School for "Clustering as a window on the hierarchical structure of quantum systems“ on 22/March/2021

BCS-BEC crossover in a two-band system with a heavy incipient band

: Effects of interband pair exchange interactions

Kazunari Ochi (Kochi Univ.)

Hiroyuki Tajima (Kochi Univ.),

Kei Iida (Kochi Univ.),

Hideo Aoki (Univ. of Tokyo, AIST)

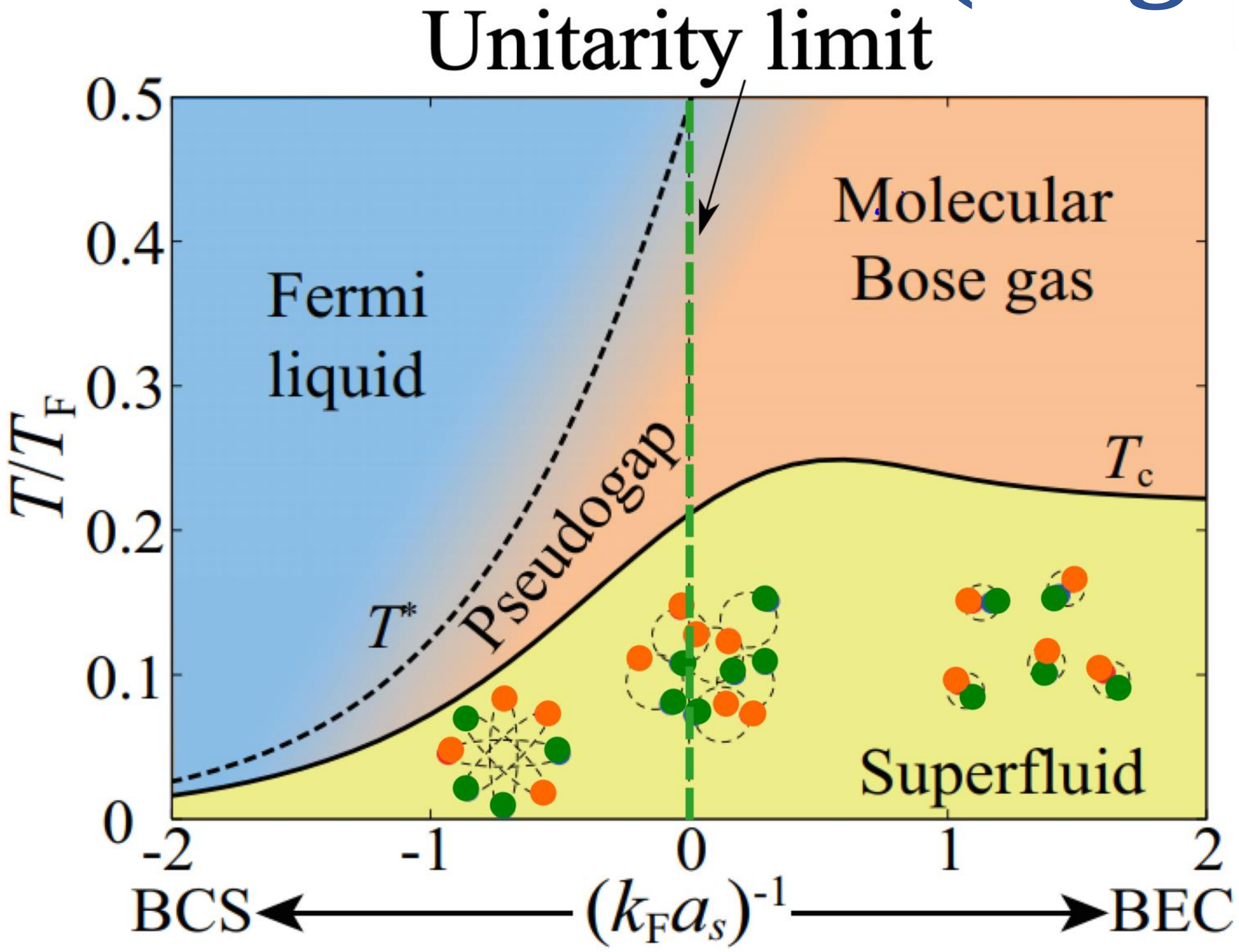
Outline

- Introduction
- Formalism
- Results
- Summary

Outline

- Introduction
- Formalism
- Result
- Summary

