Non-equilibrium dynamics in the Bose-Fermi resonance model

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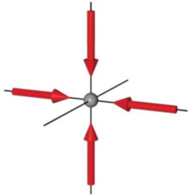
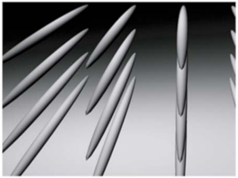
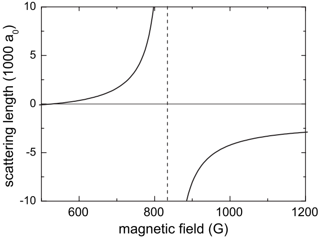
Motivation



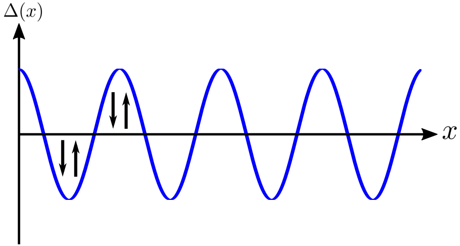




Bloch, Dalibard, Zwerger RMP **80**, 885 (2008)

$\Rightarrow$ experimental control over interactions

1D: exact methods (Bethe ansatz), powerful numerics (DMRG)

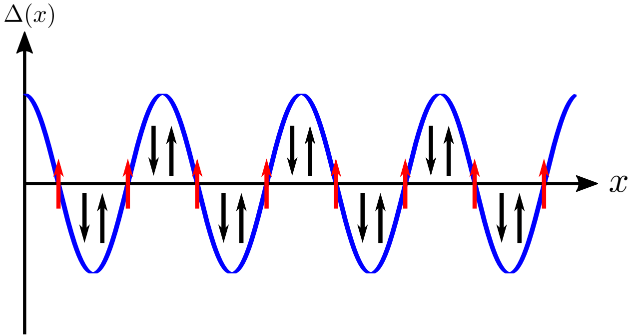


spin-polarized Fermi gases
$\Rightarrow$ unconventional superfluid order

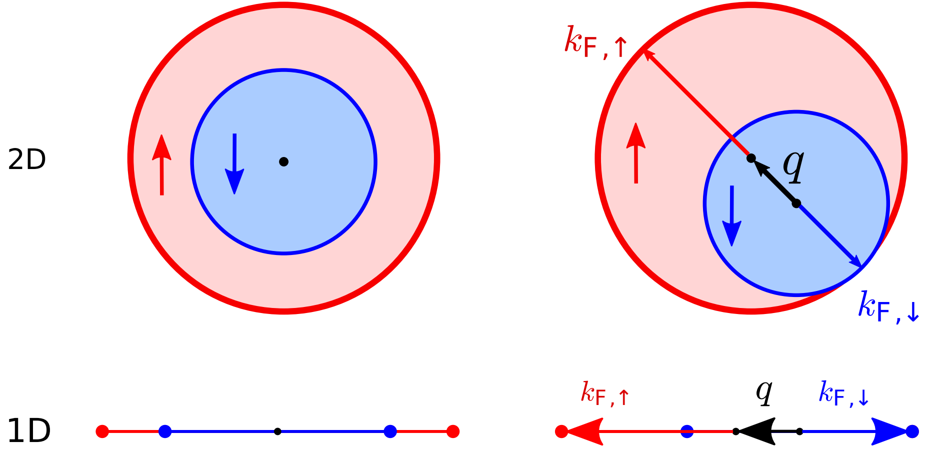
Outline

FFLO phase

- predicted by Fulde and Ferrell (1964), Larkin and Ovchinnikov (1964)
- pairing + magnetization ($p \neq 0$) $\to$ FFLO phase: $\Delta(x) = \Delta \cos(qx)$
- $q = k_{F,\uparrow} - k_{F,\downarrow}$ (in 1D: $q = \pi n p$)



FFLO mechanism, nesting of Fermi surfaces

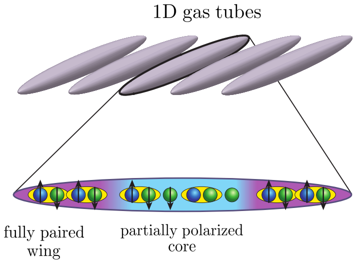


$\Rightarrow$ q = center-of-mass momentum of Cooper pair

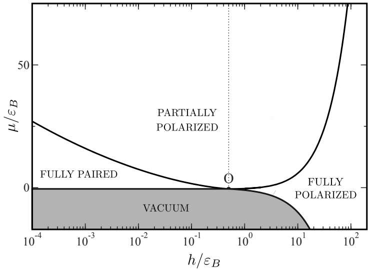
$\Rightarrow$ nesting effect is much larger in 1D $\rightarrow$ FFLO phase more stable

