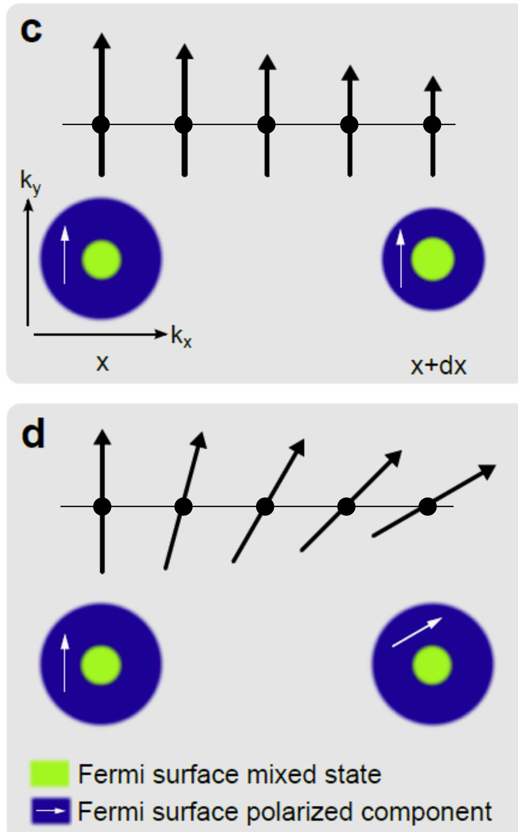
Longitudinal vs. transverse diffusion

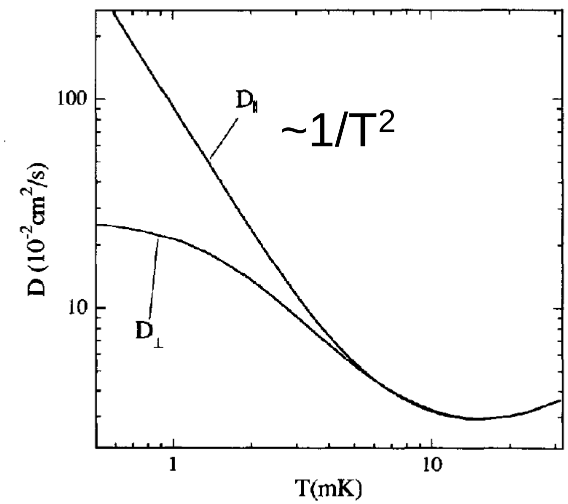
Magnetisation: $\vec{M}(\vec{r},t) = M(\vec{r},t)\,\vec{p}(\vec{r},t)$

longitudinal

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

transverse





Mullin & Jeon (1992)

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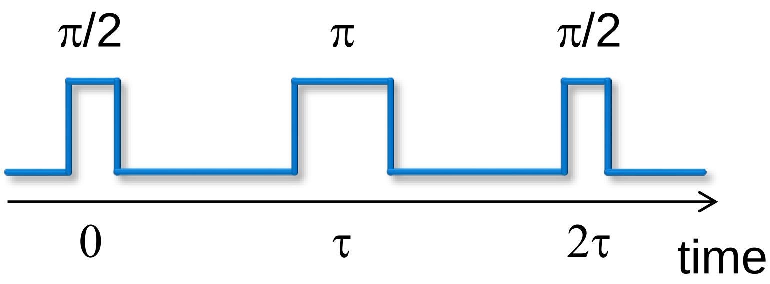
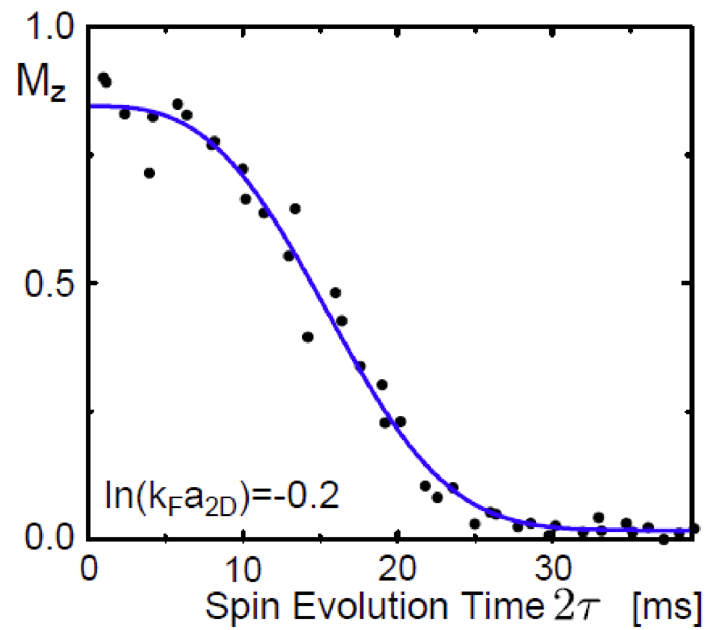
Spin-echo technique