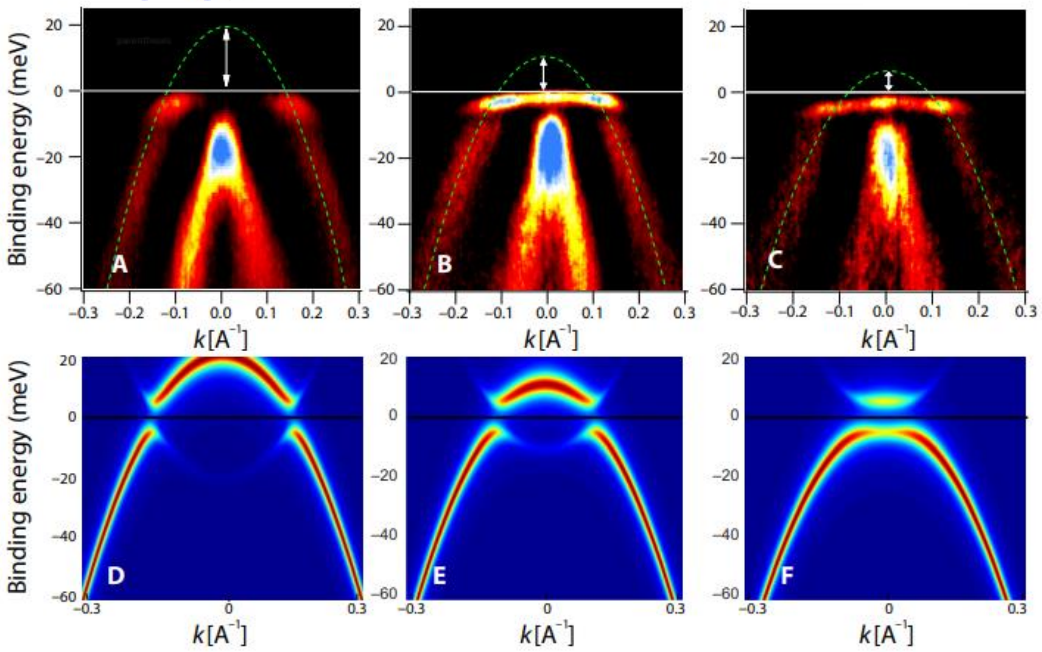
BCS-BEC crossover(single band)



BCS-BEC crossover phase diagram of two-component Fermi gas

Multi-band systems

BCS ——— Decreasing y in $Fe_{1+y}Se_xTe_{1-x}$ ———→ **BEC**

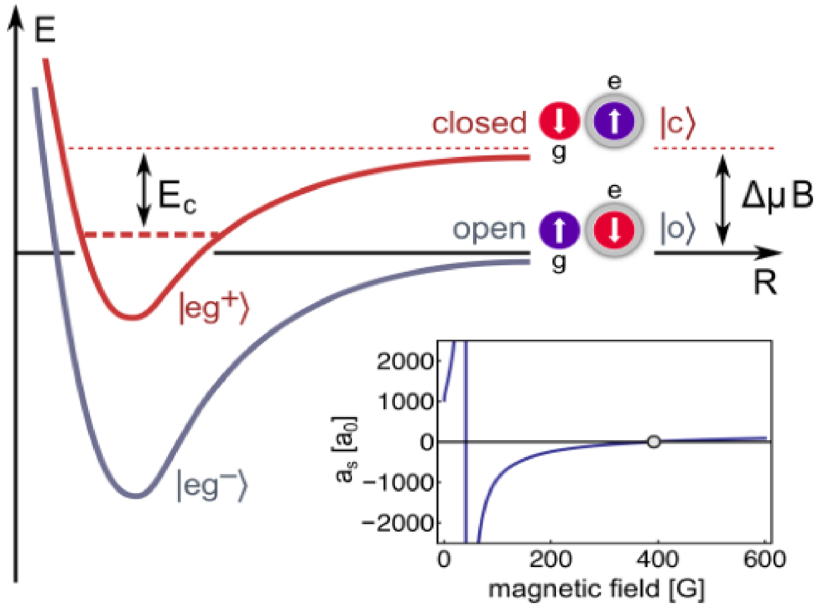


Rinott et al., Sci. Adv. 2017;3:e1602372

▶ FeSe iron based superconductor

$$\Delta/E_{\mathrm{F}} = 0.16\sim0.5$$

・The unitarity limit and the strong-coupling BEC regime are realized in both solid-state systems and cold atomic systems.



