Theoretical Study of Non-Hermitian(NH) Superfluidity in a Finite Fermi System under Harmonic Trapping

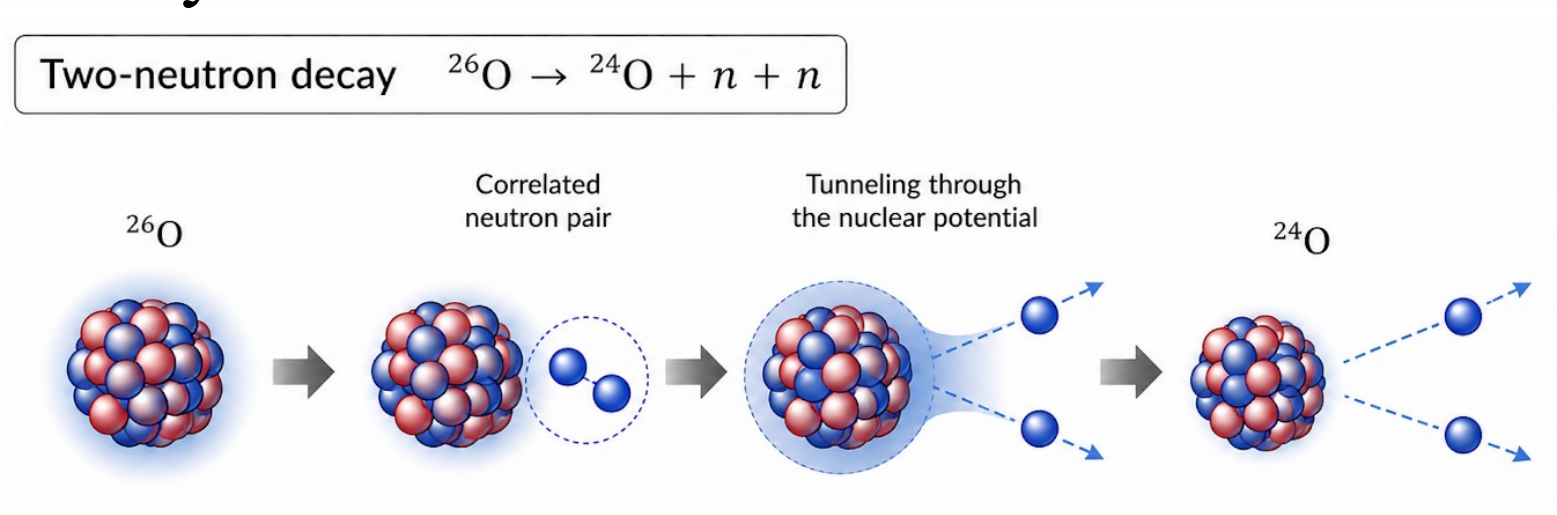
Yunosuke Kamitsubo, Hiroyuki Tajima, Liang Haozhao
Department of physics, the university of Tokyo
27 Aug. 2026

東京大学
THE UNIVERSITY OF TOKYO

Pairing correlation in open quantum system

Introduction

In nuclear system …

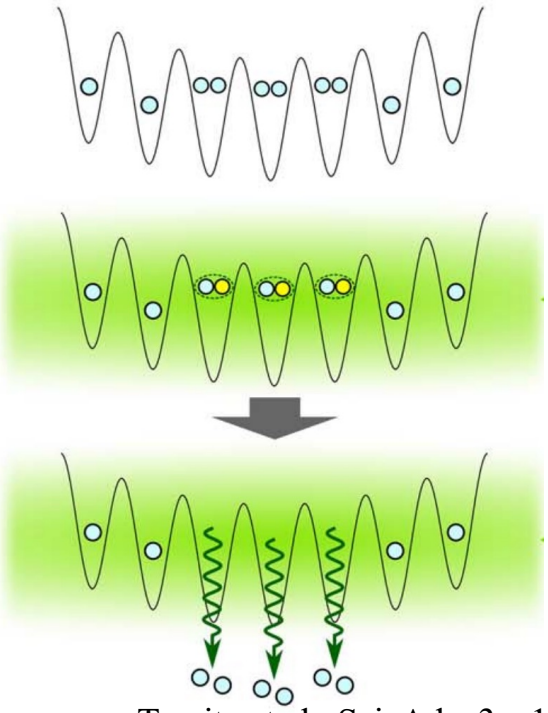


If pairing exists in ^{26}O, does it occur under two-neutron loss?