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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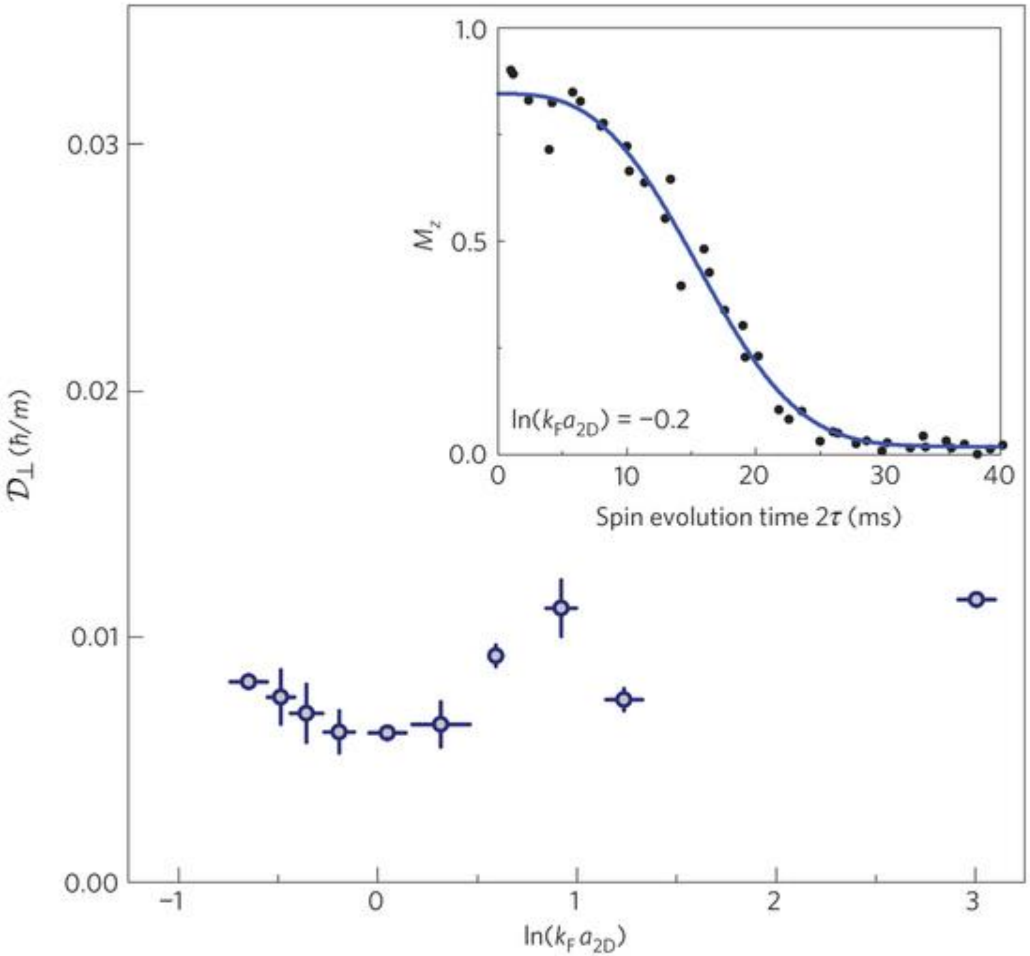
Spin diffusion in the strongly interacting regime



Smallest spin diffusion constant ever measured: 0.07(1) ħ/m.

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

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Implications of D< ħ/m?

