Universal induced interaction between heavy polarons in superfluid

KF, M. Hongo, & T. Enss, arXiv:2206.01048 (2022)

Keisuke Fujii

Institut für Theoretische Physik, Universität Heidelberg

1day workshop on “Quantum dynamics of few-body systems”
23 August 2022

自己紹介

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▶経歴：

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(修士論文 : 有効場の理論に基づく超流動3He-B相の普遍的性質の研究)

2018 - 2021　東工大 西田研究室 博士課程

(博士論文 : Transport Properties of Resonant Fermi Gases)

Universal induced interaction between heavy polarons in superfluid

— Effective field theory approach to polaron physics —

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Plan of this talk

1. **Introduction of the polaron**
   - Polaron in ultracold atoms
   - Induced interaction between polarons

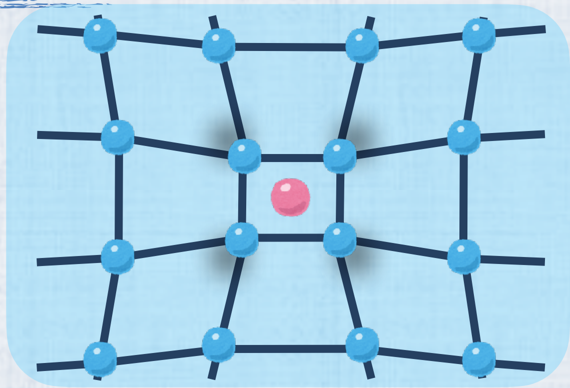
2. **Induced interaction between polarons**
   - Theoretical formulation of polaron physics
   - Yukawa potential
   - Van der Waals potential mediated by phonons

3. **Magnitude of the potential in the BCS-BEC cross over**

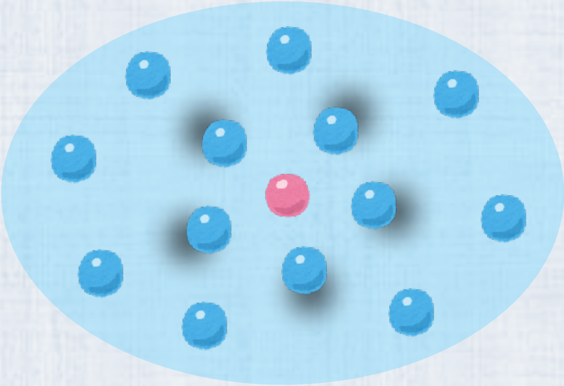
4. **Summary**

What is the polaron?

Polaron (Landau's original definition)
: an electron interacting with phonons in a crystal
lattice wave inducing **polarization**



Polaron in ultracold atoms
: an impurity interacting with quantum gas particles



▸ Ultracold atoms provide a simple and ideal research platform.

✓ **High experimental controllability**

- quantum statistics & internal degrees of freedom
- impurity-medium and medium-medium interaction

▸ For example, {Bose / Fermi} polaron : an impurity in {a Bose gas (often in a superfluid) / a free Fermi gas (single-component)}

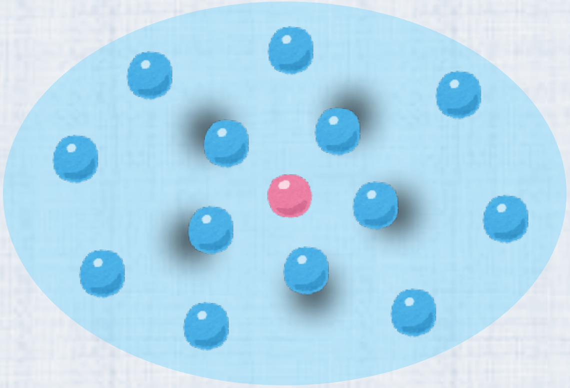
From one-body to two-body

Bose polaron : impurities immersed in a superfluid

interacting with superfluid phonons

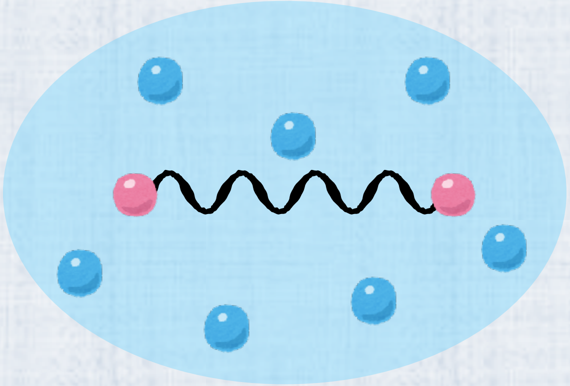
One impurity problem

: effective mass, mobility, dressing cloud, etc.



Two impurity problem

: induced interaction, bipolaron state, etc.



Interaction mediated by exchanging bosonic quanta

✓ **Crucial in modern physics**

e.g.

- the fundamental interaction by gauge bosons
- the nuclear force by pions
- an attractive electron-electron interaction by lattice phonons for superconductivity

Induced Interaction between impurities

Bose polaron : impurities immersed in a superfluid

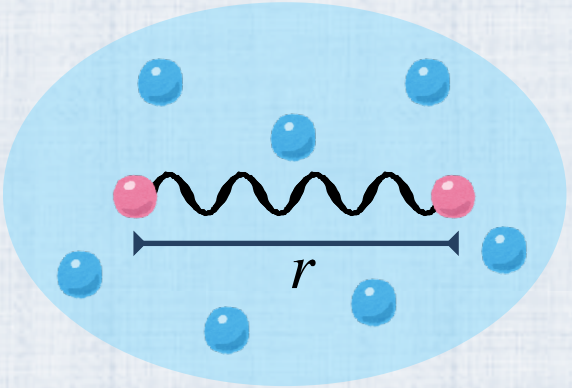
interacting with superfluid phonons

Two impurity problem

: induced interaction, bipolaron state, etc.

