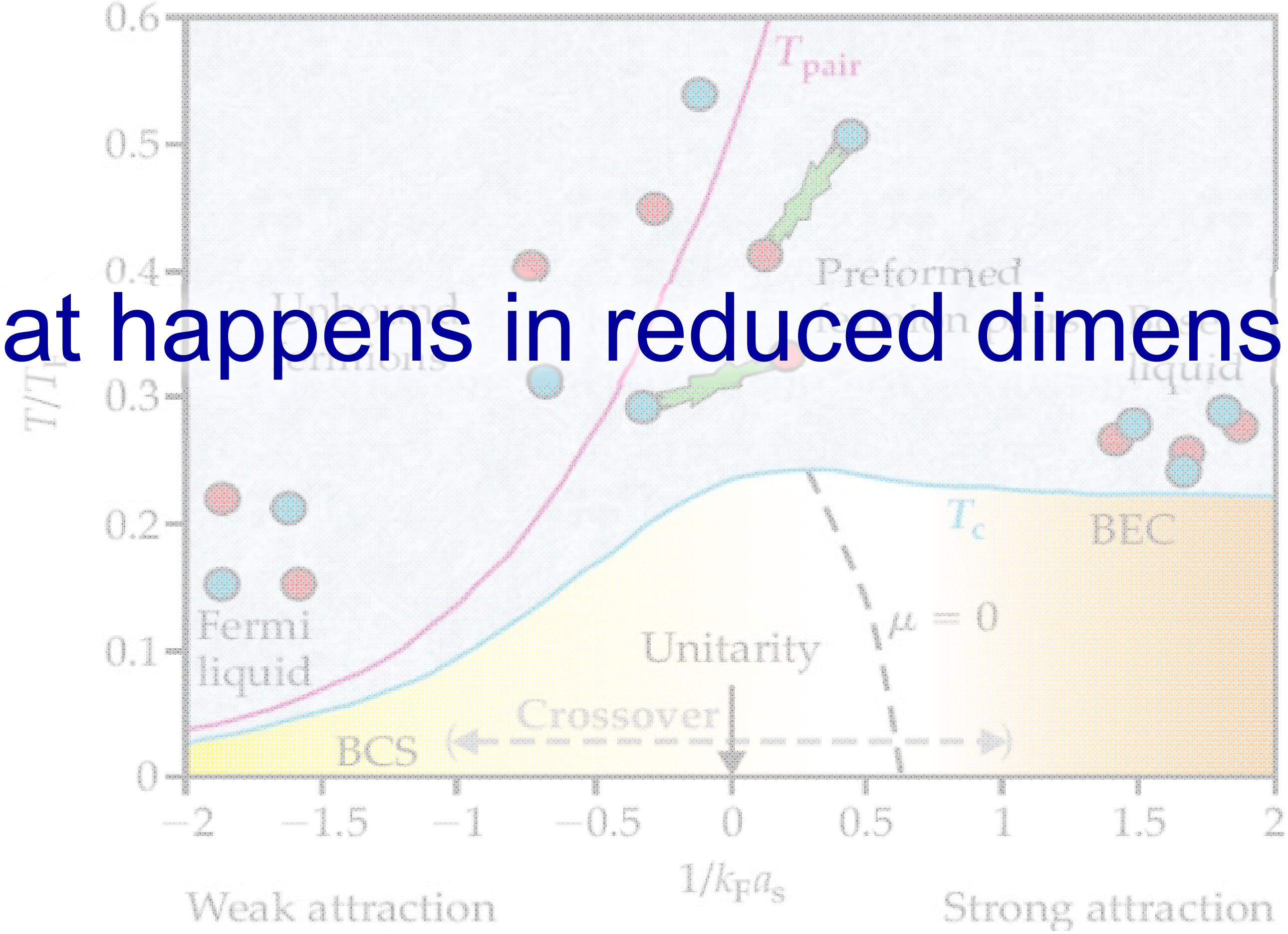
Two-dimensional Fermi gases

Michael Köhl

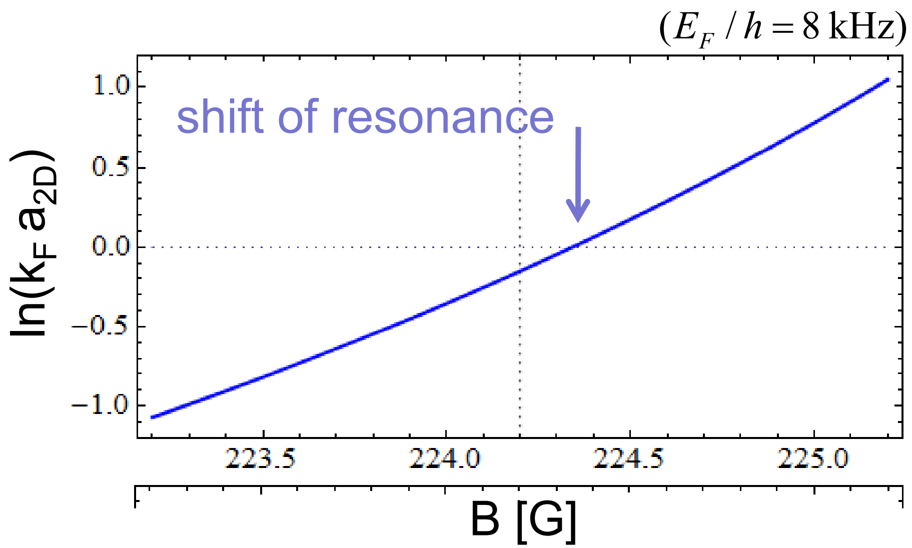
BEC-BCS crossover



What happens in reduced dimensions?

Sa de Melo, Physics Today (2008)

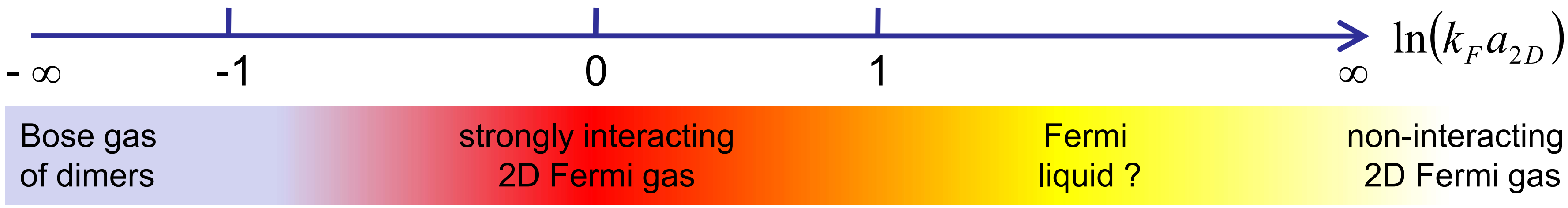
A very short theory overview for 2D



Mean-field coupling in 2D
(Bloom 1975)

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

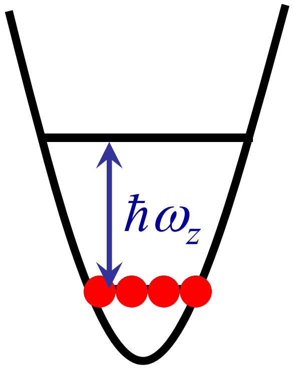
$$\left(g_{3D} = \frac{4\pi\hbar^2}{m} a_{3D} \right)$$