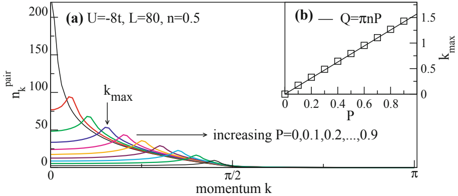
Theory

1D + attractive fermions ⇒ Gaudin-Yang model (only single-channel)
(phase diagram for imbalanced gas: Orso (2007), Hu et al. (2007))



Orso PRL **98**, 070402 (2007)



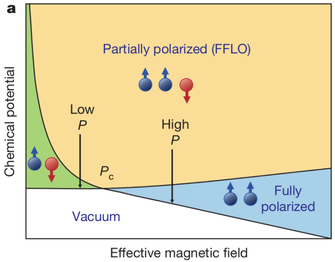


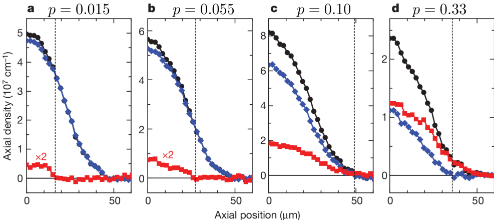
Feiguin, Heidrich-Meisner PRB **76**, 220508 (2007)

⇒ in 1D, partially polarized phase indeed is FFLO phase!

Experimental status

- probing density profiles of two-spin mixture of ultracold ^{6}Li atoms trapped in array of 1D tubes

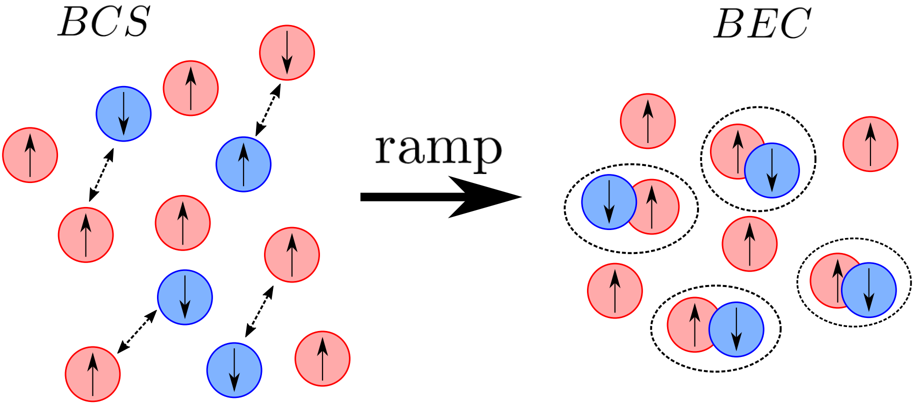




Liao et al. Nature **467**, 567 (2010), phase diagram originally calculated by Orso PRL **98**, 070402 (2007)

BUT: only indirect evidence of FFLO phase
Goal: direct measurement of pair momentum distribution function (TOF)
⇒ imprint FFLO correlations onto the molecules in BFRM!

Idea



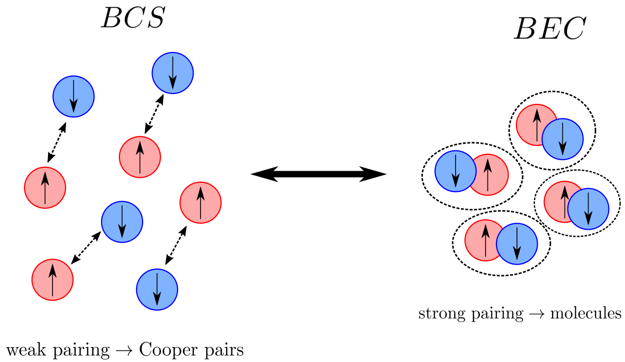
$k = q$ (FFLO) $\longrightarrow$ $k = ?$

Outline

Bose-Fermi resonance model (BFRM)