Interaction mediated by exchanging bosonic quanta

Superfluid phonons

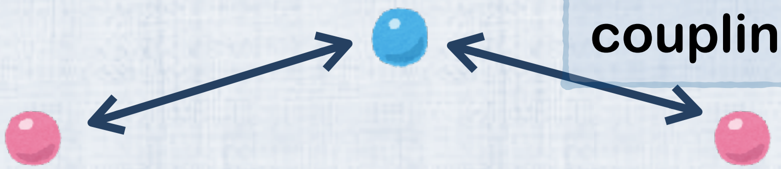


▸ **The** { **Yukawa** / **Efimov** } **potential** at { weak / strong } impurity-medium coupling

N. Pascal, J. Phys. Soc. Jpn. **87**, 043002 (2018)

$$V(r) \sim -\frac{e^{-\sqrt{2}r/\xi}}{r} \qquad -\frac{1}{r^2}$$

weak → strong g_{IM}



coupling g_{IM}

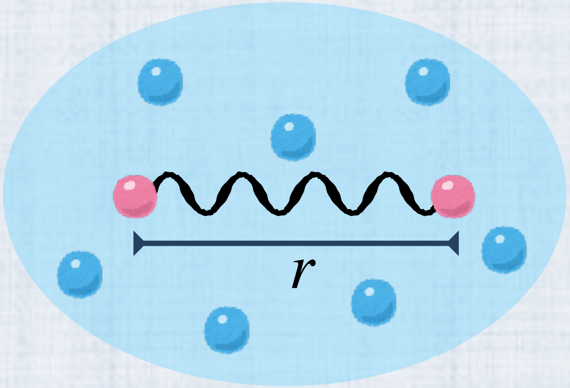
Induced Interaction between impurities

Bose polaron : impurities immersed in a superfluid

interacting with superfluid phonons

Two impurity problem

: induced interaction, bipolaron state, etc.



Interaction mediated by exchanging bosonic quanta

Superfluid phonons

The Yukawa potential at weak impurity-medium interaction

$$V(r) \sim -\frac{e^{-\sqrt{2}r/\xi}}{r}$$ (ξ : healing length)

See e.g. Pethick & Smith's text book "Bose-Einstein condensation in Dilute gases"

- Short-range potential mediated by a **gapped** mode
- There is a **gapless** mode (superfluid phonon) governing long-range physics

Why does a gapped mode appear?

Is there a long-range induced interaction mediated by gapless modes?

Plan of this talk

1. Introduction of the polaron

Why does a gapped mode appear?

Is there a long-range induced interaction mediated by gapless modes?

2. **Induced interaction between polarons**
    - Theoretical formulation of polaron physics
    - Yukawa potential
    - Van der Waals potential mediated by phonons

3. Magnitude of the potential in the BCS-BEC cross over

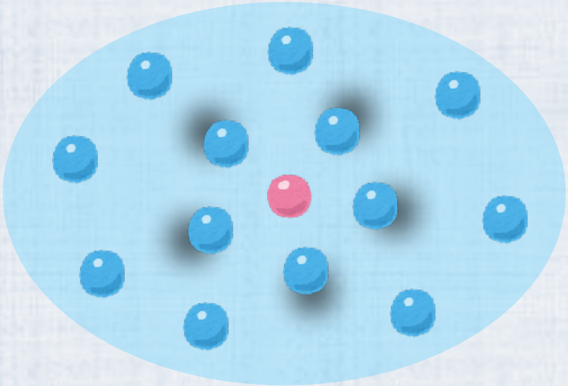
4. Summary

Theoretical formulation of polaron physics

✓ Microscopic model :

Bose gas interacting with impurities

$$\mathcal{L}_{\mathrm{micro}}(x) = \mathcal{L}_{\mathrm{imp}}(x) + \mathcal{L}_{\mathrm{medium}}(x) + \mathcal{L}_{\mathrm{int}}(x)$$



▸ Impurity-medium interaction in the contact *s*-wave channel

$$\mathcal{L}_{\mathrm{int}}(x) = -g_{IM} \underbrace{\Phi^\dagger(x)\Phi(x)}_{\text{Impurity density}} \underbrace{\psi^\dagger(x)\psi(x)}_{\text{Medium density}}$$

✓ Our problem is to find $S_{\mathrm{polaron}}[\Phi, \Phi^\dagger]$ by integrating out the medium

$$\exp\left[iS_{\mathrm{polaron}}[\Phi, \Phi^\dagger]\right] = \int \mathcal{D}(\psi, \psi^\dagger)\ \exp\left[i\int dt d^3x\, \mathcal{L}_{\mathrm{micro}}(x)\right]$$