J. S. Langer et al., Phys. Rev. Lett. 110, 152501 (2013).

Introduction

Two-body loss in ultra cold atom

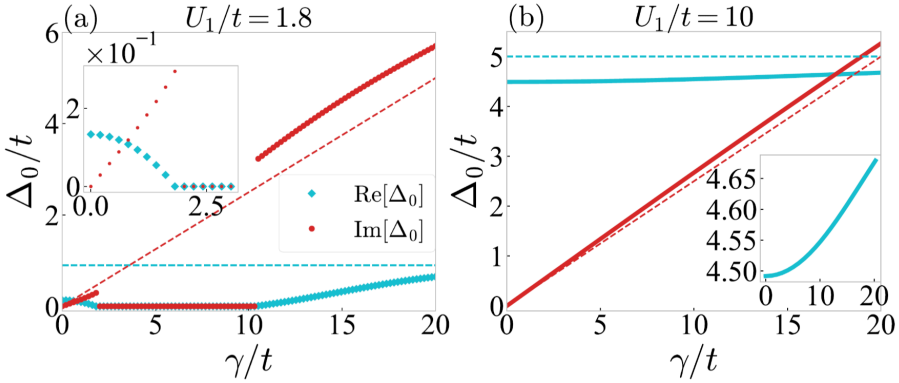


Tomita et al., Sci. Adv. 3, e1701513 (2017)

Experimentally controllable "two-body loss" has been realized using photoassociation.

NH BCS in uniform system

U: Complex valued interaction



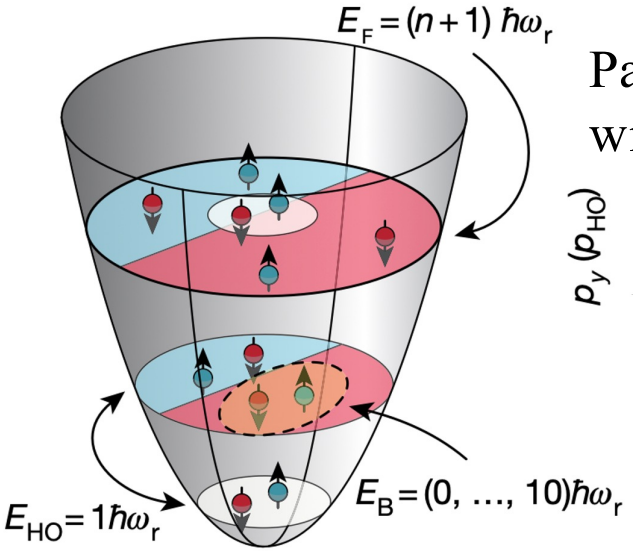
K. Yamamoto *et al.*, *Phys. Rev. Lett.* **123**, 123601 (2019).

Theoretical work of NH BCS including two-body dissipation

Introduction

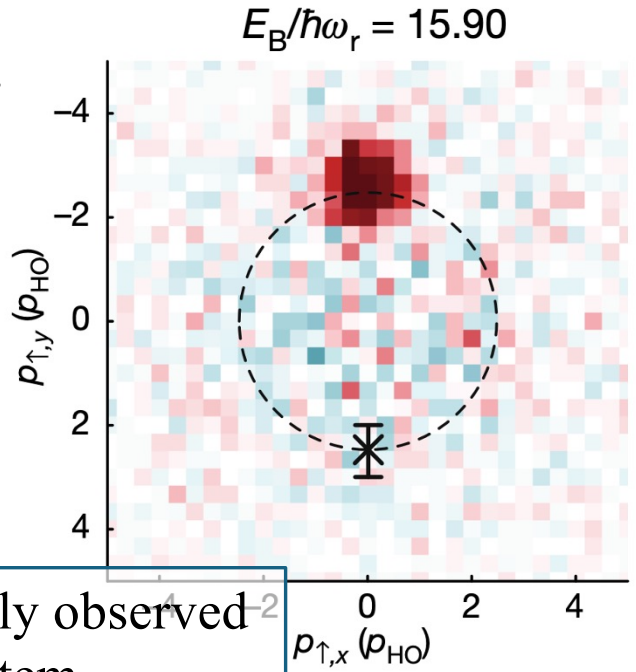
Prior research in “ultra cold atomic system”