- single-channel model (Fermi-Hubbard) $\rightarrow$ PP $\hat{=}$ FFLO
- composite fermions can form molecules $\rightarrow$ second channel needed
- Bose-Fermi resonance model (3D: Holland et al. (2001), Timmermans et al. (2001), 1D: Recati et al. (2005))

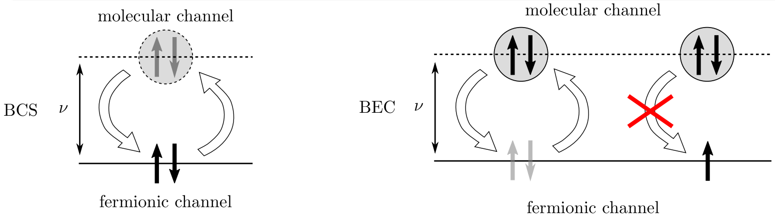
$\Rightarrow$ minimal model of 1D Feshbach resonance



Hamiltonian

BFRM Hamiltonian (lattice version)

$$H = -t \sum_{i,\sigma} \left(c_{i,\sigma}^\dagger c_{i+1,\sigma} + \text{h.c.} \right) - \frac{t}{2} \sum_i \left(m_i^\dagger m_{i+1} + \text{h.c} \right)$$
$$-(\nu + 3t) \sum_i m_i^\dagger m_i + g \sum_i \left(m_i^\dagger c_{i,\uparrow} c_{i,\downarrow} + \text{h.c.} \right) \qquad (1)$$

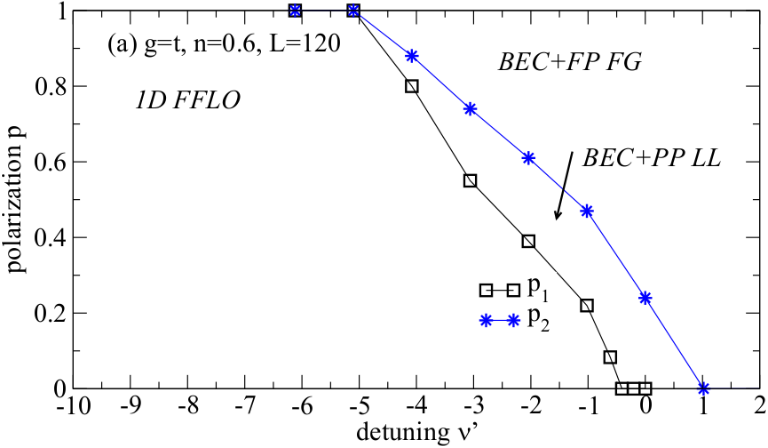


$\Rightarrow$ coupling leads to effective interaction: $U \propto g^2/\nu$

1D, 3-body calculation: Baur et al. PRA **81**, 033628 (2010)

Finite Imbalance, Phase Diagram

- $p = 0$: smooth BCS-BEC crossover
- $p \neq 0$: quantum phase transitions

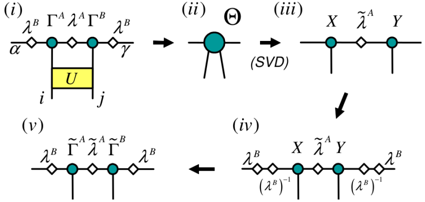


Heidrich-Meisner et al. PRA **81**, 023629 (2010)

Outline

Numerical Method

- Time Evolving Block Decimation (TEBD) (Vidal 2003) with MPS: efficient simulation of slightly entangled 1D many-body systems

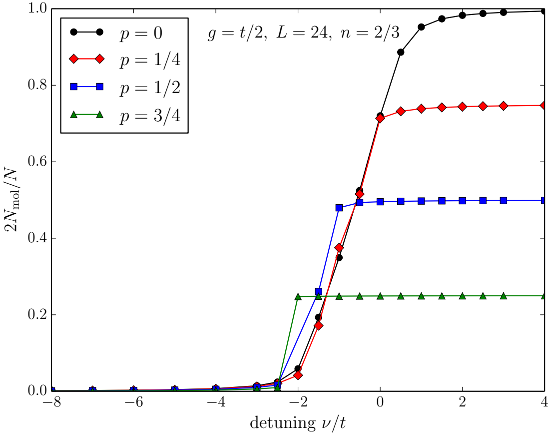


- ground state search by imaginary-time-evolution

$$|\psi_0\rangle = \lim_{\tau\to\infty} \frac{\exp(-H\tau)|\psi\rangle}{||\exp(-H\tau)|\psi\rangle||}$$