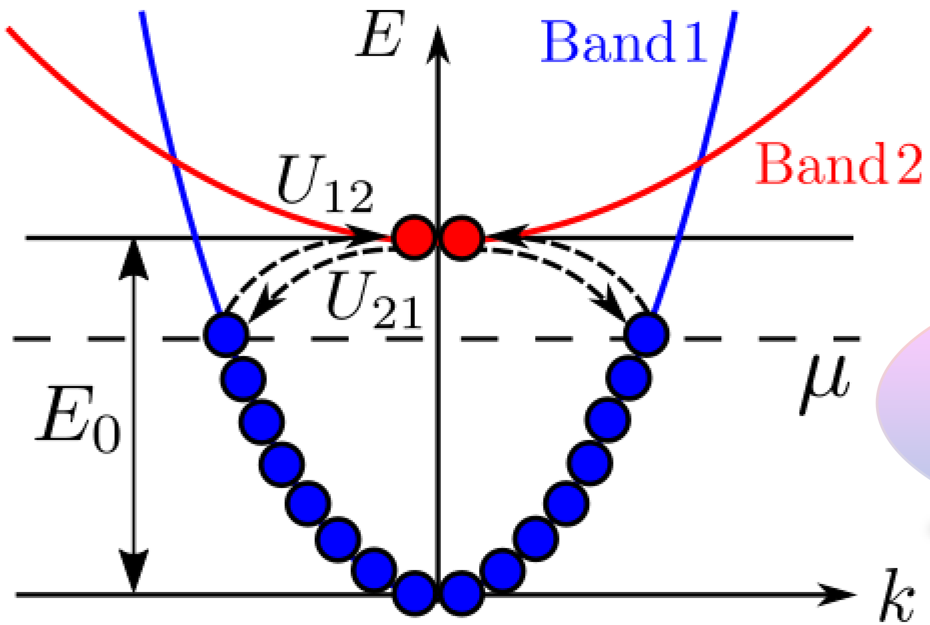
G. Pagano, et al., Phys. Rev. Lett. **115**,265301 (2015).

▶Yb Fermi gases near the orbital Feshbach resonance

・The multi-band system has also been realized in a cold atomic system.