▸ Formally simple, but difficult to perform the integration

Usual method: Bogoliubov approximation

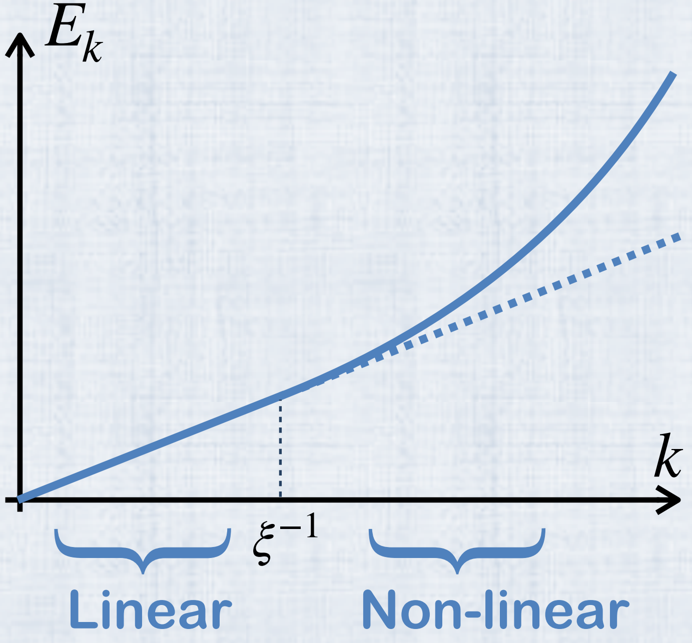
✓ Bogoliubov approximation for the medium

Medium = weak interacting Bose gas

$$\int d^3x\, \mathcal{L}_{\text{medium}}(x) \simeq \sum_{\boldsymbol{k}} \left[i b^\dagger_{\boldsymbol{k}}(t)\partial_t b_{\boldsymbol{k}}(t) - E_{\boldsymbol{k}} b^\dagger_{\boldsymbol{k}}(t) b_{\boldsymbol{k}}(t) \right]$$

▸ **Bogoliubov dispersion** $E_{\boldsymbol{k}} = \sqrt{\epsilon_{\boldsymbol{k}}(\epsilon_{\boldsymbol{k}} + 2\mu)}$

$$\epsilon_{\boldsymbol{k}} = \frac{\boldsymbol{k}^2}{2m}$$



✓ Fröhlich interaction term

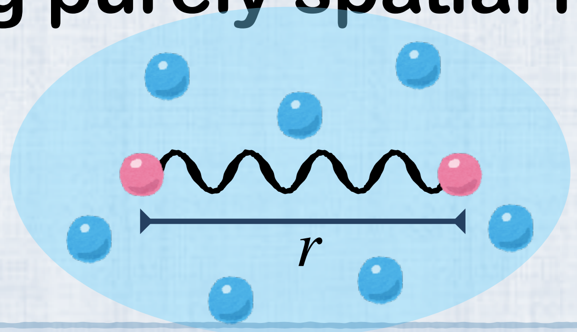
$$\mathcal{L}_{\text{int}}(x) \simeq -g_{IM}\Phi^\dagger(x)\Phi(x)\sqrt{\frac{n}{V}}\sum_{\boldsymbol{k}}\sqrt{\frac{\epsilon_{\boldsymbol{k}}}{E_{\boldsymbol{k}}}}\left[b_{\boldsymbol{k}}(t) + b^\dagger_{-\boldsymbol{k}}(t)\right]e^{i\boldsymbol{k}\cdot\boldsymbol{x}} + O(b^2)$$

Momentum-dependent coupling

Derivation of the Yukawa potential

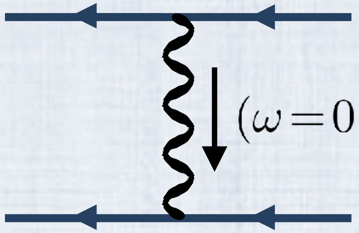
✓ **Static potential = exchanging purely spatial modes with $(\omega = 0,\ \boldsymbol{k})$**

$$V(r) = \int \frac{d^3k}{(2\pi)^3}\,\tilde{V}(k) e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$



▸ **Fröhlich interaction term ➡ One Bogoliubov-mode exchange**

$$\mathcal{L}_{\mathrm{int}}(x) \simeq -g_{IM}\Phi^\dagger(x)\Phi(x)\sqrt{\frac{n}{V}}\sum_{\boldsymbol{k}}\sqrt{\frac{\epsilon_{\boldsymbol{k}}}{E_{\boldsymbol{k}}}}\left[b_{\boldsymbol{k}}(t) + b^\dagger_{-\boldsymbol{k}}(t)\right]e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

$\tilde{V}(k) \sim$  $(\omega=0,\ \boldsymbol{k})$

$$\sim \left(-g_{IM}\sqrt{\frac{n}{V}}\sqrt{\frac{\epsilon_{\boldsymbol{k}}}{E_{\boldsymbol{k}}}}\right)^2 G(\omega=0,\boldsymbol{k}) = g_{IM}^2\frac{n}{V}\frac{\epsilon_{\boldsymbol{k}}}{E_{\boldsymbol{k}}}\left(\frac{1}{-E_{\boldsymbol{k}}}\right) = -g_{IM}^2\frac{n}{V}\frac{1}{\epsilon_{\boldsymbol{k}}+2\mu}$$