- usage of conserved quantum numbers (N, S_z) to improve performance

Resonance region

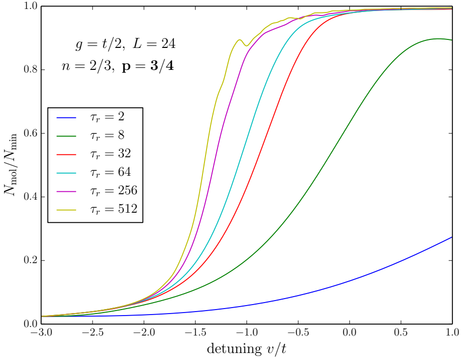


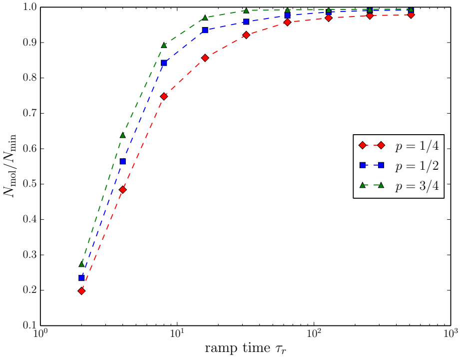
- N_{mol} saturates for $\nu > t$ for $p \neq 0$
- perform ramps: $\nu_0 = -3t \to \nu_1 = t$

$\Rightarrow$ should capture the whole resonance region!

Number of molecules during ramp

$$\nu(T) = \nu_0 + \frac{\nu_1 - \nu_0}{\tau_r} T$$

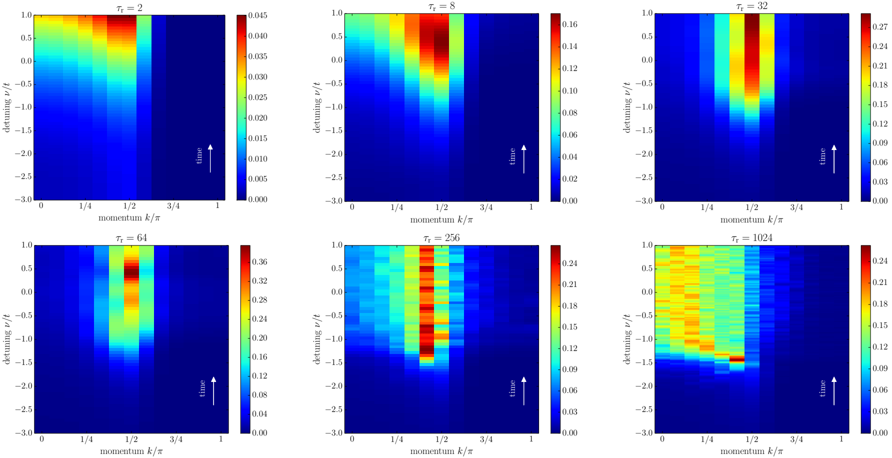




⇒ N_{mol} reaches its maximum value for large ramp times

⇒ adiabatic limit? $q \to 0$ (no FFLO peak)?

Molecule momentum distribution function ($p = 3/4$)

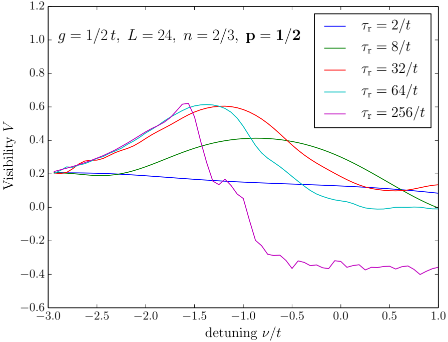


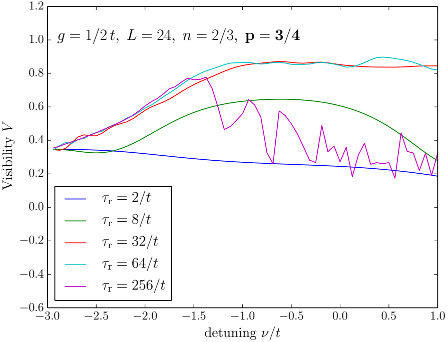
$\Rightarrow$ FFLO peak vanishes in the long ramp time limit