Multi-band systems

2band system



Interband interaction
U_{12}, U_{21}

Energy shift E_0

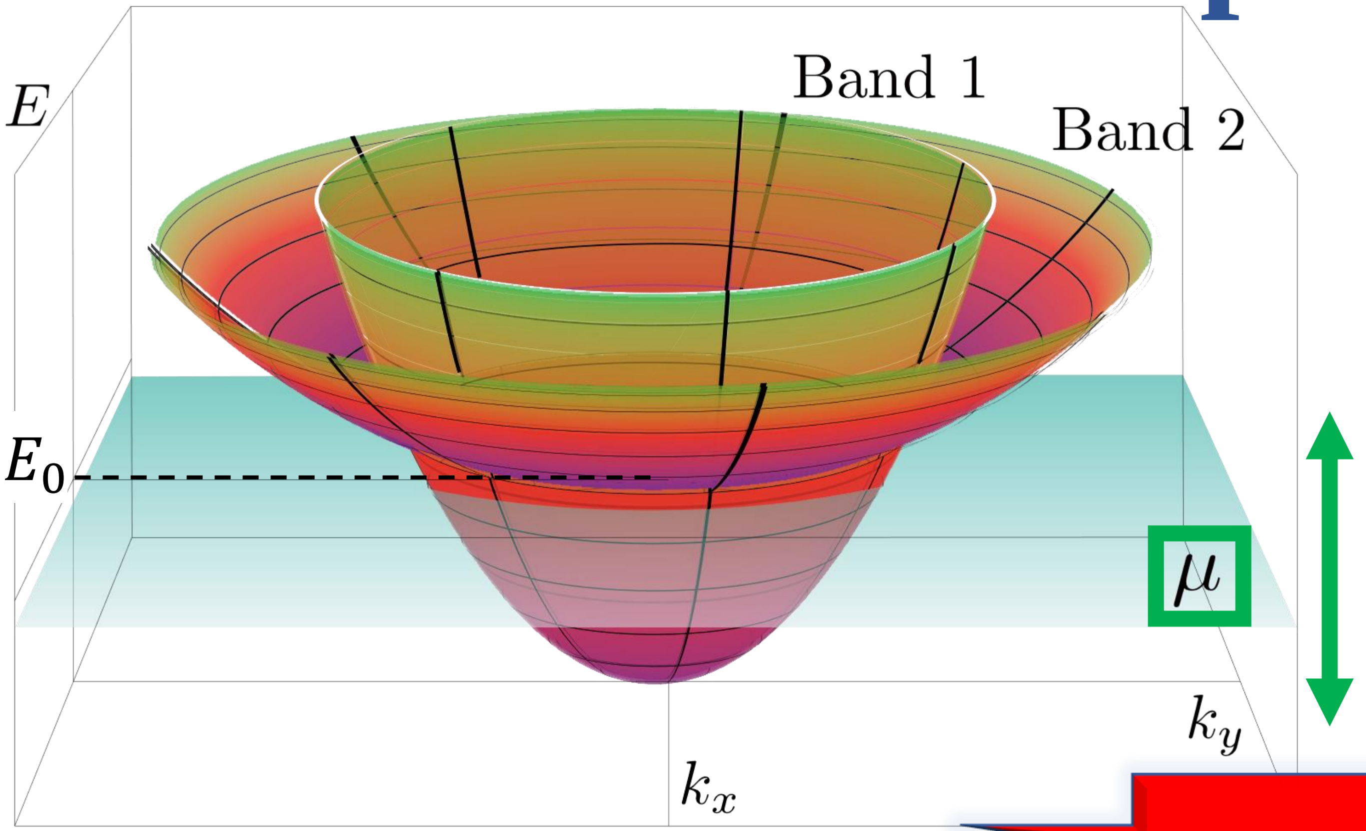
Mass ratio
m_1/m_2

Intraband interaction
U_{11}, U_{22}

The multi-band systems involve various degrees of freedom not found in single band.

Our purpose

($k_z = 0$ projection)



We investigate the two band BCS-BEC crossover when the second band has its edge located close to the chemical potential (incipient band).

・Interaction strengths are fixed.
・μ is controllable.

We clarify how the superfluid/superconducting gaps and effective intraband interaction behave in the presence of the pair-exchange coupling and the effective mass difference between the two bands.