- 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, **...**

Quasi-2D geometry



<u>Conditions for 2D</u>

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

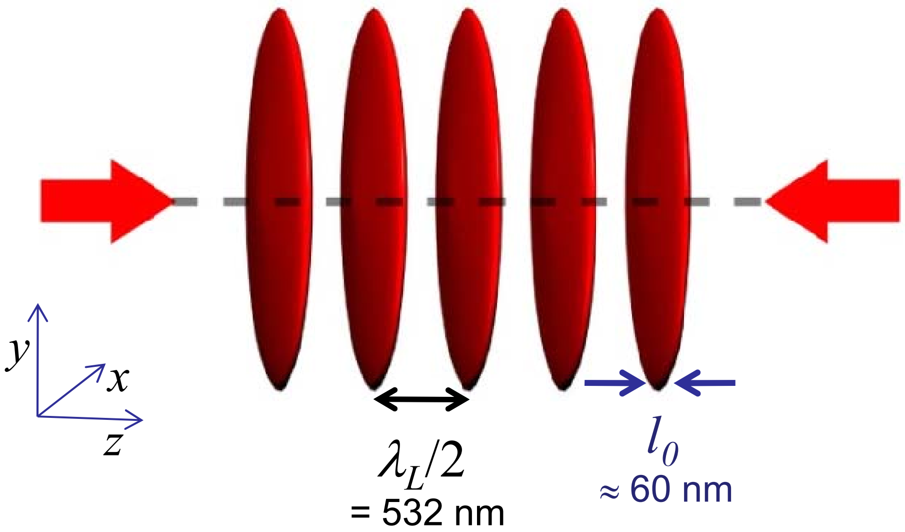
Strong axial confinement required

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

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

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

Optical lattice: array of 2D quantum gases

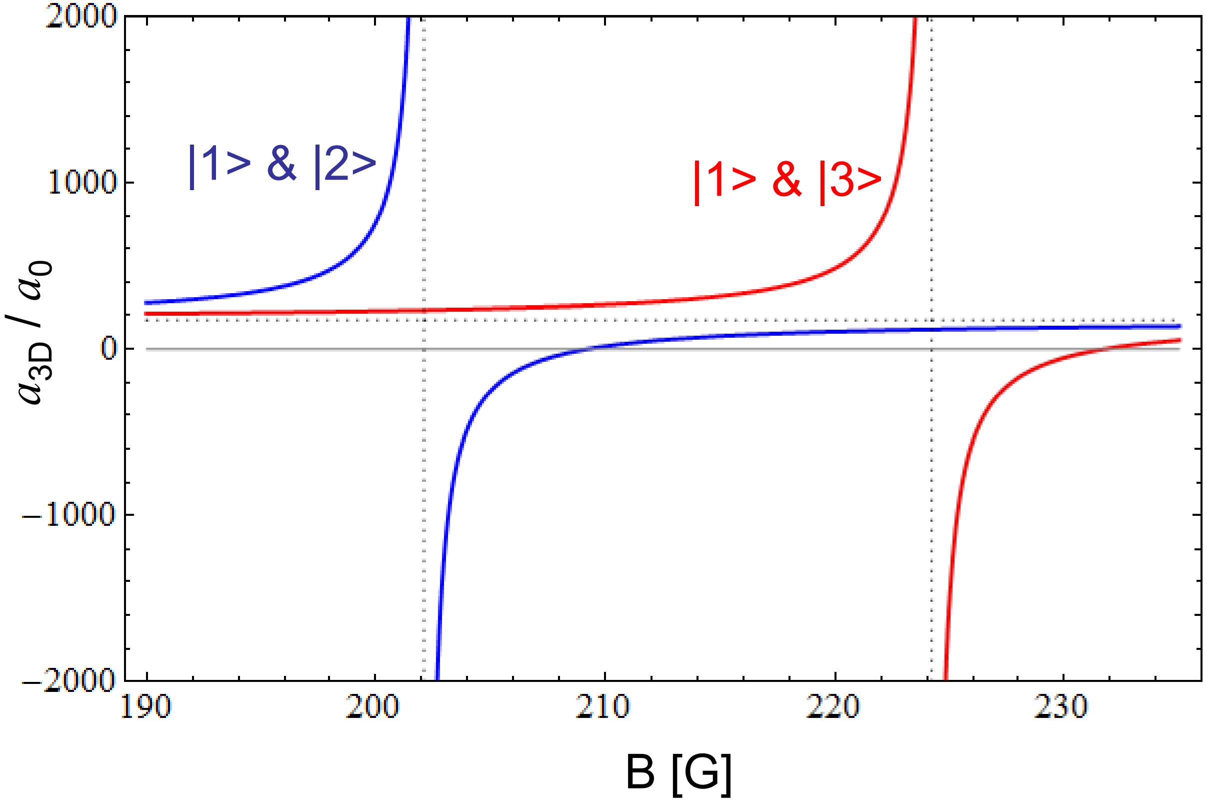


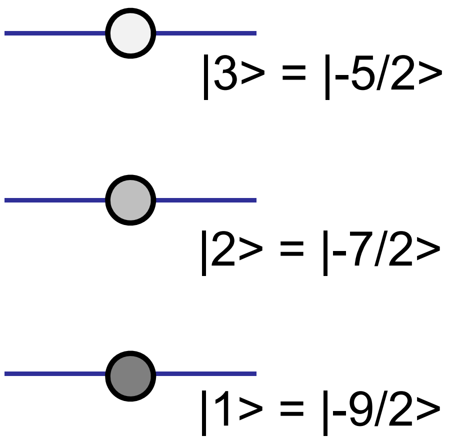
- lattice depth 83 E_{rec}
- hopping rate 0.002 Hz
- ~ 2000 Fermions per spin state
- ~ 30 "pancakes" / layers

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

Preparing strongly interacting 2D systems

Feshbach resonances in ^{40}K

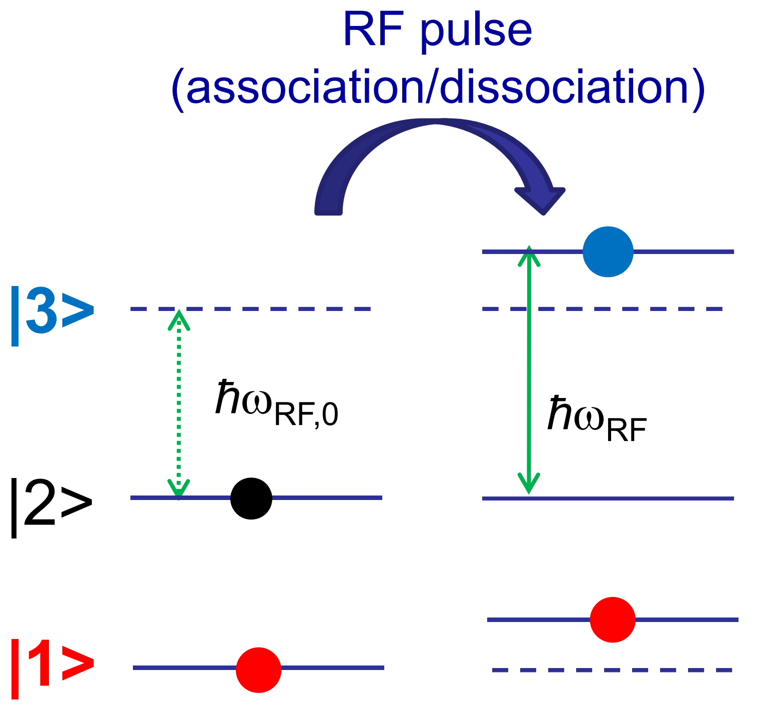




|2> & |3>

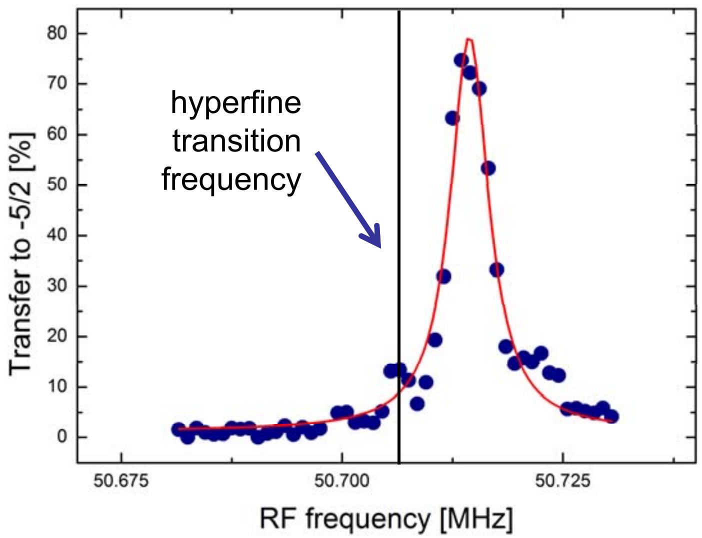
$$a_{BG} = 174 a_0$$

Radio-frequency spectroscopy



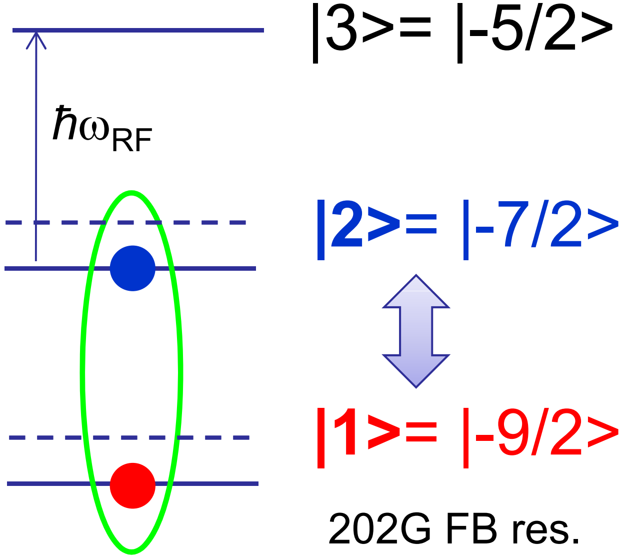
e.g. repulsively
interacting gas

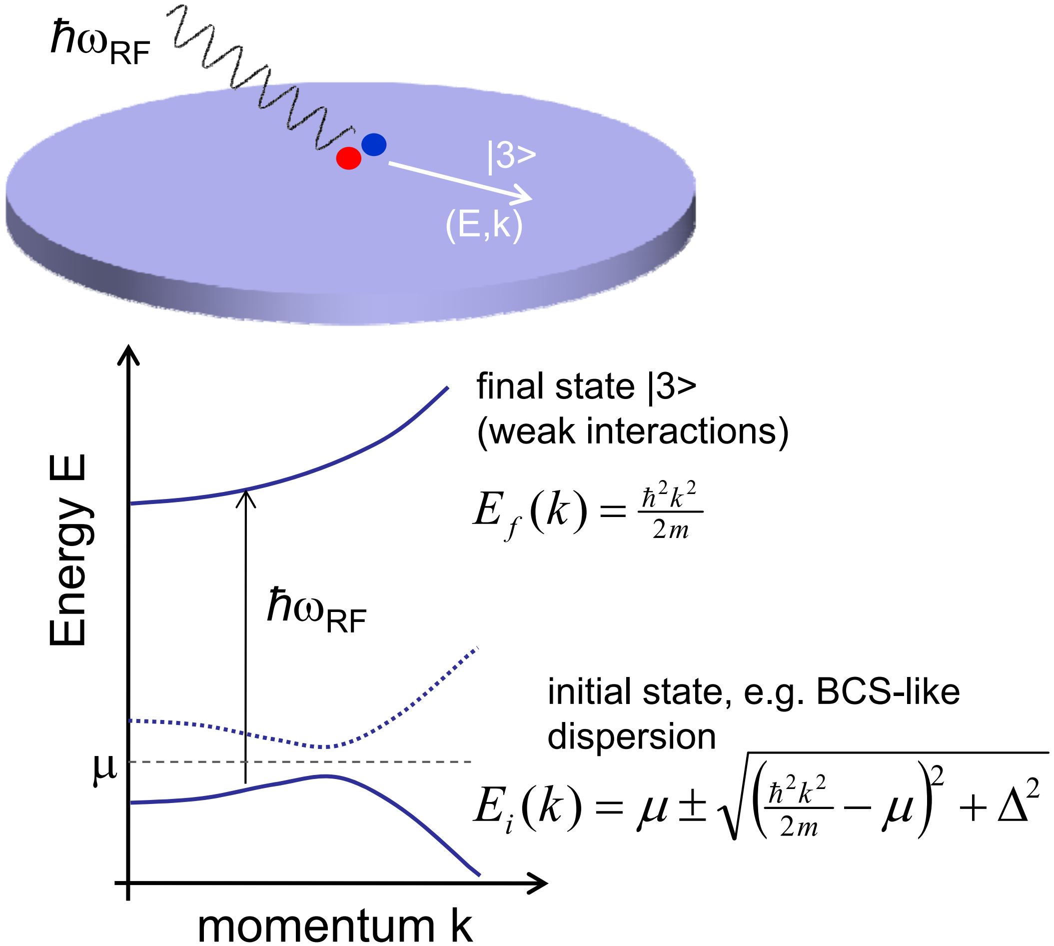
|1> & |3>
224G FB res.