$\Rightarrow$ most pronounced in the intermediate regime ($\tau_r \approx 32/t$)

Visibility of the FFLO peak

$$V = \frac{n^{\mathrm{mol}}_{k=q} - n^{\mathrm{mol}}_{k=0}}{n^{\mathrm{mol}}_{k=q} + n^{\mathrm{mol}}_{k=0}}$$

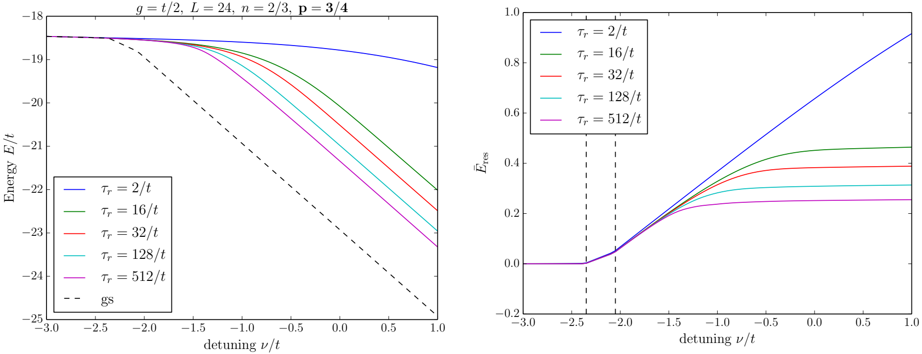




$\Rightarrow$ Visibility of FFLO peak in molecule MDF enhanced during ramp for large polarization and intermediate ramp times

Energy during ramp

$E(T) = E_{\text{kin+fesh}}(T) - (\nu(T) + 3\,t)N_{\text{mol}}(T)$ $\qquad \bar{E}_{\text{res}}(T) = \frac{E(T)-E_0(T)}{E_{\psi_0}(T)-E_0(T)}$



- $N_{\text{mol}}(T = \tau_r)/N_{\text{min}} \approx 1 \Rightarrow$ excess energy comes from kinetic and Feshbach part of H $\rightarrow$ change in correlations
- $\bar{E}_{\text{res}}(\tau_r) \rightarrow 0$? $\rightarrow$ 'adiabatic' limit? Ongoing: connection to Kibble-Zurek theory

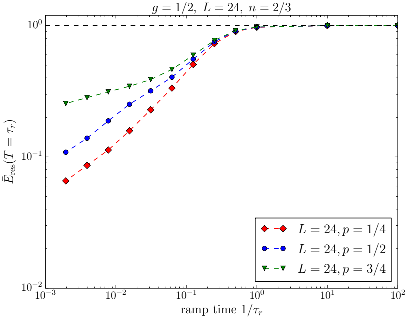
Outline

Summary

- 1D FFLO, detection in experiments
- projection of pair FFLO correlations onto molecules
- visibility of FFLO correlations in molecule MDF enhanced for intermediate ramp times and large polarizations ($p = 3/4$)

Outlook:

- understand ramp over QPT
  $\rightarrow$ Kibble-Zurek scaling?
- larger system sizes, trapping potential



Thank you for your attention!

Kibble-Zurek mechanism (KZM)

- studied by Kibble (1976) and Zurek (1985) in the context of domain structure formation in early universe
- intuitive explanation of defect formation and coherence lengths when crossing 2nd order PT at finite velocity
- also valid for quantum phase transitions (Zurek et al. PRL **95**, 105701 (2005)
- main result: $\xi \sim v^{-\frac{\nu}{1+z\nu}}$ and $n_{ex} \sim v^{\frac{\nu}{1+z\nu}}$ (in 1D)

KZM: intuitive picture

- Gapped system: $\Delta \sim |\lambda - \lambda_c|^{z\nu} \to \tau \sim 1/\Delta \sim |\lambda - \lambda_c|^{-z\nu}$
- ramping protocol: $\lambda(t) = \lambda_c + \frac{t}{\tau_{\mathrm{ramp}}}$
- $\Delta \sim \left(\frac{t}{\tau_{\mathrm{ramp}}}\right)^{z\nu}$ and $\tau \sim \left(\frac{t}{\tau_{\mathrm{ramp}}}\right)^{-z\nu}$