Spin diffusion $D = \frac{v}{n\sigma} = v\, l_{MFP}$

$v = \hbar k_F / m$

$n \approx k_F^2$

Particle separation

Spin diffusivity D < ħ/m implies $l_{MFP} < n^{1/D} = d$

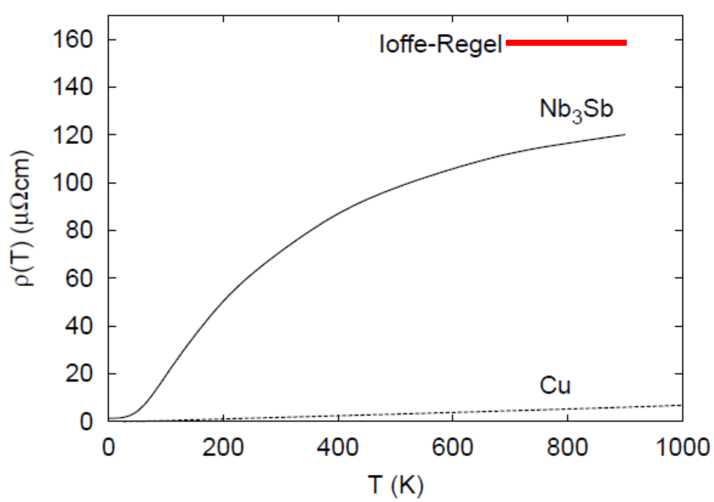
Resistivity of metals (semiclassically): $\rho = \frac{3\pi^2\hbar}{e^2 k_F^2 l_{MFP}}$

Mean-free path for collisions with phonons or electrons

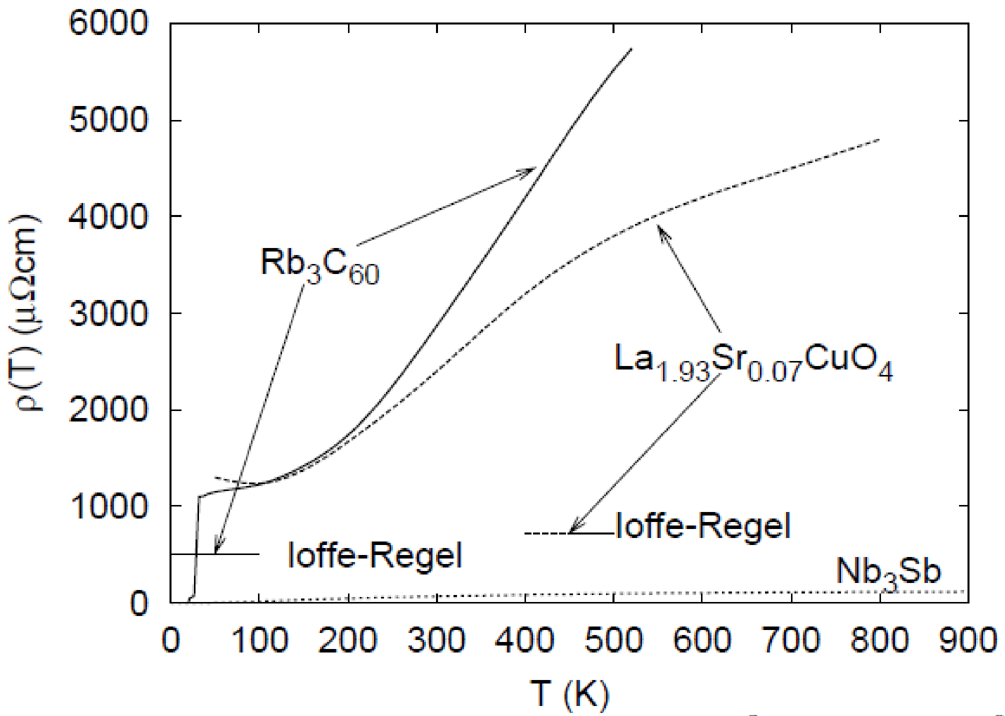
As function of temperature: $l_{MFP} \sim 1/T$

BUT: **Ioffe-Regel criterion** $l_{MFP} > d$

→ Saturation of resistivity



Strongly correlated materials



Possible ideas for resistivity in solids:

- Violation of quasiparticle picture [Nature 405, 1027-1030 (2000)]
- Modification of kinetic theory by correlation effects du to stong interactions [PRB 66, 205105 (2002)]

For cold atoms → ?