▸ **Bogoliubov dispersion** $E_{\boldsymbol{k}} = \sqrt{\epsilon_{\boldsymbol{k}}(\epsilon_{\boldsymbol{k}}+2\mu)}$

$$\epsilon_{\boldsymbol{k}} = \frac{\boldsymbol{k}^2}{2m}$$

Derivation of the Yukawa potential

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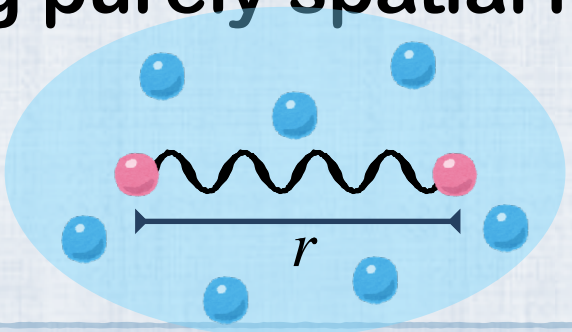
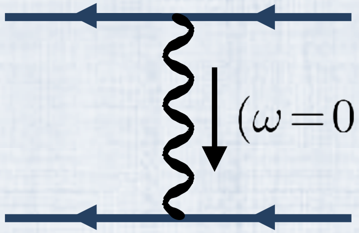
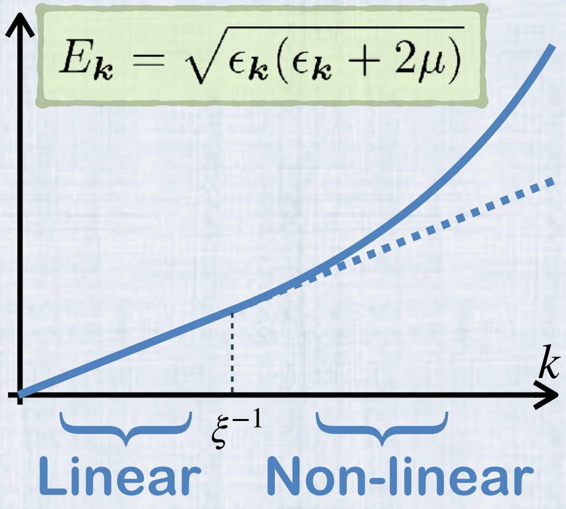


- **Fröhlich interaction term ➡ One Bogoliubov-mode exchange**

$$\mathcal{L}_{\text{int}}(x) \simeq -g_{IM}\Phi^\dagger(x)\Phi(x)\sqrt{\frac{n}{V}}\sum_{\boldsymbol{k}}\sqrt{\frac{\epsilon_{\boldsymbol{k}}}{E_{\boldsymbol{k}}}}\left[b_{\boldsymbol{k}}(t) + b^\dagger_{-\boldsymbol{k}}(t)\right]e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

$\tilde{V}(k) \sim$  $(\omega = 0,\ \boldsymbol{k}) \sim -g_{IM}^2 \frac{n}{V}\frac{1}{\epsilon_{\boldsymbol{k}} + 2\mu}$



- Only the non-linear part survives
- like a **gapped-mode** propagator

➡ $V(r) \sim -\frac{e^{-\sqrt{2}r/\xi}}{r}$ **: Yukawa potential**

Plan of this talk

Why does a gapped mode appear?

➡ The non-linear dispersion part only survives and behaves like a gapped propagator

Is there a long-range induced interaction mediated by gapless modes?

2. Induced interaction between polarons

- Theoretical formulation of polaron physics
- Yukawa potential
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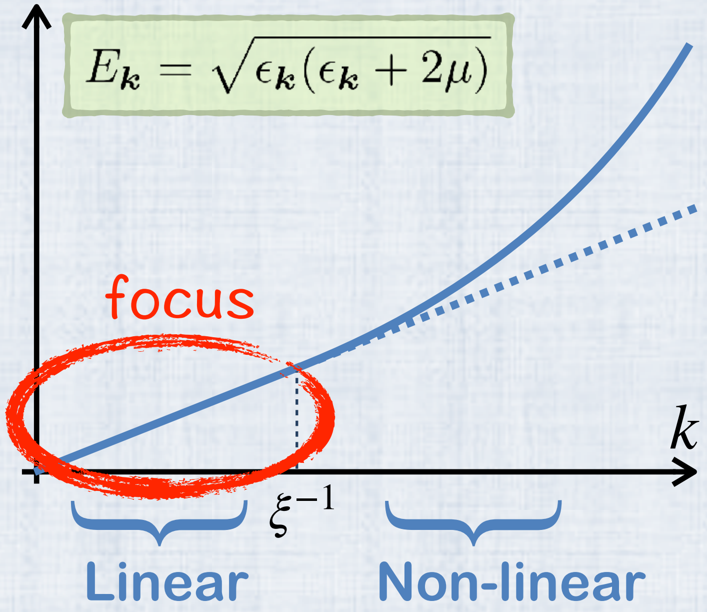
Effective field theory method: Superfluid EFT

Focus only on the linear dispersion regime

DoF: phonon field $\phi(x)$, showing a linear dispersion



Due to **the Galilean invariance** of the medium,
the Lagrangian is **generally** given in

✓ Galilean superfluid EFT for the medium

$$\mathcal{L}_{\text{medium}}(x) = \mathcal{P}(\theta(x))$$

$\mathcal{P}(\mu)$: Pressure as a function of μ

Galilean invariant combination $\theta(x) = \mu - \partial_t \phi(x) - \dfrac{(\nabla\phi(x))^2}{2m}$

M. Greiter, F. Wilczek, & E. Witten, Mod. Phys. Lett. B **3**, 903 (1989);
D. T. Son & M. Wingate, Ann. Phys. **321**, 197 (2006).