3D: Regal et al., Nature (2003)
2D: B. Fröhlich, M. Feld, E. Vogt, M. Koschorreck, W. Zwerger, MK, PRL 106, 105301 (2011)

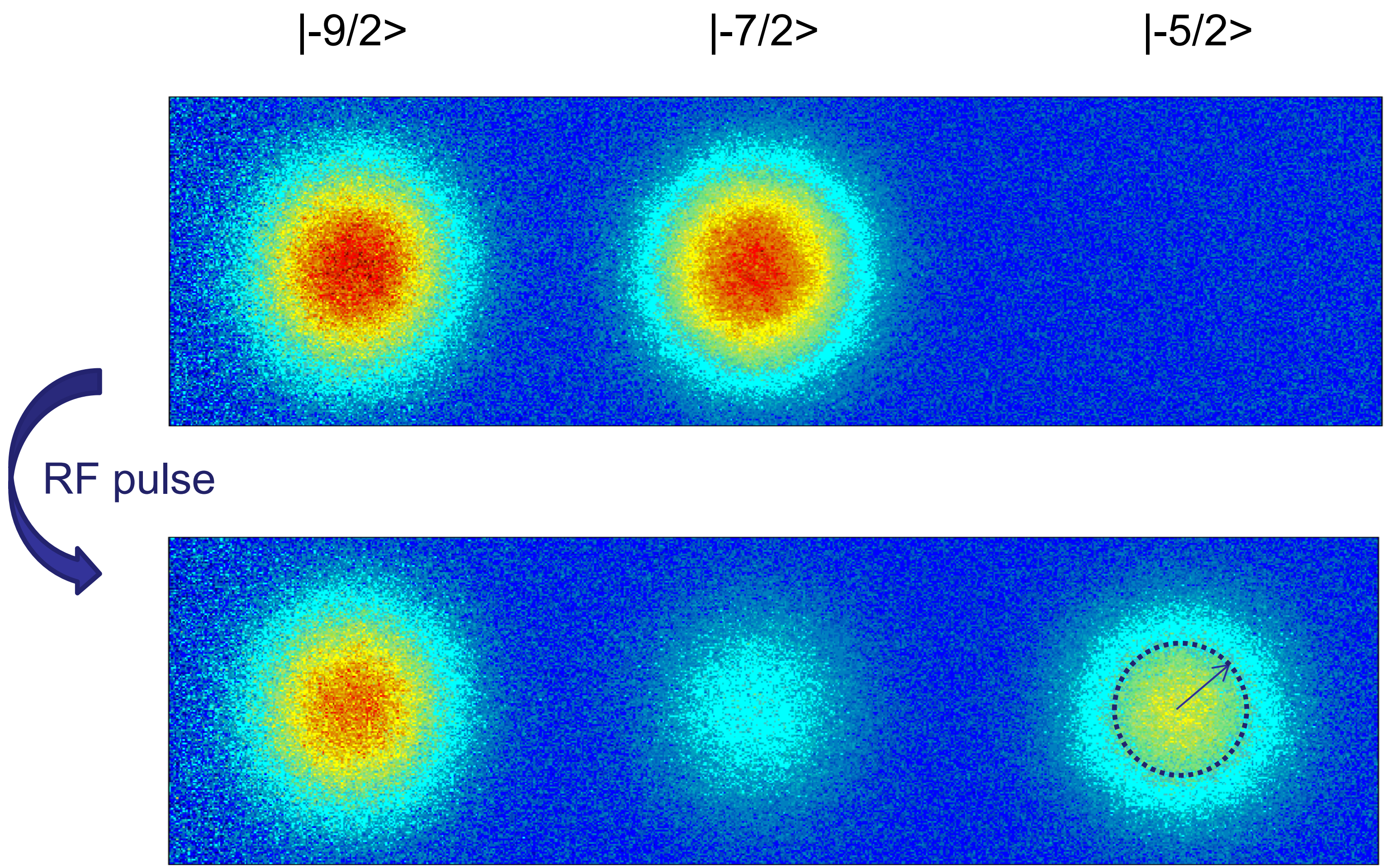
Momentum-resolved RF spectroscopy *("ARPES")*





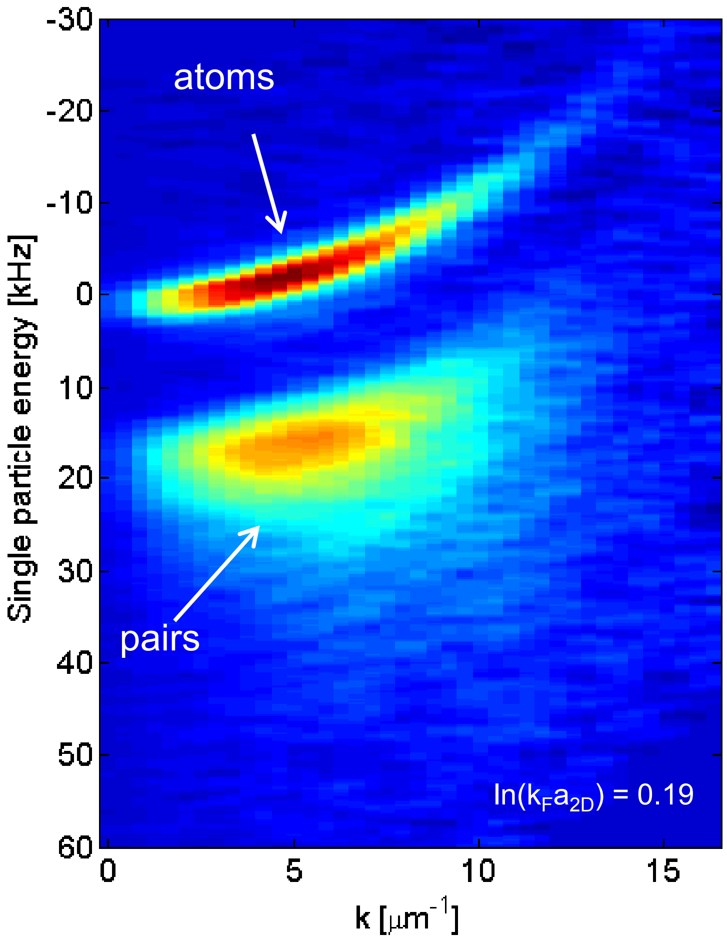
ARPES in 3D Experiment: Jin *Theory:* Georges, Strinati, Levin, Ohashi, Zwerger, Drummond, **...**

Population of the spin states



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

Single-particle spectral function



"BCS" side

$\ln(k_F a_{2D}) > 0$, $E_B < E_F$

no isolated dimers, attractive interactions, pairs are huge compared to inter-particle spacing

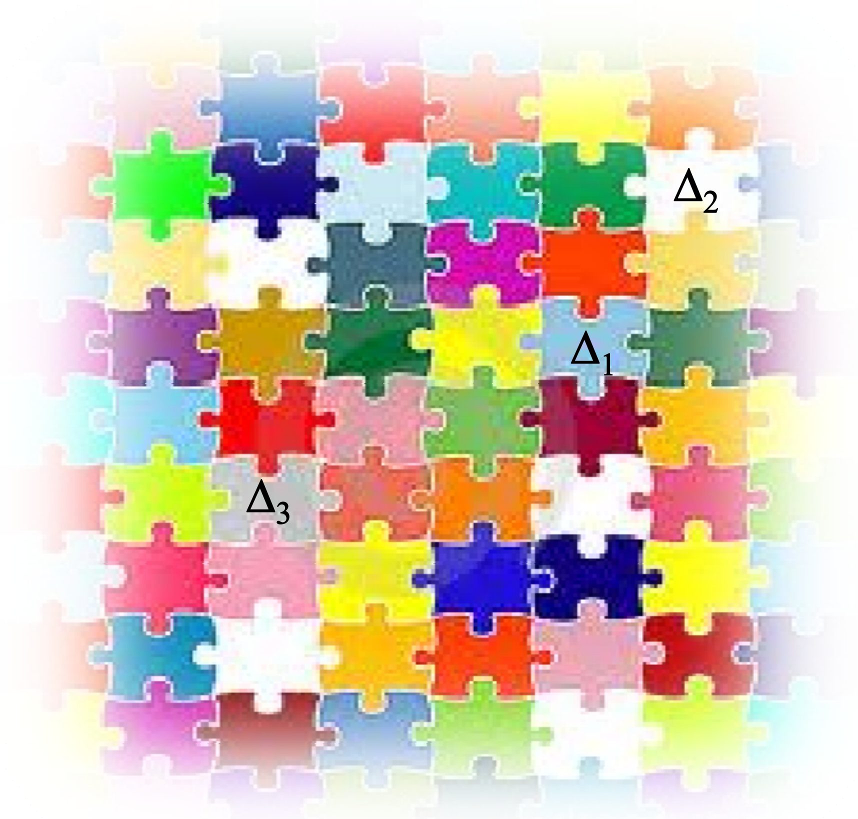
"Condensation energy" of Cooper pairs
(MF theory, T=0, Randeria 1989)

$$E_{th}(k=0) = \frac{\Delta^2}{2E_F} = E_B$$

Only the case in 2D
(in 3D: $E_B=0$ on the BCS side)