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Hubbard model

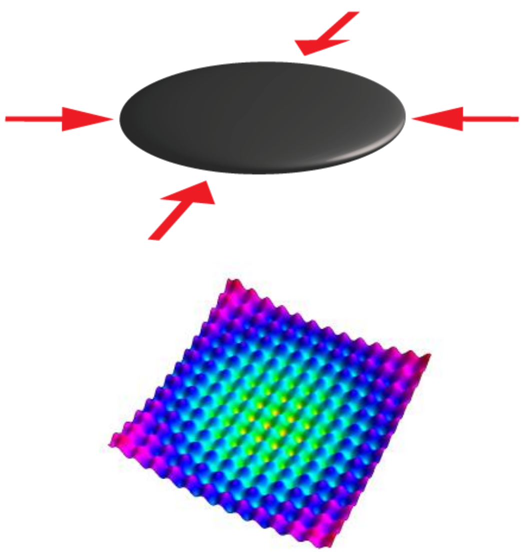
Hubbard model in two dimensions

Simplest interacting lattice model

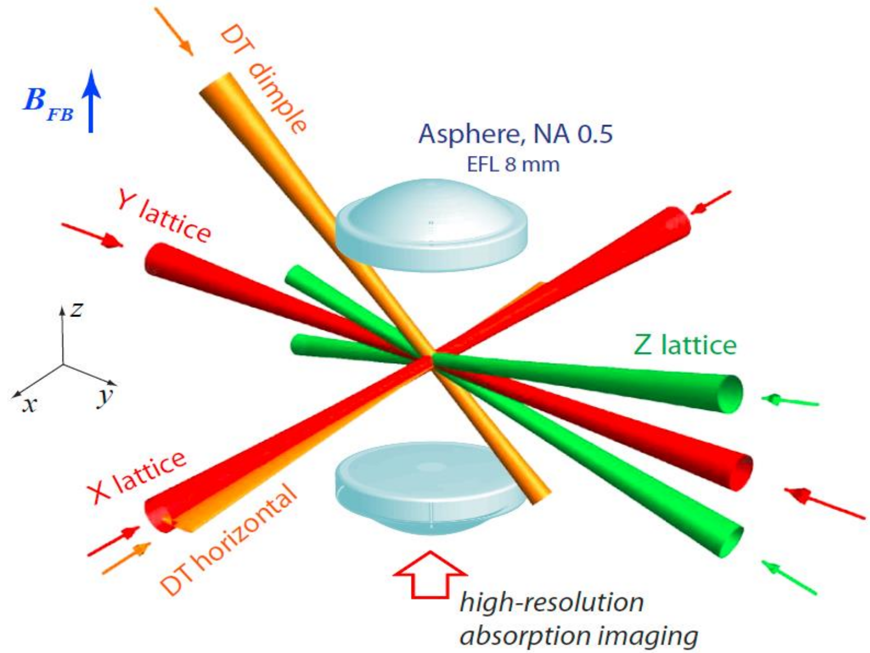
$$H = -t \sum_{<ij>\sigma} [c^{+}_{i\sigma} c_{j\sigma} + c^{+}_{i\sigma} c_{j\sigma}] + U \sum_{i} n_{i\uparrow} n_{i\downarrow} + \sum_{i\sigma} (V_i - \mu)\, n_{i\sigma}$$

tunneling — on-site interaction — trap + chem. pot.