✓ Interaction term

$$\mathcal{L}_{\text{int}}(x) = -g_{IM} \Phi^\dagger(x)\Phi(x) n(\theta(x))$$

with $n(\mu) = \mathcal{P}'(\mu)$

cf.
$\mathcal{L}_{\text{int}}(x) = -g_{IM} \Phi^\dagger(x)\Phi(x)\psi^\dagger(x)\psi(x)$

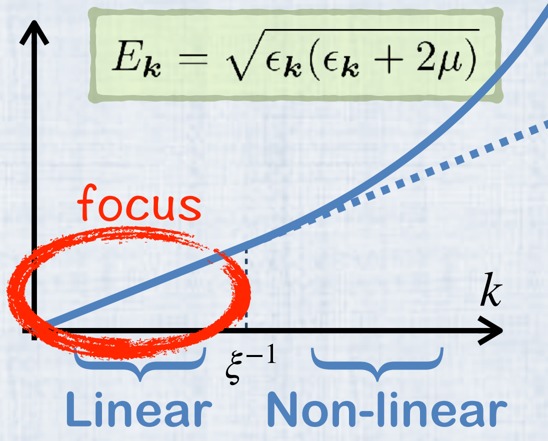
Medium density

Effective theory for Bose polarons

✓ Our effective theory

$$\mathcal{L}_{\mathrm{eff}}(x) = \mathcal{L}_{\mathrm{imp}}(x) + \mathcal{P}(\theta(x)) - g_{IM}\Phi^\dagger(x)\Phi(x)n(\theta(x))$$

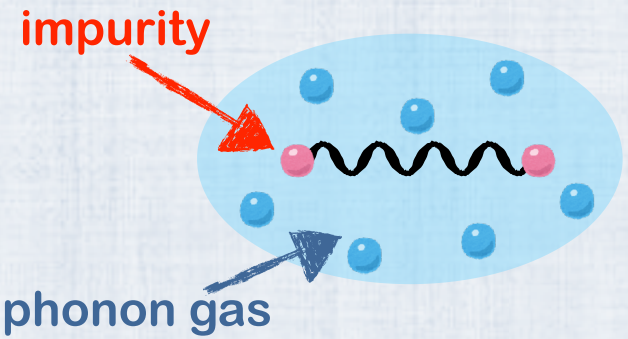
▸ **Galilean invariant combination** $\theta(x) = \mu - \partial_t\phi(x) - \frac{(\nabla\phi(x))^2}{2m}$



▸ Our assumptions are only two:

- **Galilean invariant medium**
- **Contact s-wave impurity-medium coupling**

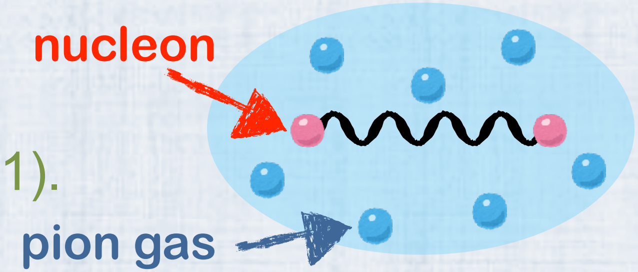
➡ Universal !! : **Independent of the details of the medium**



Our remaining task is **to calculate induced interactions from our effective theory**

cf. nuclear forces are computed from chiral effective field theory

See e.g., R. Machleidt & D. R. Entem,
"Chiral effective field theory and nuclear forces," Phys. Rept. **503**, 1 (2011).



Induced interaction mediated by phonons

Expanding $\mathcal{P}(\theta)$ & $n(\theta)$ and keeping the leading terms with rescaling $\varphi = \sqrt{\chi}\phi$

$$\mathcal{L}(x) = \mathcal{L}_{\text{imp}}(x) - g_{IM} n \Phi^\dagger \Phi + \frac{1}{2}(\partial_t \varphi)^2 - \frac{1}{2}c_s^2 (\boldsymbol{\nabla}\varphi)^2 + g_{IM}\left[\sqrt{\chi}\partial_t \varphi + \frac{(\boldsymbol{\nabla}\varphi)^2}{2m}\right]\Phi^\dagger\Phi + \cdots$$

$\chi = n'(\mu)$: compressibility

$c_s = \sqrt{n/(m\chi)}$: speed of sound

Kinetic term for phonons showing the linear dispersion

✓ Interaction terms between impurities and phonons

$g_{IM}\sqrt{\chi}\partial_t \varphi \Phi^\dagger \Phi$: one-body coupling

$g_{IM}\dfrac{(\boldsymbol{\nabla}\varphi)^2}{2m}\Phi^\dagger\Phi$: two-body coupling

- **The coefficients are constrained by the Galilean invariance**

⟷ The Bogoliubov approx. breaks the Galilean invariance.

Induced interaction mediated by phonons

Expanding $\mathcal{P}(\theta)$ & $n(\theta)$ and keeping the leading terms with rescaling $\varphi = \sqrt{\chi}\phi$

$$\mathcal{L}(x) = \mathcal{L}_{\rm imp}(x) - g_{IM} n \Phi^\dagger \Phi + \frac{1}{2}(\partial_t \varphi)^2 - \frac{1}{2} c_s^2 (\boldsymbol{\nabla}\varphi)^2 + g_{IM}\left[\sqrt{\chi}\partial_t \varphi + \frac{(\boldsymbol{\nabla}\varphi)^2}{2m}\right]\Phi^\dagger\Phi + \cdots$$

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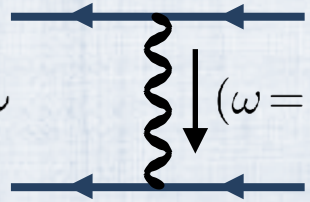
- **The coefficients are constrained by the Galilean invariance**
- One-body coupling ➡ one-phonon exchange