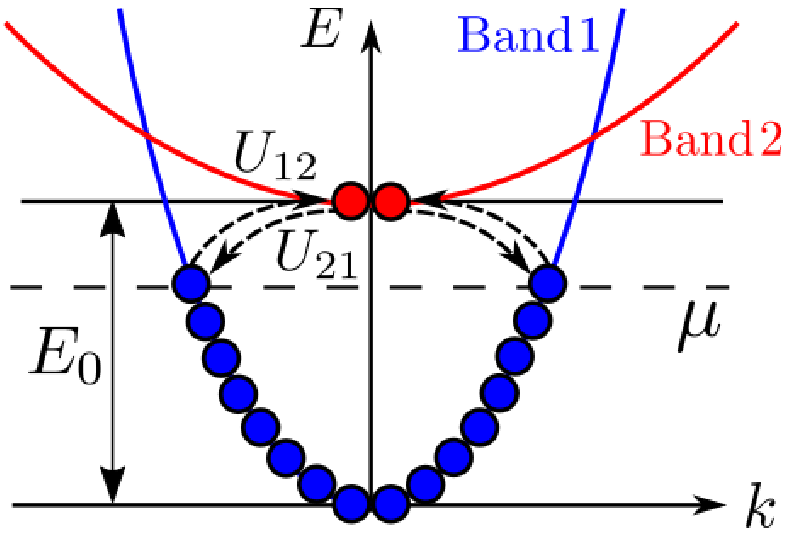
Outline

- Introduction
- Formalism
- Results
- Summary

Two band model hamiltonian

▶Hamiltonian

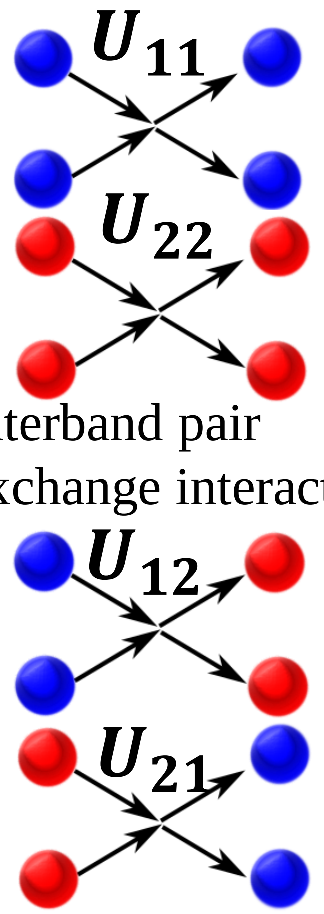
$$
\begin{aligned}
H = \sum_{i,\boldsymbol{k},\sigma} \xi_{\boldsymbol{k}i} c^{\dagger}_{\boldsymbol{k}\sigma i} c_{\boldsymbol{k}\sigma i} &- U_{11} \sum^{\Lambda}_{\boldsymbol{k},\boldsymbol{k}',\boldsymbol{q}} c^{\dagger}_{\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\uparrow,1} c^{\dagger}_{-\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\downarrow,1} c_{-\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\downarrow,1} c_{\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\uparrow,1} \\
&- U_{22} \sum^{\Lambda}_{\boldsymbol{k},\boldsymbol{k}',\boldsymbol{q}} c^{\dagger}_{\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\uparrow,2} c^{\dagger}_{-\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\downarrow,2} c_{-\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\downarrow,2} c_{\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\uparrow,2} \\
&- U_{12} \sum^{\Lambda}_{\boldsymbol{k},\boldsymbol{k}',\boldsymbol{q}} c^{\dagger}_{\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\uparrow,2} c^{\dagger}_{-\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\downarrow,2} c_{-\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\downarrow,1} c_{\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\uparrow,1} \\
&- U_{21} \sum^{\Lambda}_{\boldsymbol{k},\boldsymbol{k}',\boldsymbol{q}} c^{\dagger}_{\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\uparrow,1} c^{\dagger}_{-\boldsymbol{k}+\frac{\boldsymbol{q}}{2}\downarrow,1} c_{-\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\downarrow,2} c_{\boldsymbol{k}'+\frac{\boldsymbol{q}}{2}\uparrow,2}
\end{aligned}
$$



Band dispersion

Intraband interaction

Interband pair exchange interaction



・Cold-atom systems: orbital Feshbach resonance

・Solid state systems: Suhl-Kondo mechanism

- annihilation operator of a fermion in band i : $c_{\boldsymbol{k},\sigma,i}$

$$\xi_{\boldsymbol{k}i} = {k^2}/{2m_i} - \mu + E_0\delta_{i2}$$

- Energy difference between two bands : E_0
- different masses m_1, m_2
- chemical potential: μ
- cutoff Λ

BCS mean field theory

▶ Gap equation

$$\Delta_i = \sum_{\mathrm{j}=1,2} U_{ij}\Delta_j \sum_{\boldsymbol{k'}}^{\Lambda} \frac{\tanh\frac{E_{k'j}}{2T}}{2E_{k'j}}$$

$$E_{ki} = \sqrt{\xi_{ki}^2 + \Delta_i^2}$$

$$(i = 1,2)$$

▶ Intraband interactions

$$\frac{m_i}{4\pi a_{ii}} = -\frac{1}{U_{ii}} + \sum_{\boldsymbol{p}}^{\Lambda} \frac{1}{p^2/m_i + 2E_0\delta_{i2}}$$

$$(k_0 a_{11})^{-1} = -2,\ (k_0 a_{22})^{-1} = -2$$

▶ Interband pair exchange interactions

$$\tilde{U}_{ij} = \left(\frac{\Lambda}{k_0}\right)^2 \frac{k_0^3}{3\pi^2}\frac{1}{E_0}U_{ij}$$