Pairing pseudogap phenomenon

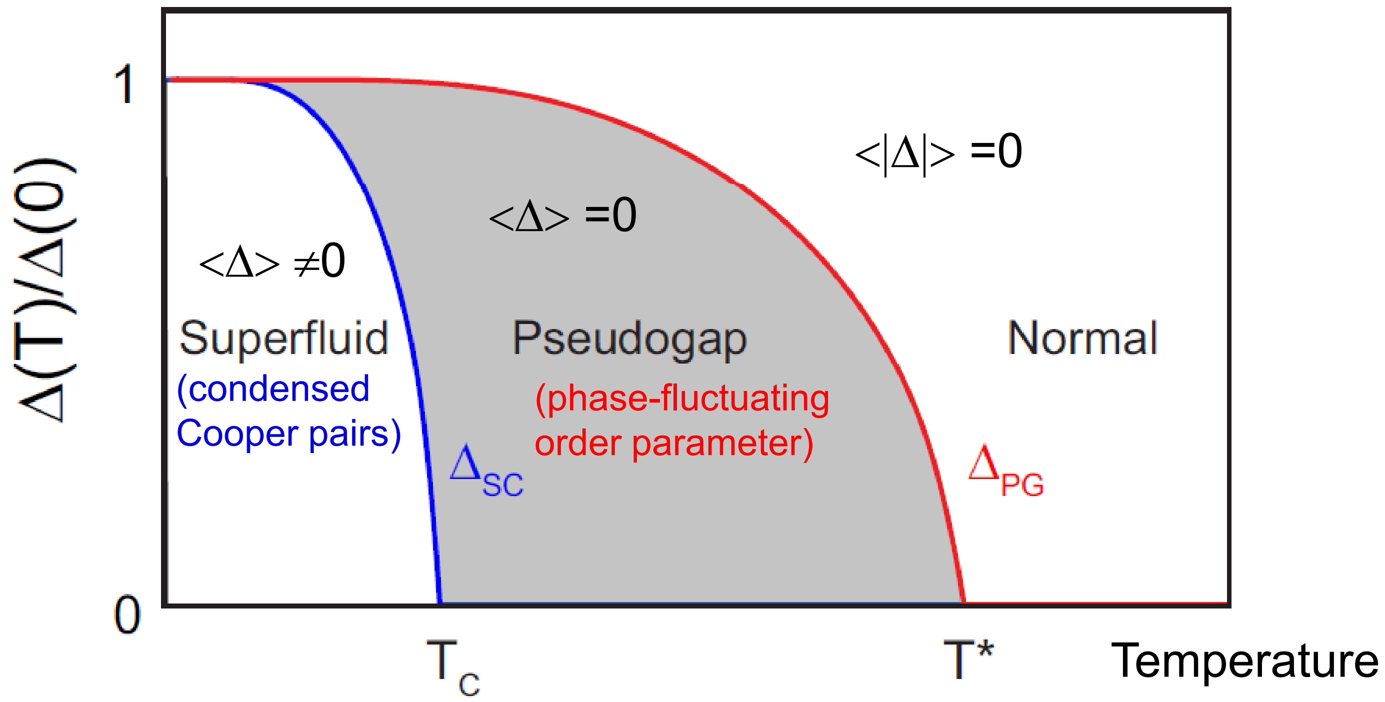
complex order parameter $\Delta(T,x) = |\Delta(T,x)| e^{i\vartheta(T,x)}$



spatial average $<\Delta> = 0$ but $<|\Delta|> \;> 0$

Pairing pseudogap phenomenon

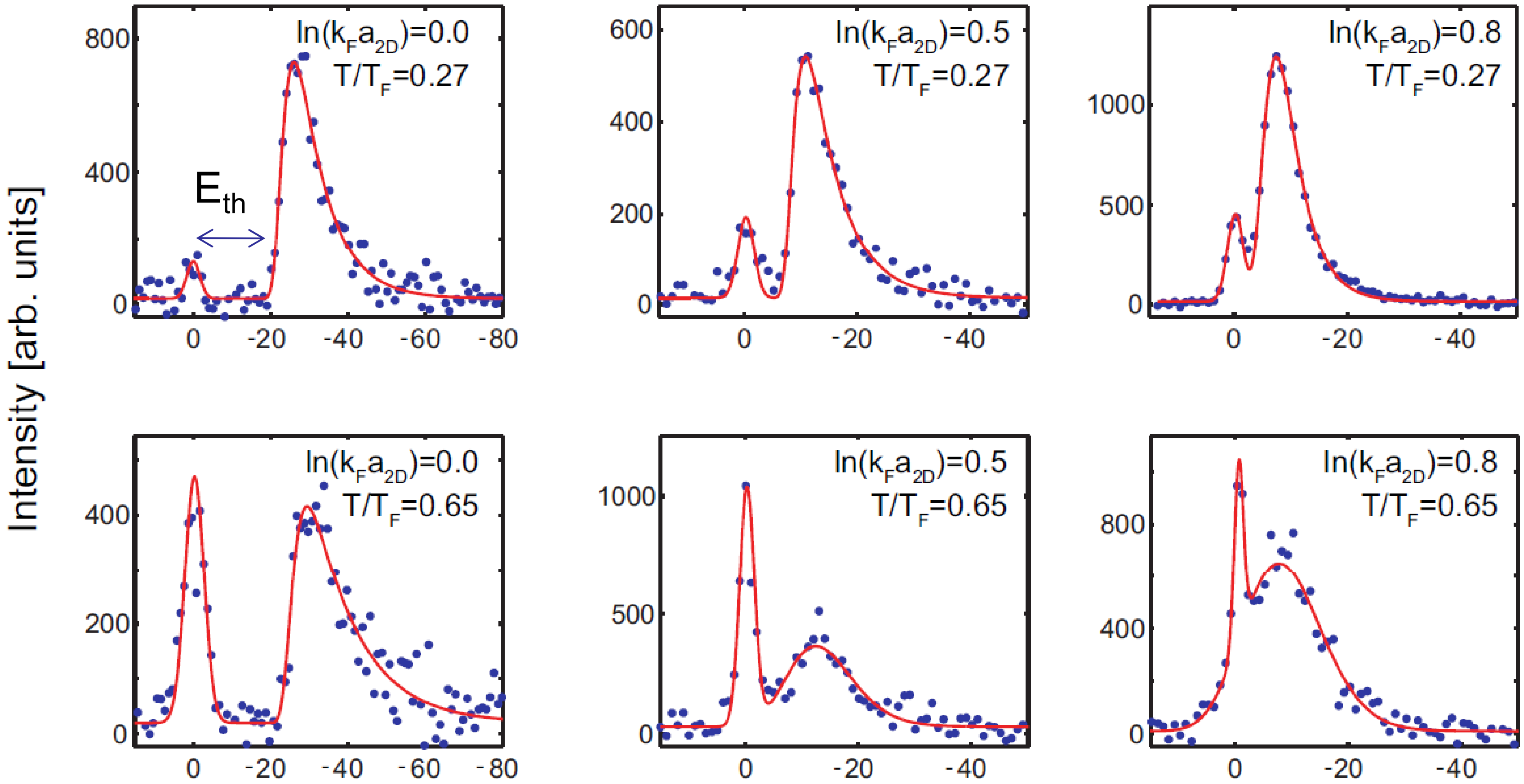
complex order parameter $\Delta(T,x) = |\Delta(T,x)| e^{i\vartheta(T,x)}$



In 3D weak coupling BCS: $T_c \approx T^*$ (pairs condense as they form)

Theory: Randeria, Levin, Sa De Melo, Kleinert, ...