BCS pairing phenomena in harmonic trapping



Pairing only occurs within same shell n

$$\Delta \propto \langle \psi_{n\downarrow} \psi_{n'\uparrow} \rangle \quad (n = n')$$



BCS pairing experimentally observed in a few-particle finite system

Finite Fermi system + two-body loss
⟶ NH BCS in finite system

G. M. Bruun, *Phys. Rev. A* **90**, 023621 (2014).
M. Holten *et al.*, *Nature* **606**, 287–291 (2022).

Purpose of this study

・Clarify the effects of **two-body loss** on superfluid states in finite open quantum systems.

・Deepen the theoretical understanding of **non-Hermitian superfluidity** in **finite** systems.

In this talk

・Formulate a **non-Hermitian BCS** theory for **finite** systems with dissipation.

・Numerically calculate and analyze the **complex** pairing gap within the **NH-BCS** framework.

Formalism: Model

Model Hamiltonian

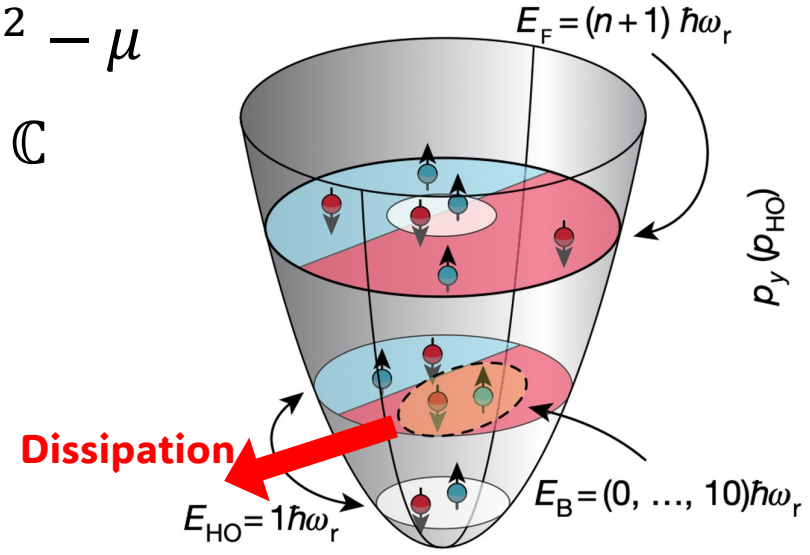
$$H = \sum_{\sigma=\uparrow,\downarrow} \int d^2\boldsymbol{r}\, \psi^\dagger(\boldsymbol{r}) h_0 \psi(\boldsymbol{r}) - g_{\mathrm{NH}} \int d^2\boldsymbol{r}\, \psi_\uparrow^\dagger(\boldsymbol{r}) \psi_\downarrow^\dagger(\boldsymbol{r}) \psi_\downarrow(\boldsymbol{r}) \psi_\uparrow(\boldsymbol{r})$$

$$h_0 = -\frac{\nabla^2}{2m} + \frac{1}{2} m\omega_r^2 r^2 - \mu$$

$$g_{\mathrm{NH}} = g_{\mathrm{R}} + i g_{\mathrm{I}} \in \mathbb{C}$$

Model setup

- Two component fermions $(\uparrow, \downarrow)$
- # of particles is **around 10**
- 2D harmonic trap
- Zero temperature $(T = 0)$
- Short-range attractive (contact) interaction



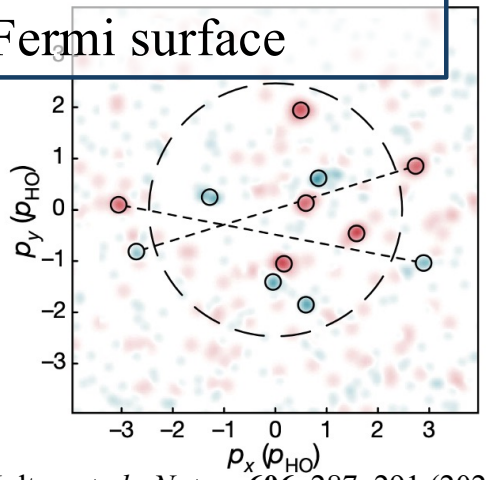
M. Holten *et al.*, *Nature* **606**, 287–291 (2022).