Experimental realization



High-resolution imaging:
Diffraction limit ~ 2 lattice sites



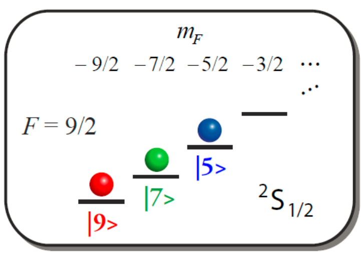
With atoms: Excellent tunability

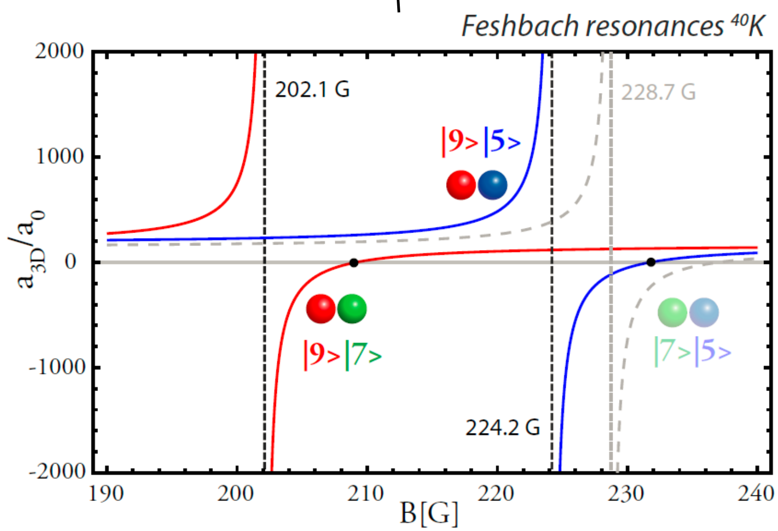
$$H = -t \sum_{<ij>\sigma} [c^{+}_{i\sigma} c_{j\sigma} + c^{+}_{i\sigma} c_{j\sigma}] + U \sum_{i} n_{i\uparrow} n_{i\downarrow} + \sum_{i\sigma} (V_i - \mu)\, n_{i\sigma}$$

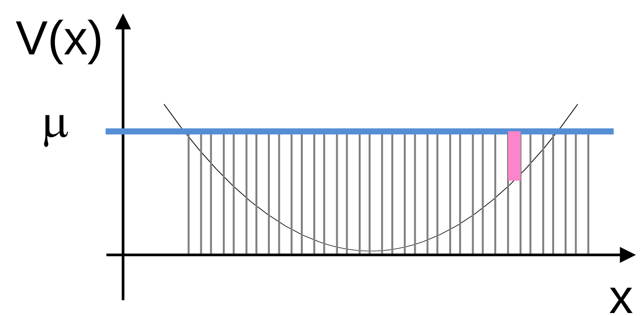
tunneling — on-site interaction — trap + chem. pot.

Depends on lattice depth (~ laser intensity)

Inhomogeneity of the trap -> convenient access to phase diagram







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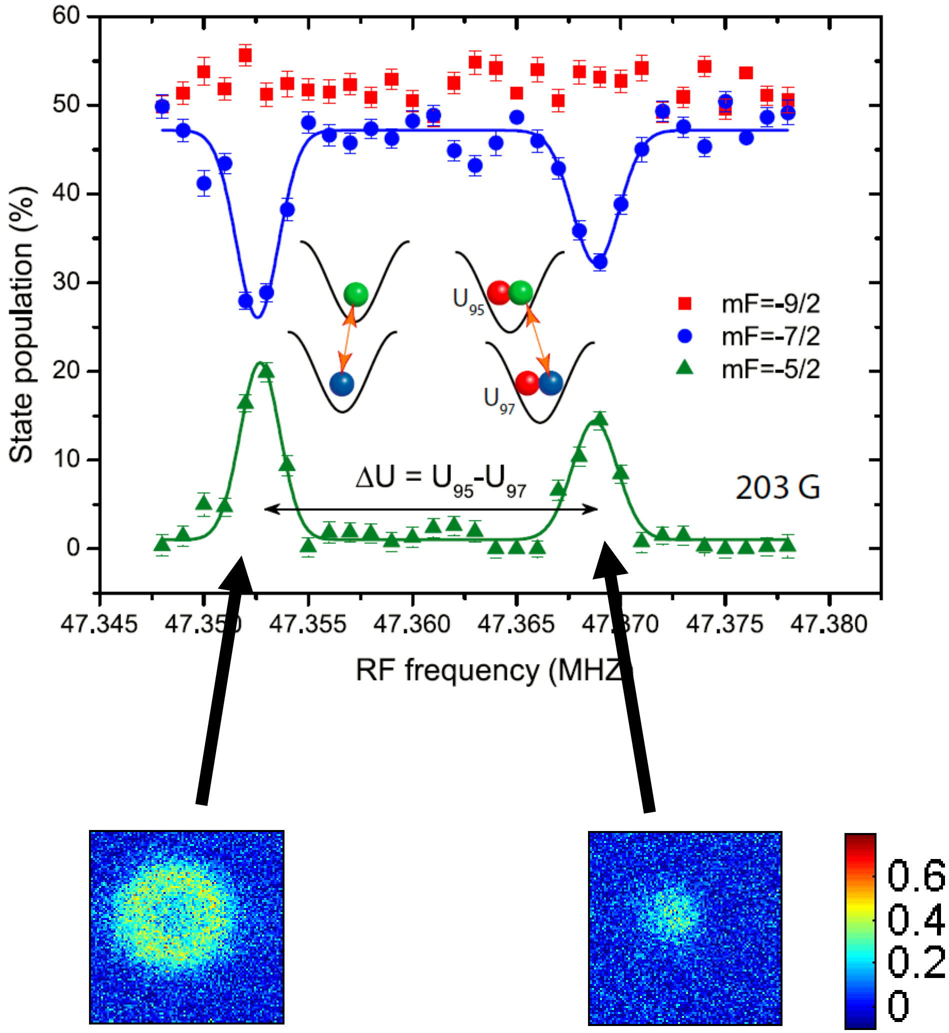
RF spectroscopy in the lattice