$\tilde{V}(k) \sim$  $(\omega = 0,\ \boldsymbol{k}) \sim \left(g_{IM}\sqrt{\chi}\omega\right)^2 \Delta(\omega = 0, \boldsymbol{k}) = 0$

proportional to $\omega = 0$ due to the time-derivative coupling

Consistent with the previous result

: One-Bogoliubov mode exchange has NO contribution from the linear dispersion part

Induced interaction mediated by phonons

Expanding $\mathcal{P}(\theta)$ & $n(\theta)$ and keeping the leading terms with rescaling $\varphi = \sqrt{\chi}\phi$

$$\mathcal{L}(x) = \mathcal{L}_{\text{imp}}(x) - g_{IM} n \Phi^\dagger \Phi + \frac{1}{2}(\partial_t \varphi)^2 - \frac{1}{2} c_s^2 (\boldsymbol{\nabla}\varphi)^2 + g_{IM}\left[\sqrt{\chi}\partial_t \varphi + \frac{(\boldsymbol{\nabla}\varphi)^2}{2m}\right]\Phi^\dagger \Phi + \cdots$$

$\chi = n'(\mu)$: compressibility

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Kinetic term for phonons showing the linear dispersion

✓ **Interaction terms between impurities and phonons**

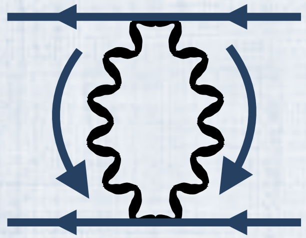
$g_{IM}\sqrt{\chi}\partial_t \varphi \Phi^\dagger \Phi$: one-body coupling

$g_{IM}\dfrac{(\boldsymbol{\nabla}\varphi)^2}{2m}\Phi^\dagger \Phi$: two-body coupling

- **The coefficients are constrained by the Galilean invariance**
- One-body coupling ➡ one-phonon exchange **(NO contribution)**

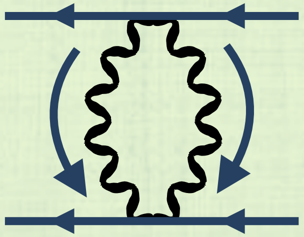
  corresponds to the Fröhlich interaction term in the low-momentum limit

- Two-body coupling ➡ two-phonon exchange



Van der Waals force from two-phonon exchange

✓ **Two-phonon exchange potential** from $g_{IM}\frac{(\nabla\varphi)^2}{2m}\Phi^\dagger\Phi$



At zero temperature

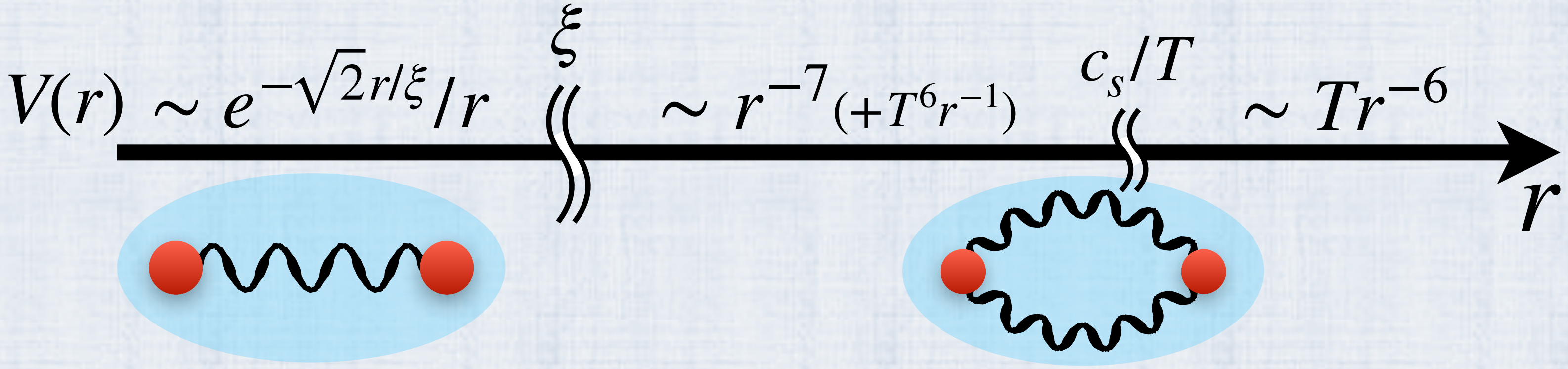
$$V_{T=0}(r) = -g_{IM}^2\frac{43}{128\pi^3 m^2 c_s^3}\frac{1}{r^7}$$

relativistic van der Waals

At finite temperatures (c_s/T : temperature length scale)

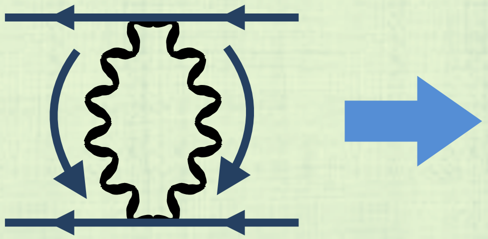
$$V(r) = \begin{cases} V_{T=0}(r) - g_{IM}^2\frac{\pi^3 T^6}{135 m^2 c_s^9}\frac{1}{r} & (r \ll c_s/T) \\ -g_{IM}^2\frac{3T}{16\pi^2 m^2 c_s^4}\frac{1}{r^6} & (r \gg c_s/T) \end{cases}$$

non-relativistic van der Waals



Van der Waals force from two-phonon exchange

✓ **Two-phonon exchange potential** from $g_{IM}\frac{(\nabla\varphi)^2}{2m}\Phi^\dagger\Phi$



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relativistic van der Waals

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non-relativistic van der Waals