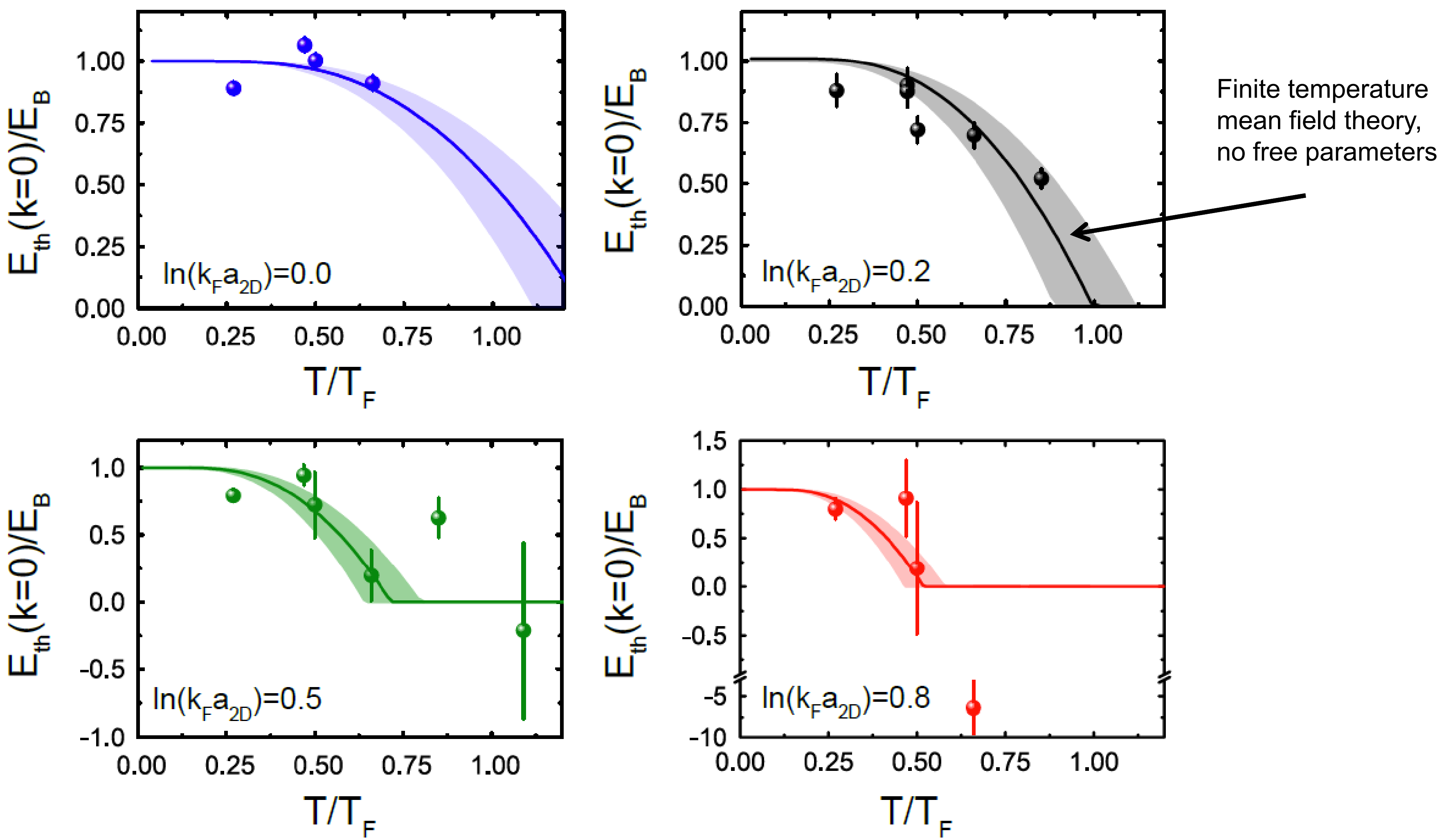
Spectra at k=0: Determining the pseudogap



$$E_{th}(k=0) = \frac{\Delta^2}{2E_F}$$

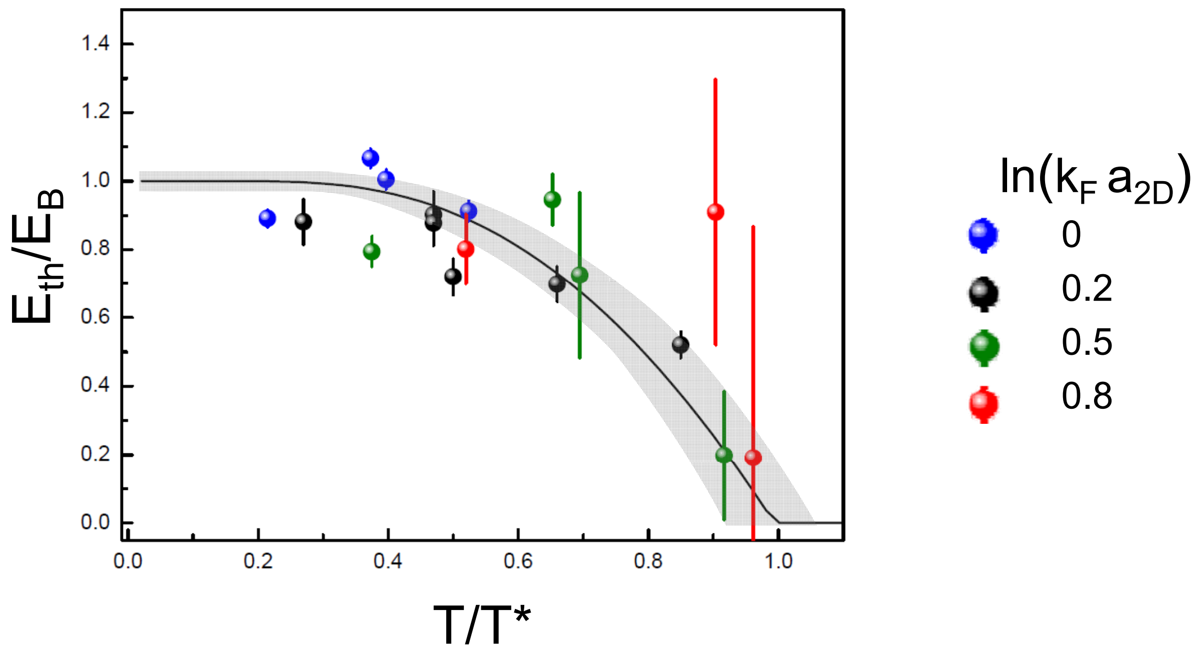
M. Feld et al., Nature 480, 75 (2011)

Temperature dependence



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

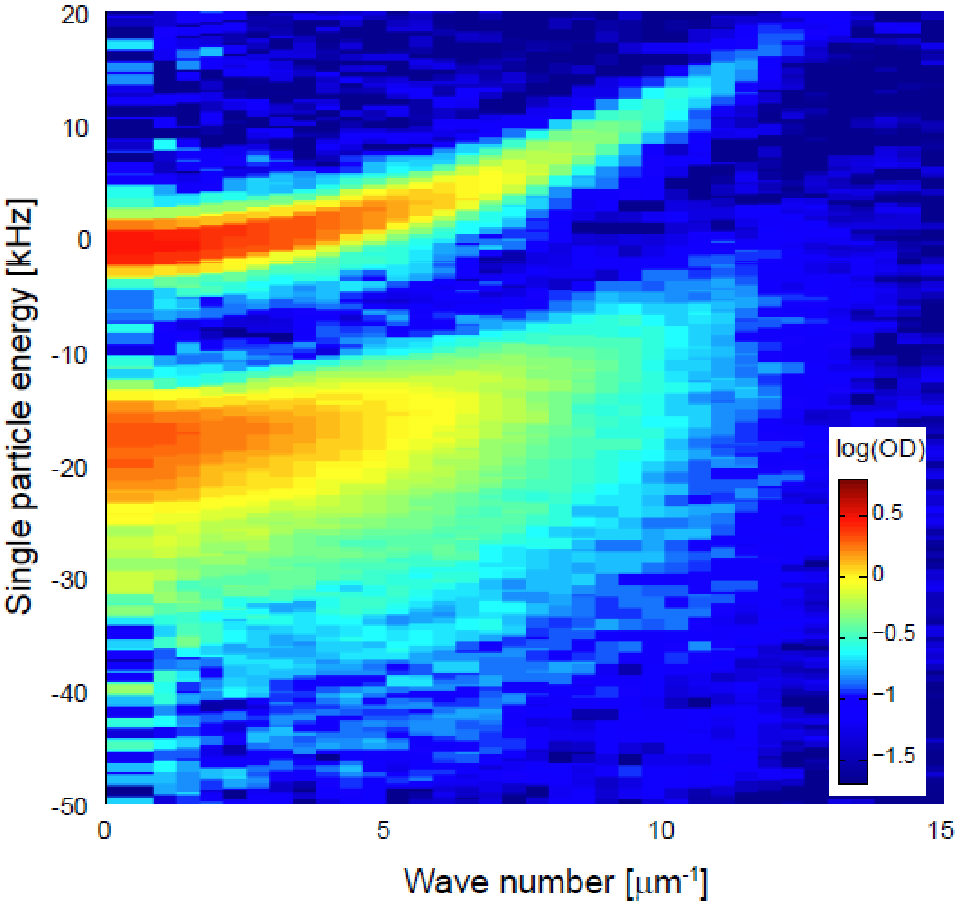
Pairing pseudogap

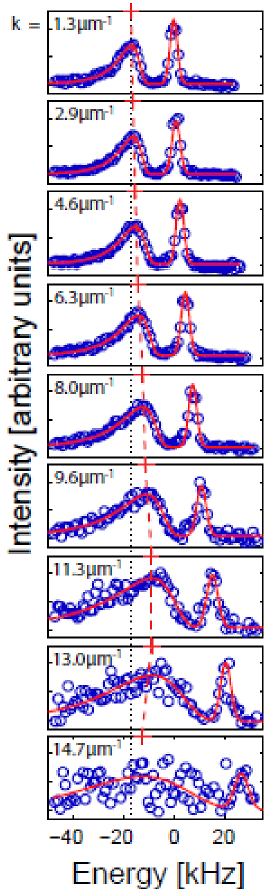


In 3D: Observation of Fermion condensates below $T/T_F \approx 0.15$ [by projection onto molecules]

In 2D: No condensation observed.