$$\left(k_0 = \sqrt{2m_1E_0}, U_{ij} = U_{ji}\right)\ (i \neq j)$$

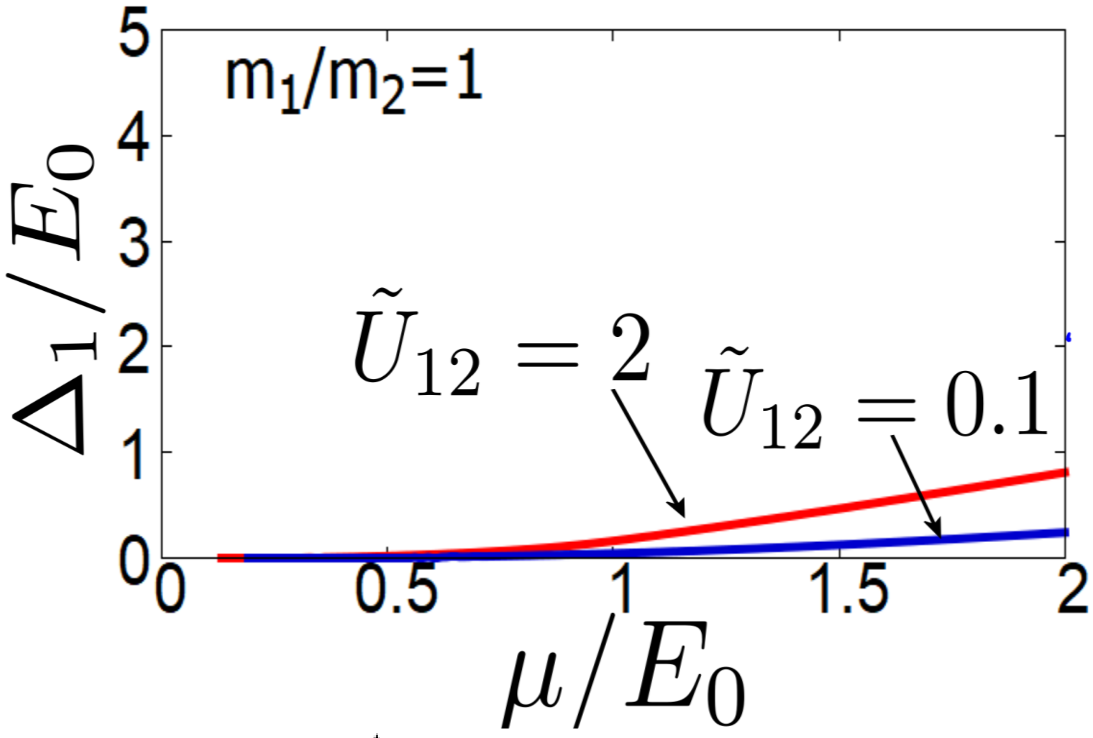
Outline

- Introduction
- formalism
- **Results**
- Summary

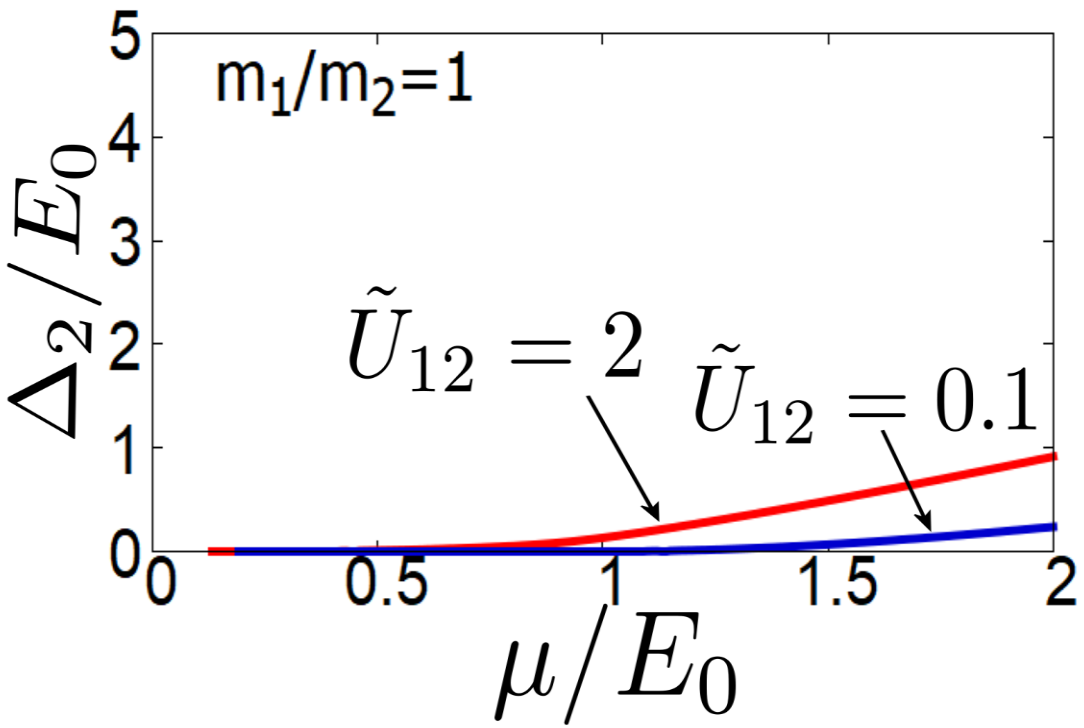
- Superfluid/superconducting gap