- proportional to g_{IM}^2, as in the Yukawa potential
- power-low behavior: weak, but stronger than the Yukawa potential at large distance
- the sound velocity controls the magnitude of the potentials
- **the phonon-induced Casimir interaction**, as an analogy to the usual Casimir effect

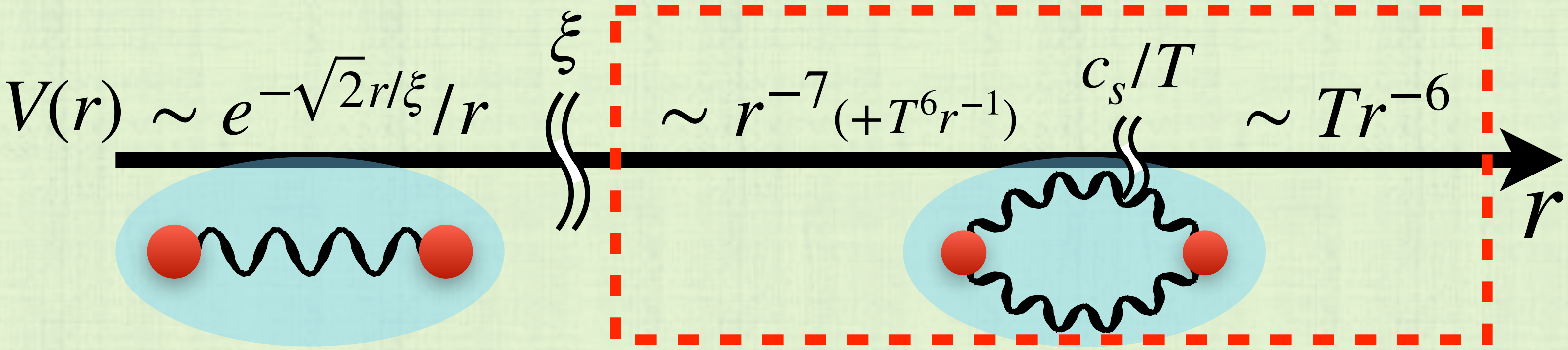
Plan of this talk

Why does a gapped mode appear?

→ The non-linear dispersion part only survives and behaves like a gapped propagator

Is there a long-range induced interaction mediated by gapless modes?

→ Yes, **Two-phonon exchange potential**



3. Magnitude of the potential in the BCS-BEC cross over

4. Summary

Induced potential in BCS-BEC crossover

Our results are based on only two assumptions

- **Galilean invariant medium**
- **Contact s-wave impurity-medium coupling**

→ Our results are valid in the entire BCS-BEC crossover

Induced potential in BCS-BEC crossover

Our results are based on only two assumptions

- **Galilean invariant medium**
- **Contact s-wave impurity-medium coupling**

➡ Our results are valid in the entire BCS-BEC crossover

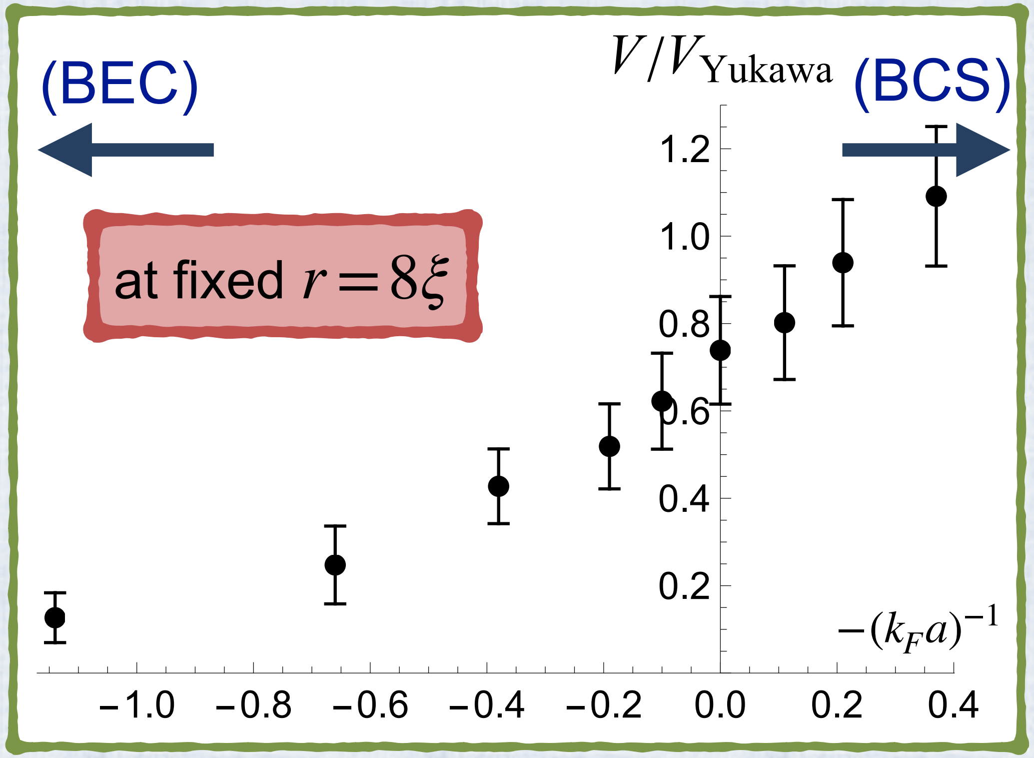
✓ Plotting the ratio of the potential $V_{T=0}(r)$ to the Yukawa potential with the use of the experimental data