Singly occupied sites

Doubly occupied sites

- resolve single 2D layer
- spectroscopically separate singly and doubly occupied lattice sites

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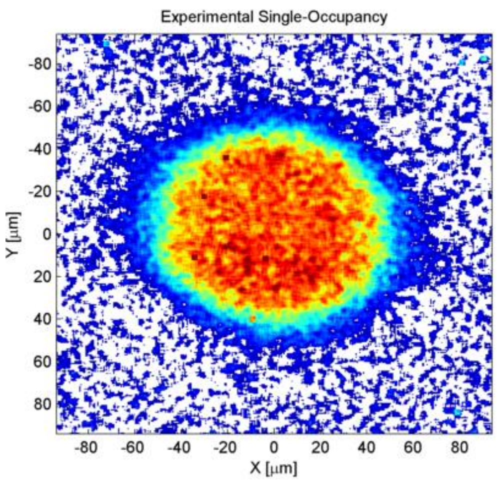
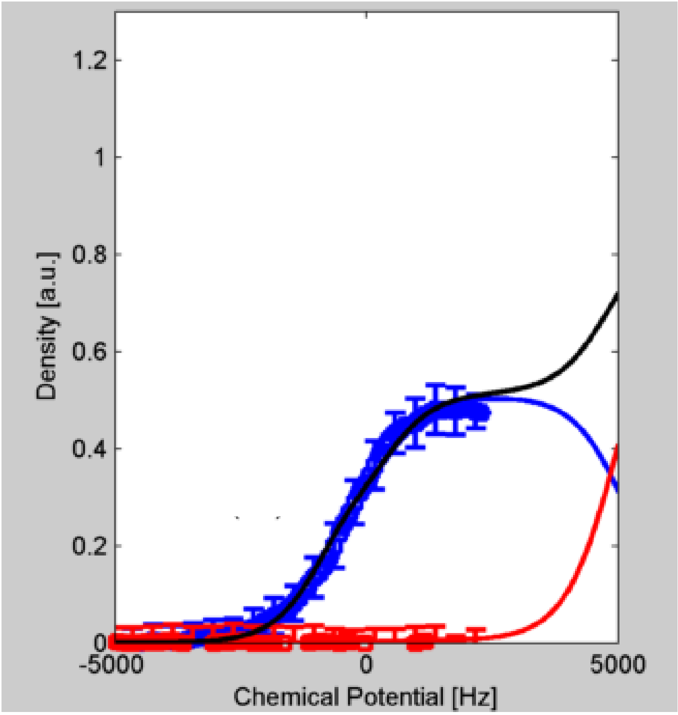
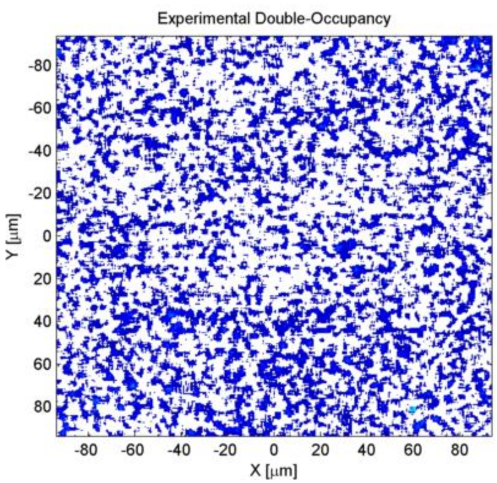
Two-dimensional Mott insulator