Formalism: Formulation

Applying
- Mean-field approximation
- Intrashell approximation

Pairing occurs mainly between opposite spin states **within the same shell** $(n,\uparrow) \leftrightarrow (n,\downarrow)$

Pairing observed within the same shell near the Fermi surface



M. Holten *et al.*, *Nature* **606**, 287–291 (2022).

Gap equation

$$\frac{1}{G} = \sum_n \frac{1}{2E_n}$$

G: Effective coupling within a harmonic-oscillator shell

$$E_n = [(\epsilon_n - \mu)^2 + \Delta_n^2]^{1/2}$$

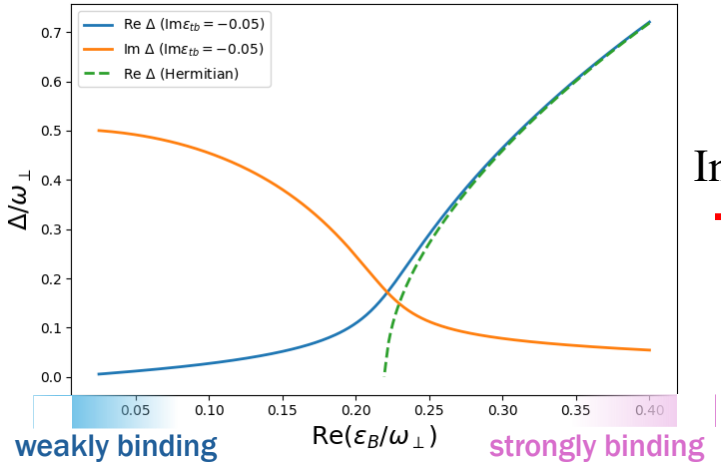
$\epsilon_n = (n+1)\omega_r$: energy of 2D harmonic oscillator