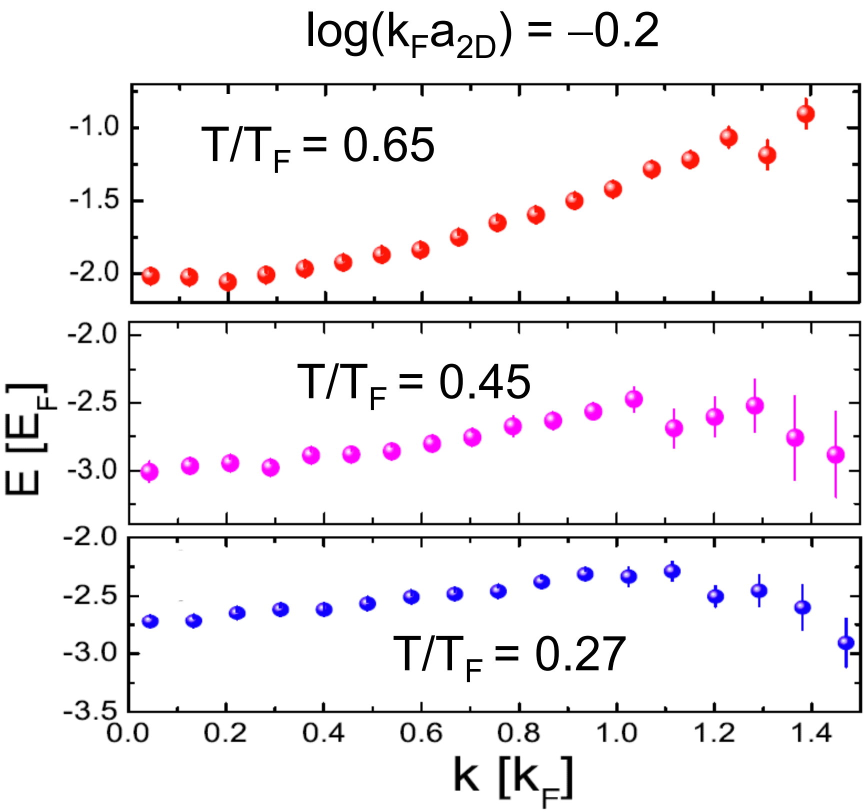
Back-bending of dispersion relation





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

Back-bending of dispersion relation



BCS-like dispersion
at low T

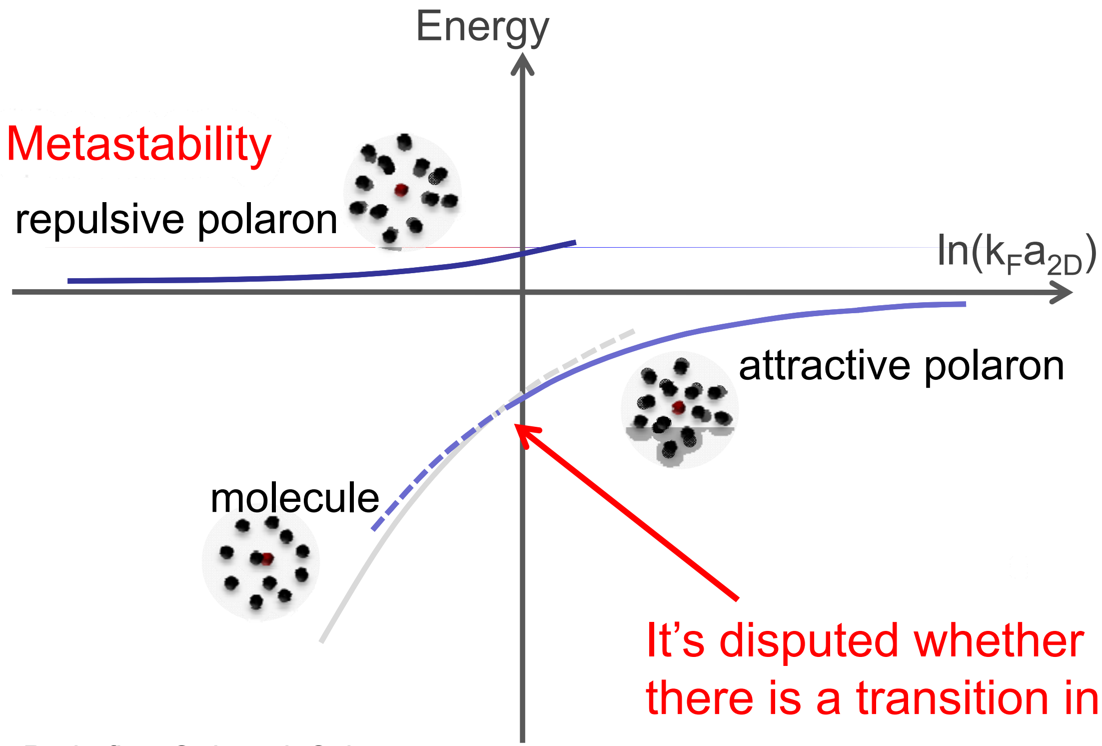
M. Feld et al., Nature 480, 75 (2011)

Strongly imbalanced Fermi gases in 2D

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

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

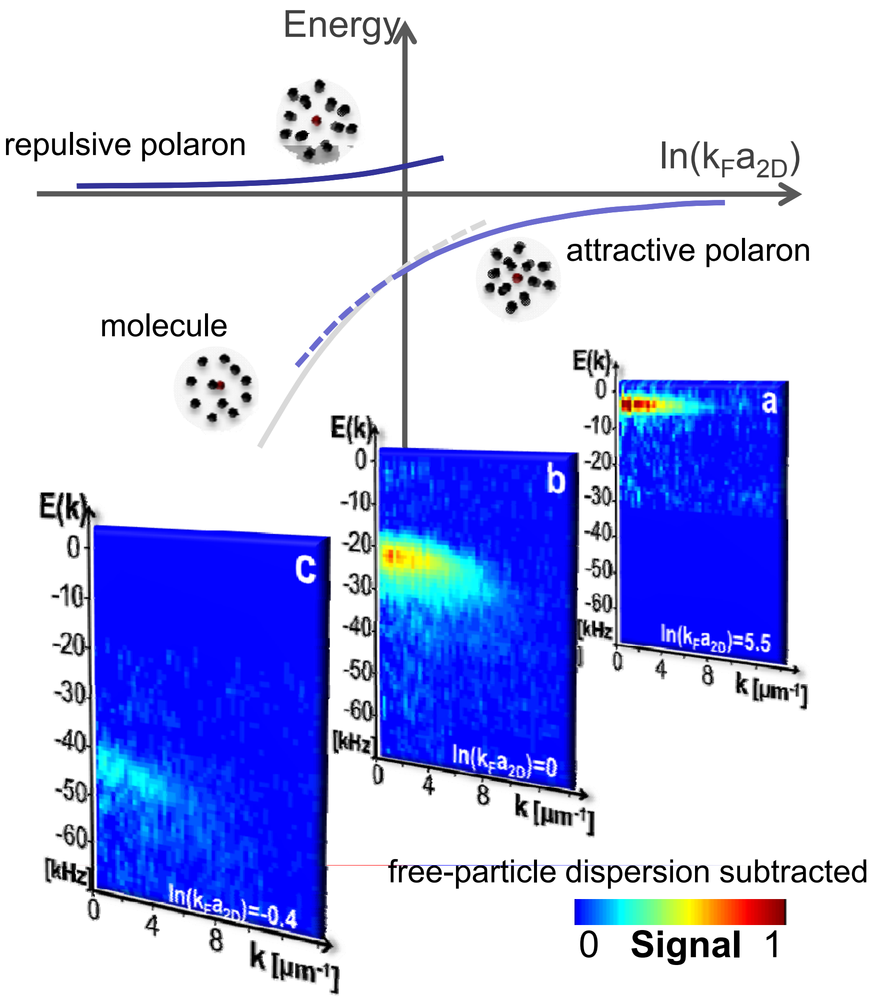
- Mobile impurity interacting with a Fermi sea of atoms
- Tunable interactions
- Polaron properties determine phase diagram of imbalanced Fermi mixtures

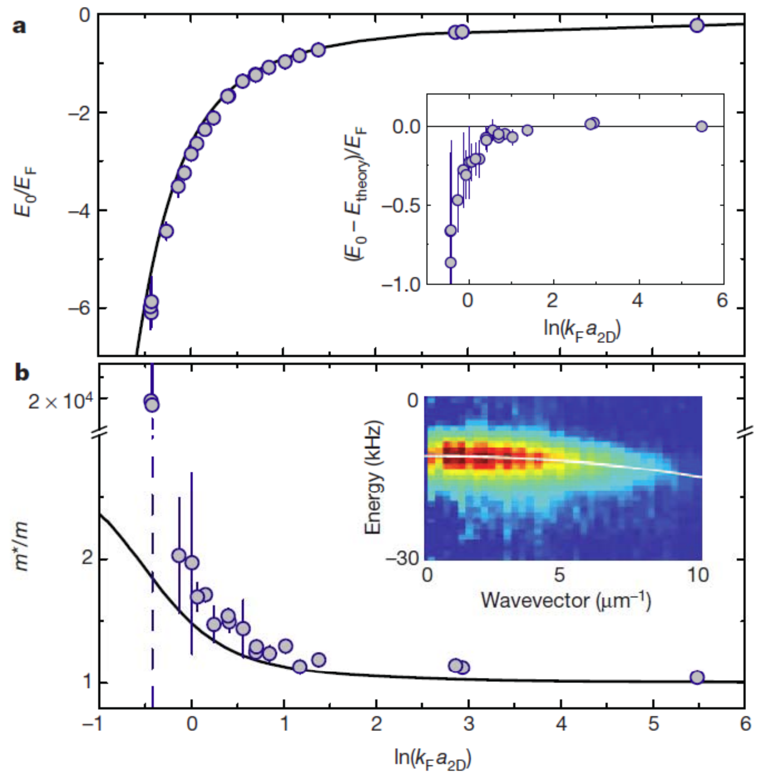


3D Theory: Bruun, Bulgac, Chevy, Giorgini, Lobo, Prokofiev, Stringari, Svistunov, ...
3D Expmt: Zwierlein, Salomon, Grimm

2D Theory: Bruun, Demler, Enss, Parish, Pethick, Recati, ...