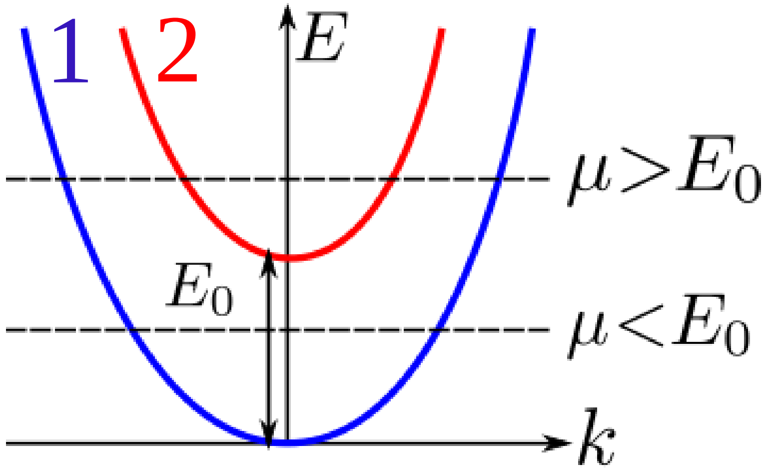
Superconducting gap$(m_1/m_2 = 1)$

▶Sc gap in Band 1



▶Sc gap in Band 2





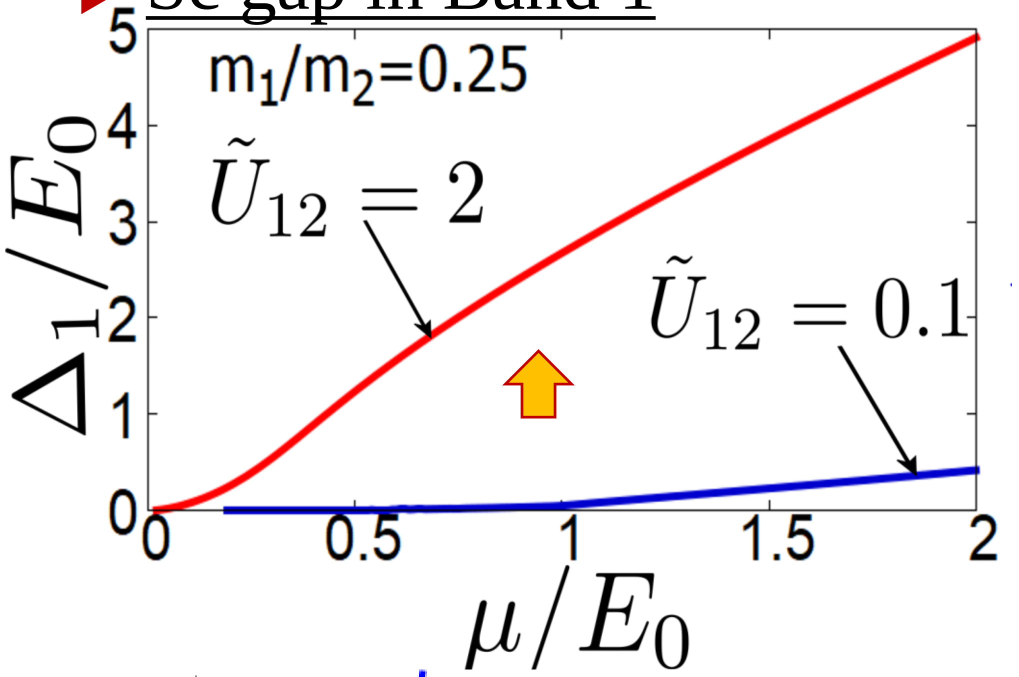
Increasing Δ_1, Δ_2 due to U_{12} is consistent with the Suhl-Kondo mechanism.