S. Hoinka, et al., Nature Physics **13**, 943 (2017)

$$V_{T=0}(r) = -g_{IM}^2 \frac{43}{128\pi^3 m^2 c_s^3} \frac{1}{r^7} \qquad V_{\rm Yukawa}(r) = -g_{IM}^2 \frac{mn}{2\pi} \frac{e^{-\sqrt{2}r/\xi}}{r}$$

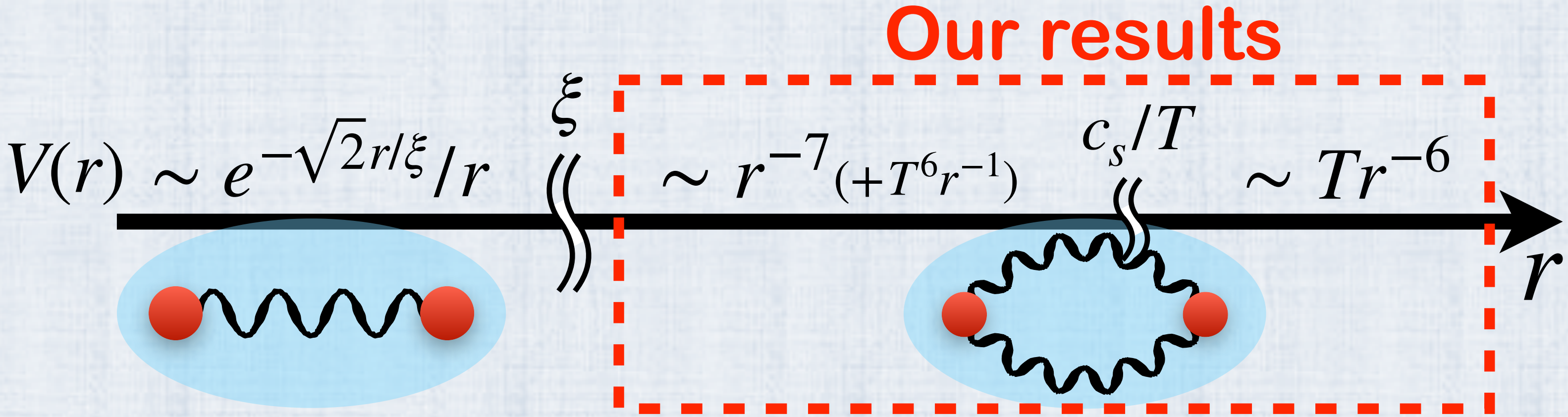
▸ The van der Waals potential becomes relatively larger when $-(k_F a)^{-1}$ increases

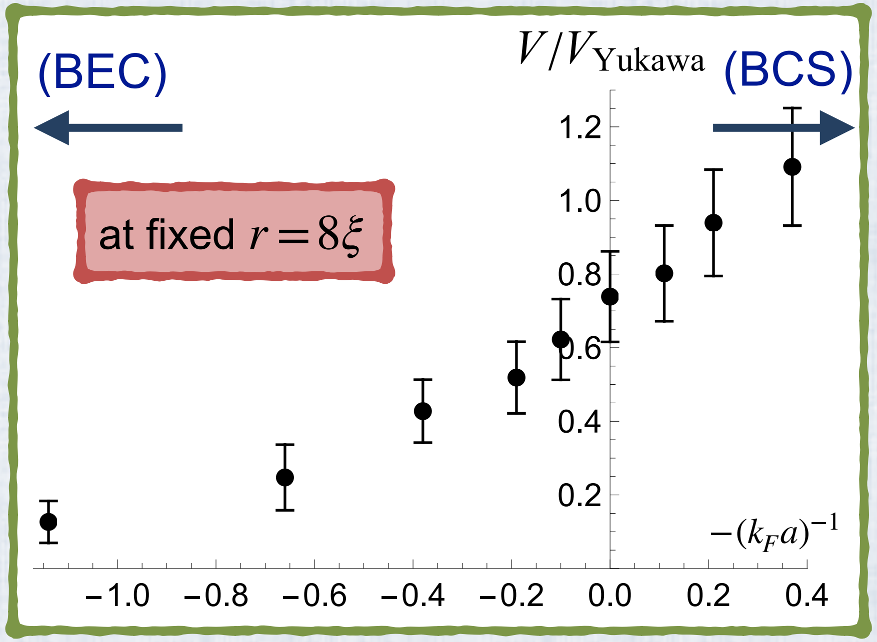
▸ At unitarity, the van der Waals potential is dominant in $r \gtrsim 8\xi$.



Summary

✓ Induced interaction between impurities in a superfluid

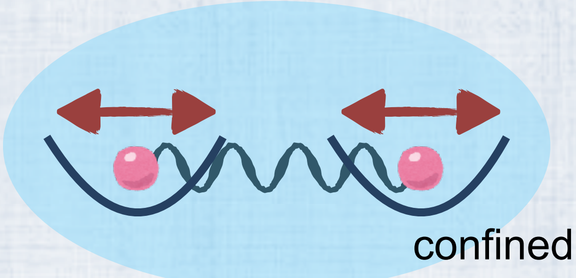




- ▸ based on only two assumptions:
  - **Galilean invariant medium**
  - **Contact s-wave impurity-medium coupling**
- ▸ The van der Waals potential becomes relatively larger when $-(k_F a)^{-1}$ increases

Experimental Observation

- Ramsey interferometry
- Frequency shift of the out-of-phase mode



confined to separate micro-traps

Thank you!! & Danke schön!!