complex pairing gap Δ

Results & Discussion

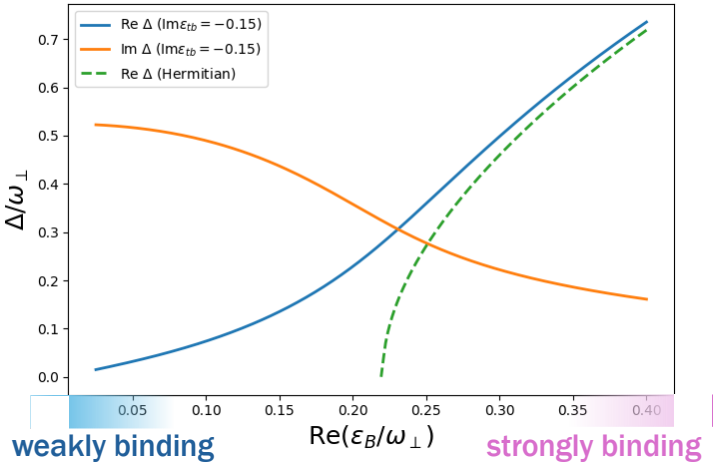
Closed shell

$\langle N \rangle = 6$



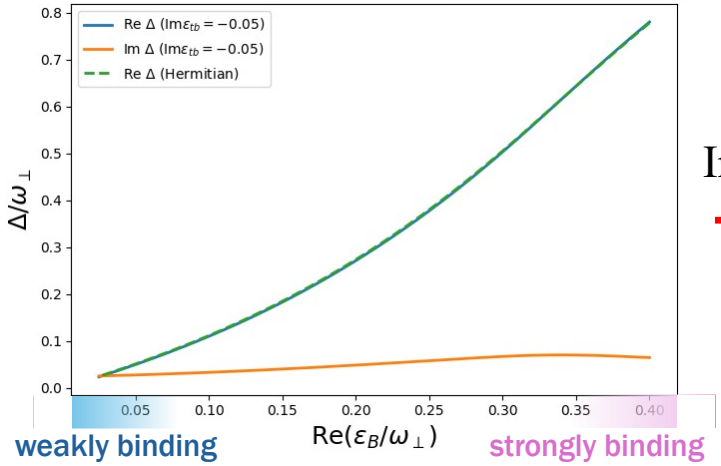
Increasing dissipation

$\langle N \rangle = 6$



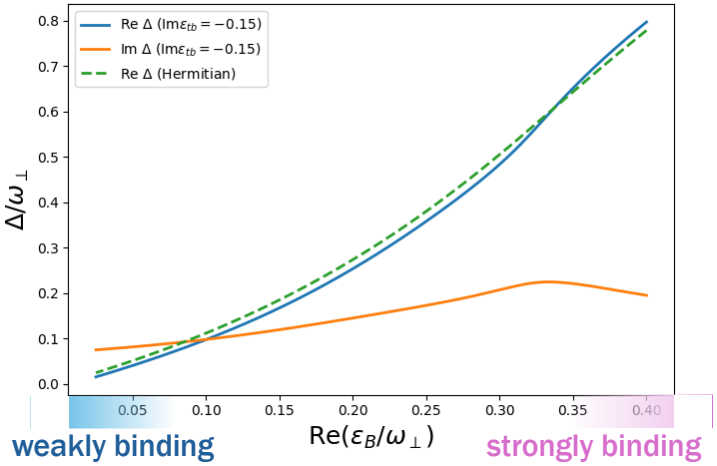
Open shell

$\langle N \rangle = 8$



Increasing dissipation

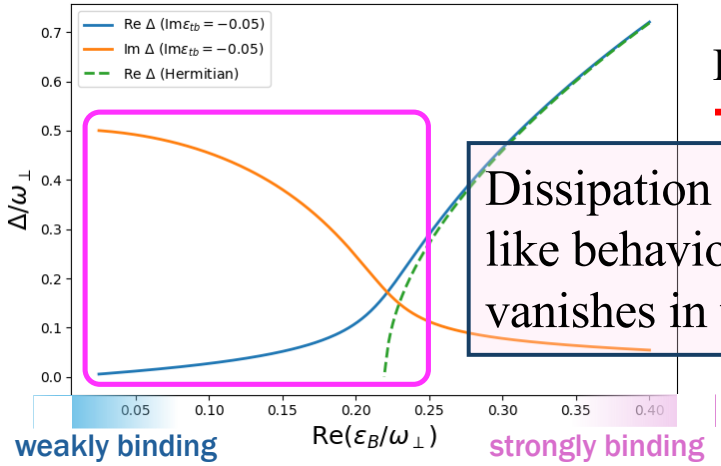
$\langle N \rangle = 8$



Results & Discussion

Closed shell

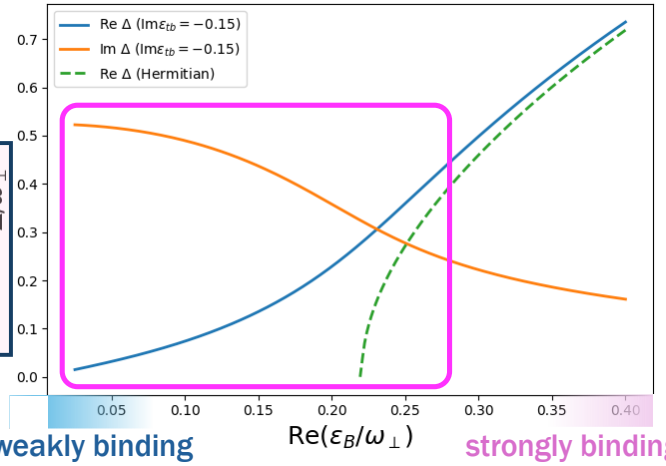
$\langle N \rangle = 6$



Increasing dissipation

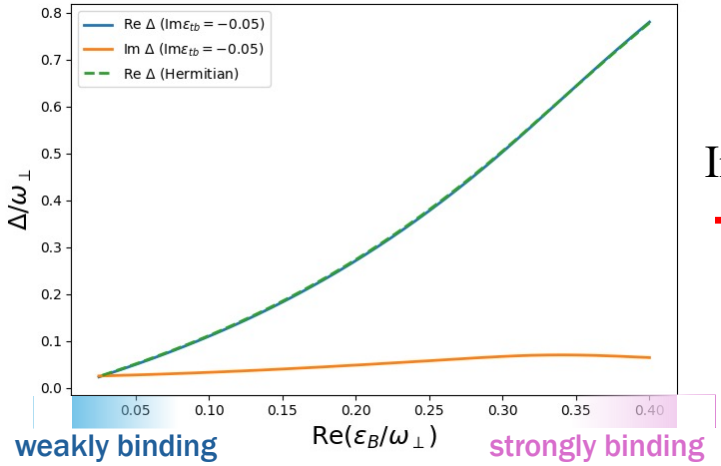
Dissipation induces open-shell like behavior even where Re(Δ) vanishes in the Hermitian case.