(Stabilaized by interband transition)

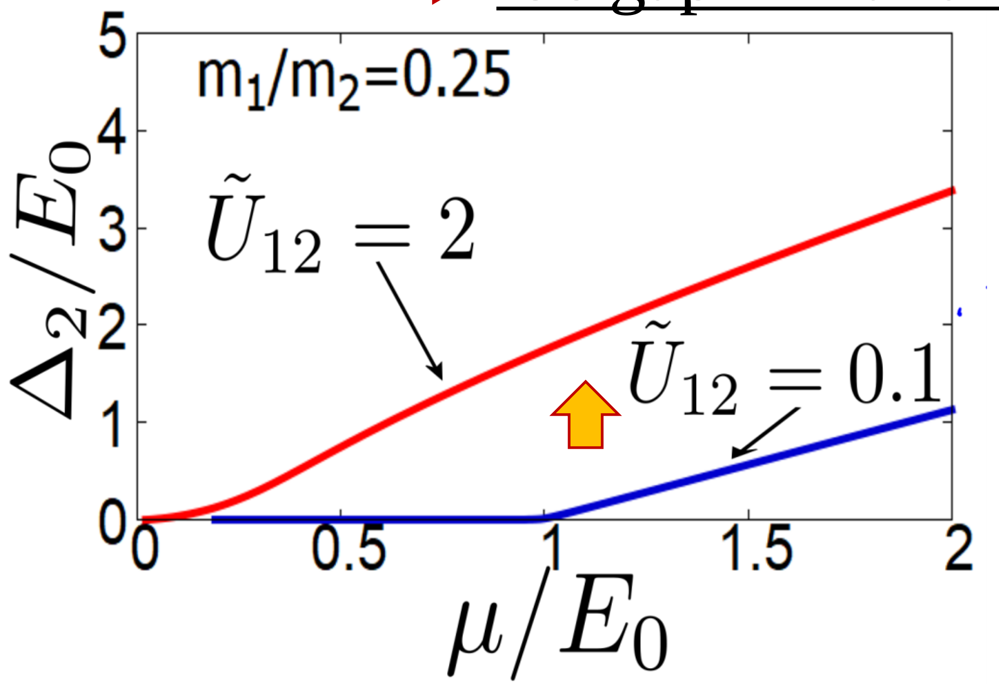
Superconducting gap($m_1/m_2 = 0.25$)

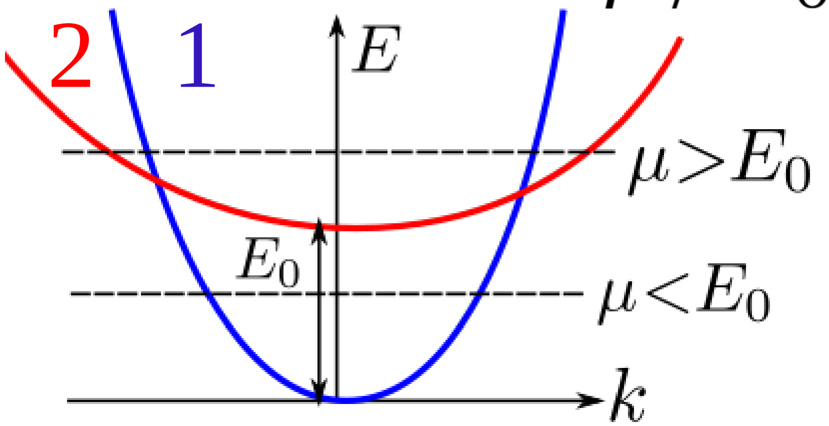
$\Delta_{1,2}$ is prominent for the smallest m_1/m_2 where the incipient band dispersion becomes flat.

▶Sc gap in Band 1



▶Sc gap in Band 2





The presence of pair condensation in the incipient band located far above μ.

$\Delta_{1,2}$ is remarkably enhanced with increasing m_2 due to increment in the density of state.