Characterizing the attractive polaron

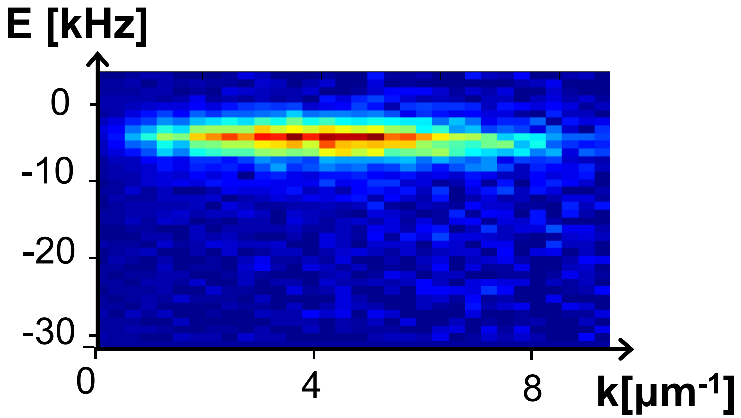




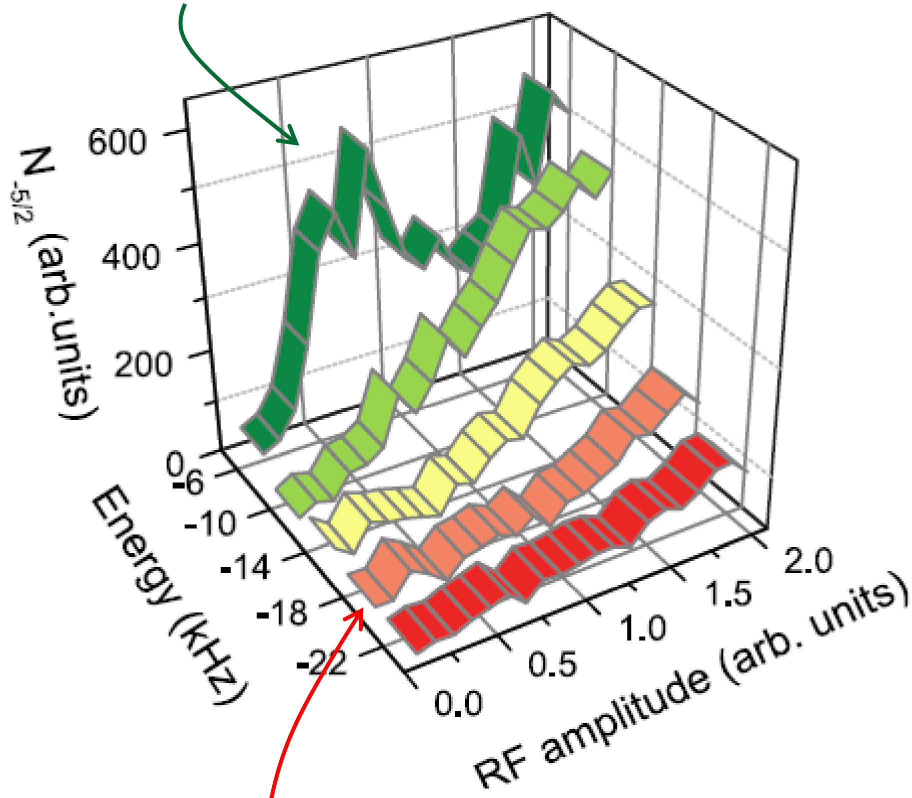
Theory from: R. Schmidt, T. Enss,
V. Pietilä, E. Demler, PRA 85, 021602 (2012)

M. Koschorreck et al., Nature (2012), Advanced Online Publication 23/5/2012

Coherence of the polaron



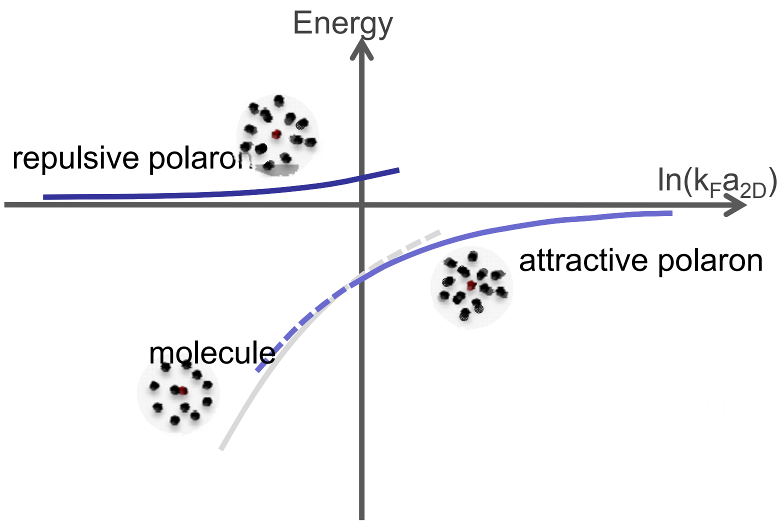
Rabi oscillations between polaron and free particle

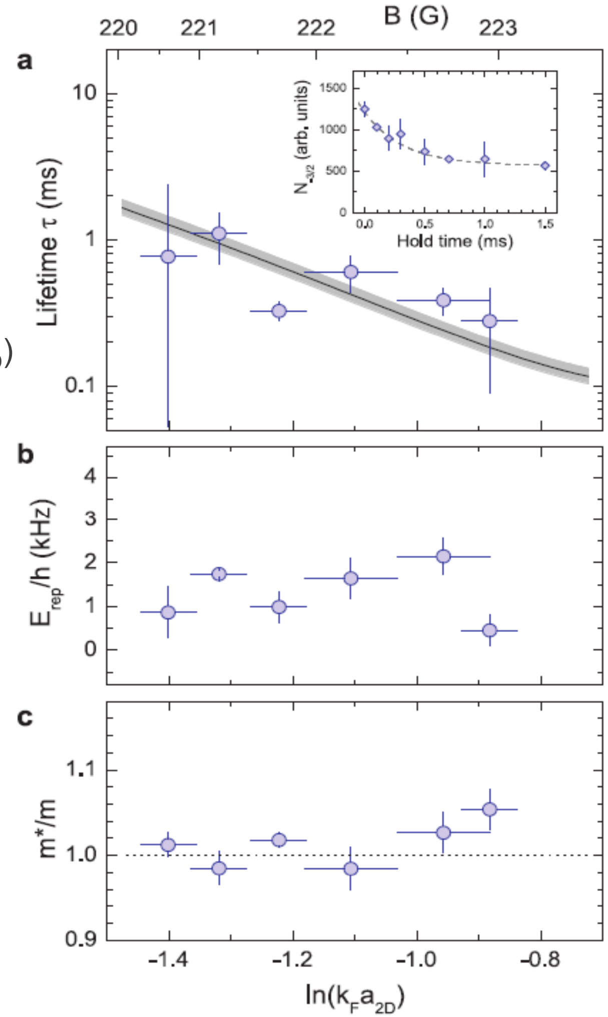


Incoherent transfer: rate ~ amplitude

M. Koschorreck et al., Nature (2012), Advanced Online Publication 23/5/2012

Repulsive polaron





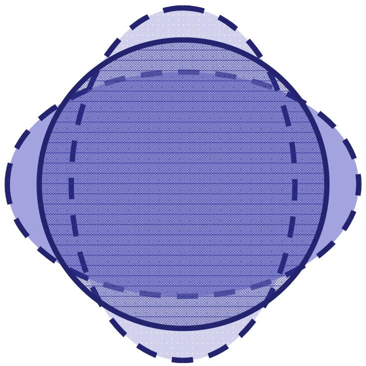
Theory:
V. Ngampruetikorn et al., EPL 98 30005 (2012).