Singly occupied lattice sites

Density vs. chemical potential





Doubly occupied lattice sites

T/t = 3, U/t ~ 30

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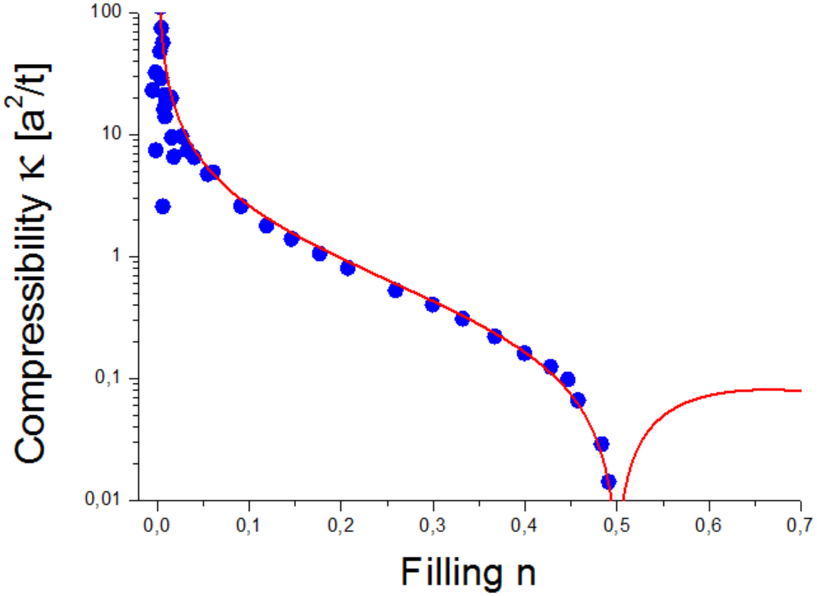
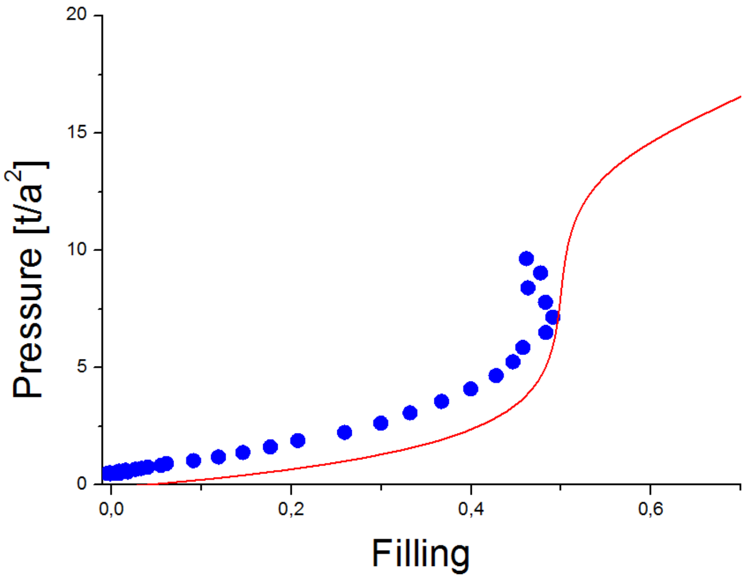
Thermodynamic quantities

Compressibility $\kappa = \frac{1}{n^2}\frac{\partial n}{\partial \mu}$

Pressure $P = \int_{-\infty}^{\mu} n(\mu')\ d\mu'$





Theory curves: High-temperature series expansion (2nd order)
T/t = 3, U/t ~ 30

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Summary

- Quasiparticle spectroscopy of 2D Fermi gases
- Very low spin diffusion $D \sim 0.07\ \hbar/m$ in a strongly interacting 2D Fermi gas
- In-situ measurement of thermodynamics properties of 2D Hubbard model (-> equation of state)

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Thanks

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Trapped ions T. Ballance, L. Carcagni, M. Link, H.-M. Meyer, R. Maiwald, J. Silver

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