$\langle N \rangle = 6$



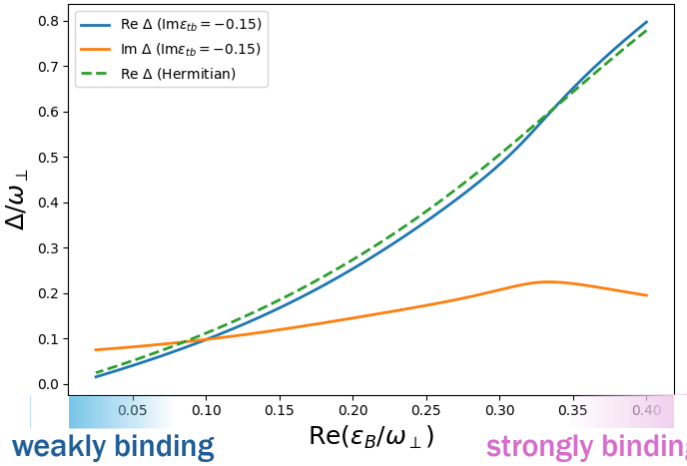
Open shell

$\langle N \rangle = 8$



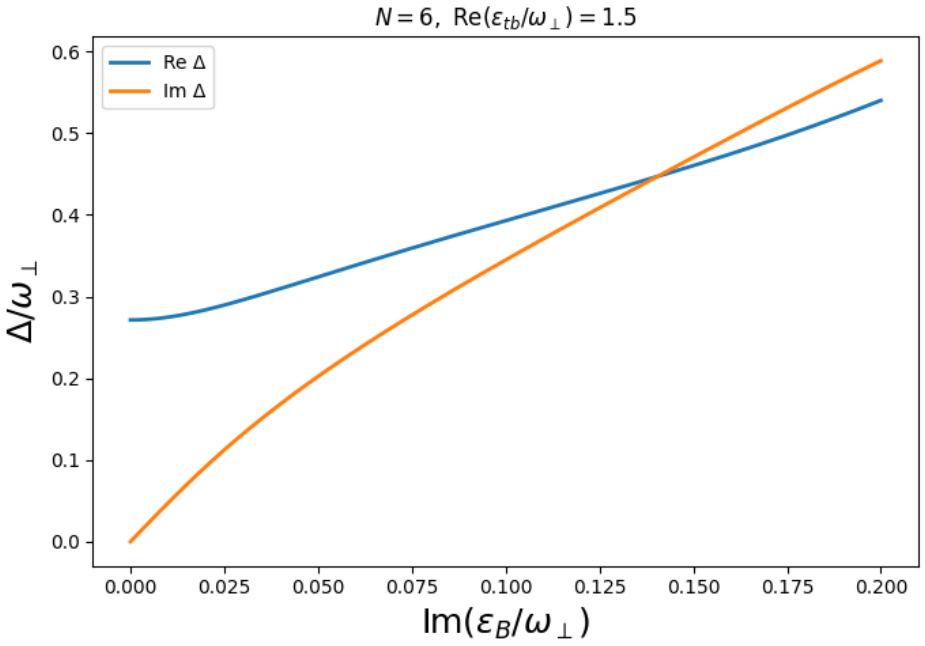
Increasing dissipation

$\langle N \rangle = 8$

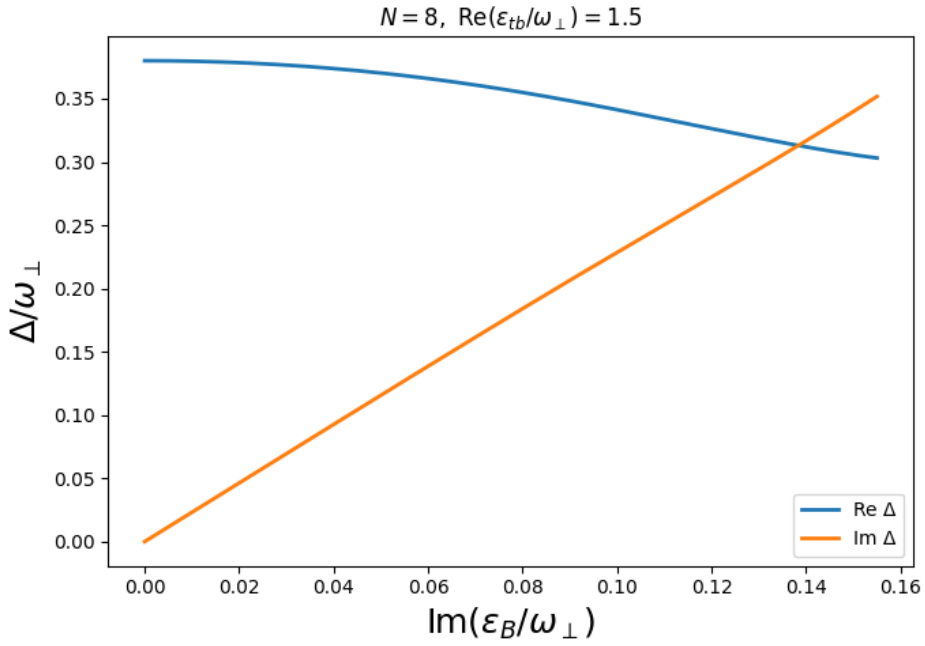


Results & Discussion

Closed shell



Open shell

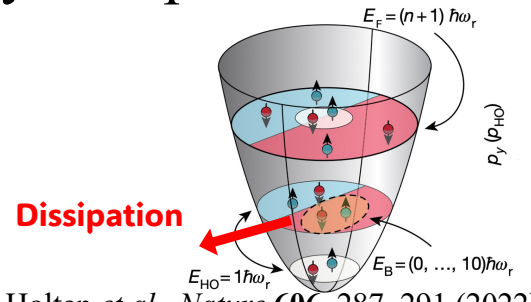


- Two-body loss weakns shell effects, leading to an increase in Re(Δ).
- Im(Δ) increases both closed- and open-shell systems.

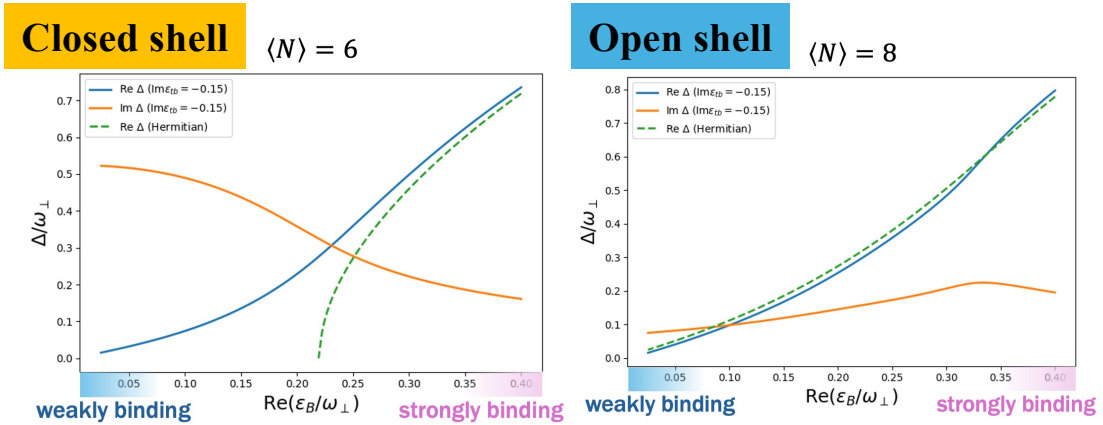
Summary & Outlook

Summary

- We formulated Non-Hermitian superfluidity for a finite trapped system.
- We investigated the complex pairing gap numerically as a function of two-body binding energy and dissipation strength.
- We found that closed-shell systems behave like open-shell systems under two-body dissipation.



M. Holten *et al.*, *Nature* **606**, 287–291 (2022).



Outlook

- Further analysis of pairing in the weakly bound region.
- Free-energy analysis and characterization of the phase transition.