Energies comparable to:
R. Schmidt, T. Enss, V. Pietilä, E. Demler, PRA 85, 021602 (2012)

Similar experiments in 3D: Ketterle & Grimm groups

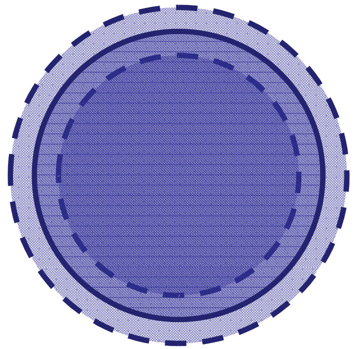
M. Koschorreck et al., Nature (2012), Advanced Online Publication 23/5/2012

Scale invariance and viscosity of a 2D Fermi gas



Quadrupole mode

• insensitive to EoS
• measures shear viscosity



Breathing mode

• measures compressibility
• measures bulk viscosity

Equation of state and scale invariance

- Scale invariance in a homogeneous system: $H(\lambda x)= H(x)/\lambda^2$
  $\rightarrow$ Simple equation of state $P=2\varepsilon/D$

- In cylindrically symmetric trap: scale invariance is replaced by a SO(2,1) Lorentz symmetry (Pitaevskii/Rosch, 1997)

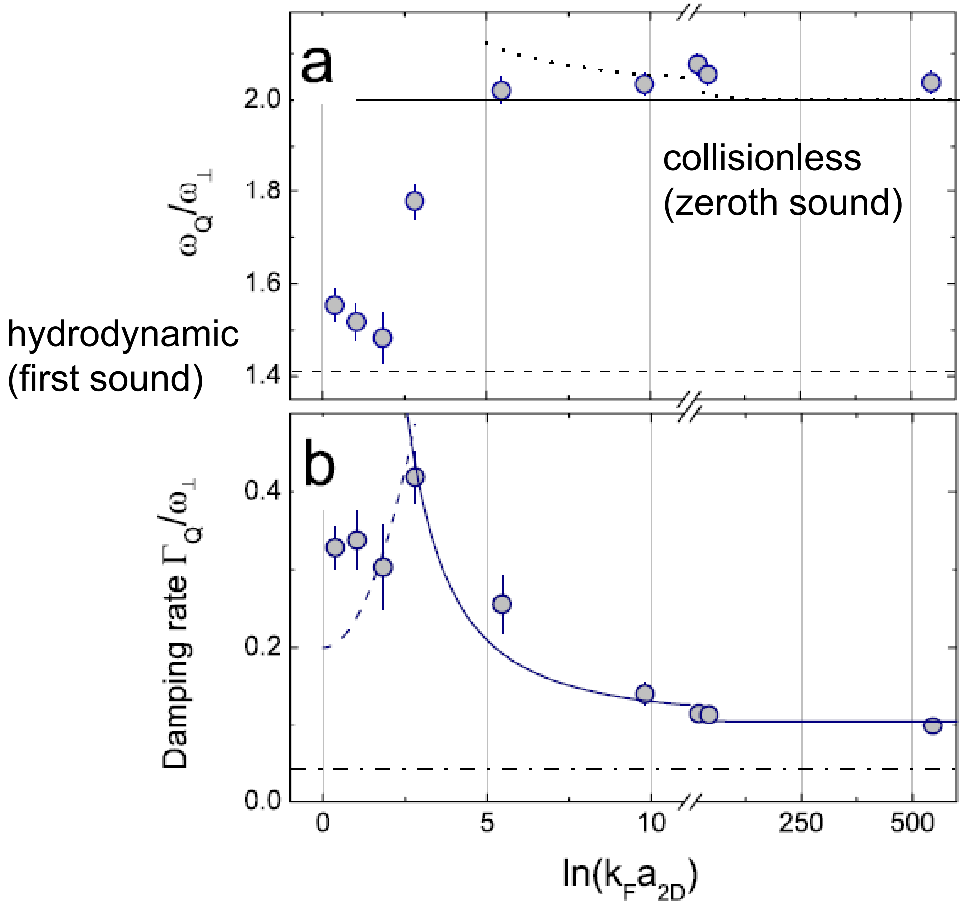
  Two remarkable predictions:
  1. Breathing mode: $\omega_B=2\omega_\perp$ (independent of interaction strength!)
  2. bulk viscosity is zero

- Quantum anomaly due to log-dependence of coupling strength?
  (Olshanii 2010)

For bosons: Pitaevskii/Rosch, Perrin/Olshanii, Chin, Dalibard; for fermions: Schaefer, Hofmann, Randeria/Taylor, Bruun,...

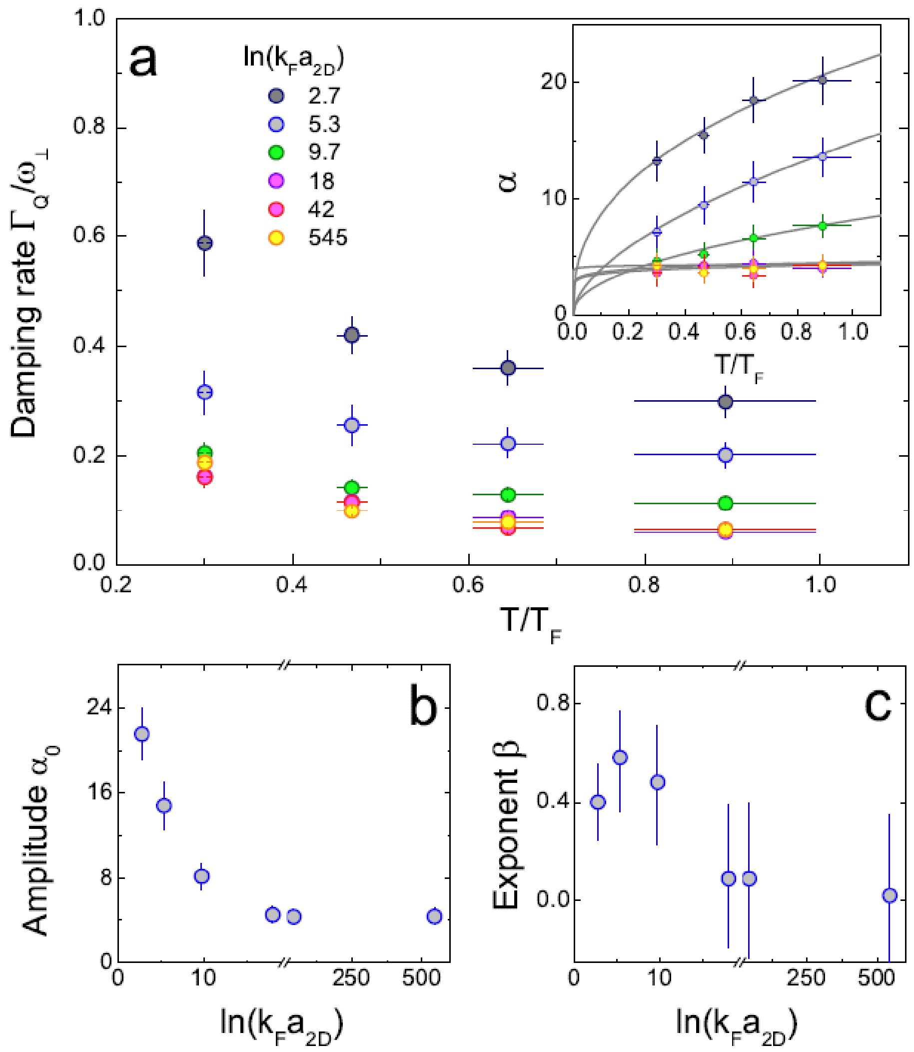
Collective modes

Quadrupole mode



E. Vogt et al, PRL 108, 070404 (2012).

Temperature dependent damping



Shear viscosity

$$\eta = \hbar\, n\, \alpha\left(T/T_F\right)$$

dimensionless function

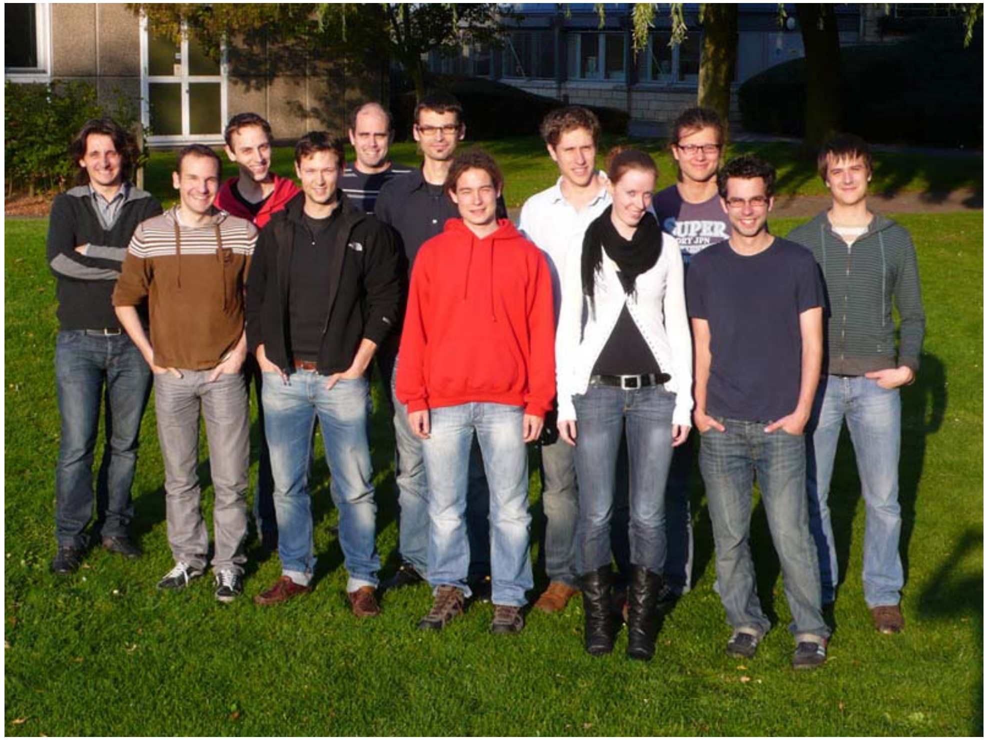
$$\alpha\left(T/T_F\right) = \alpha_0 \times \left(T/T_F\right)^{\beta}$$

E. Vogt et al, PRL 108, 070404 (2012).

Summary

- ARPES measurements in 2D
- Pairing pseudogap
- 2D Fermi polaron
- Collective modes to determine equation of state

Thanks



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Funding: EPSRC, ERC, Leverhulme Trust

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