FLEET

ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

SWINBURNE UNIVERSITY OF TECHNOLOGY

Higgs Mode in the BCS-BEC crossover

Paul Dyke

Allan Pennings, Andrew Hogan, Ivan Herrera, Carlos Kuhn, Sascha Hoinka, and Chris Vale.

Optical Sciences Centre, Swinburne University of Technology

Theory Collaborators

Silvia Musolino, Denise Ahmed-Braun, Servas Kokkelmans (TU/E), Hadrien Kurkjian, (CNRS/FR) Victor Collusi (Trento/IT) Matt Davis (UQ)

Non-equilibrium dynamics

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- Non-equilibrium phenomena is ubiquitous in nature.
  - Expansion of the early universe
  - Constant erosion of mountains
  - Many-body systems

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- Highly relevant for quantum material/technologies:

- Cold atoms provide a convenient setting for studying non-equilibrium physics
  - Timescales for dynamics are on the **μs – ms** scale.
  - Relevant parameters can be easily tuned, e.g., interaction strength

Non-equilibrium experiments in cold atoms

Bosons
M. Davis et al., Formation of Bose-Einstein condensates, Universal Themes of Bose-Einstein Condensation.

Excitations beyond Bogoliubov Theory
S. B. Papp et al., Phys. Rev. Lett. 101, 135301 (2008).
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- Slow quench compared to the many-body timescale

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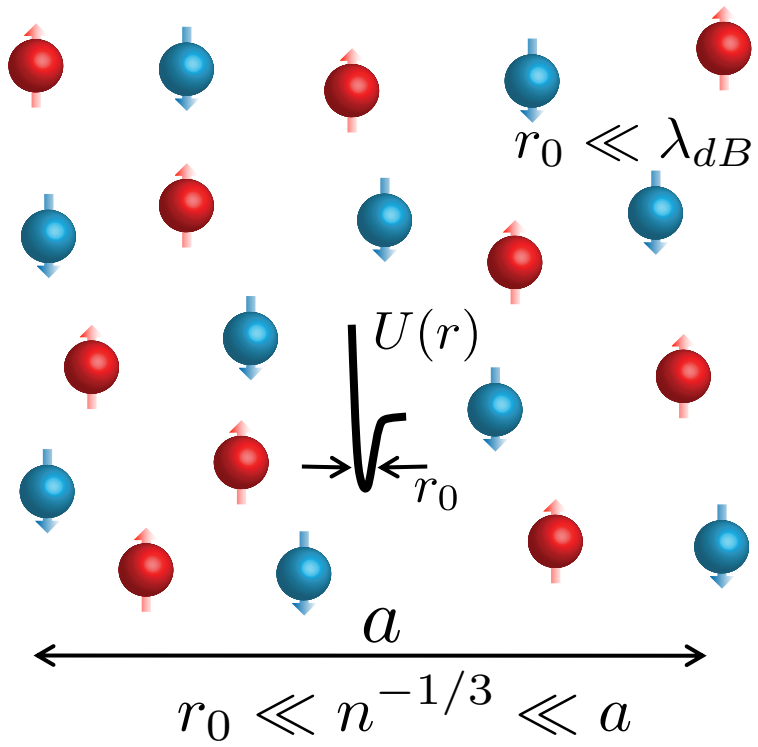

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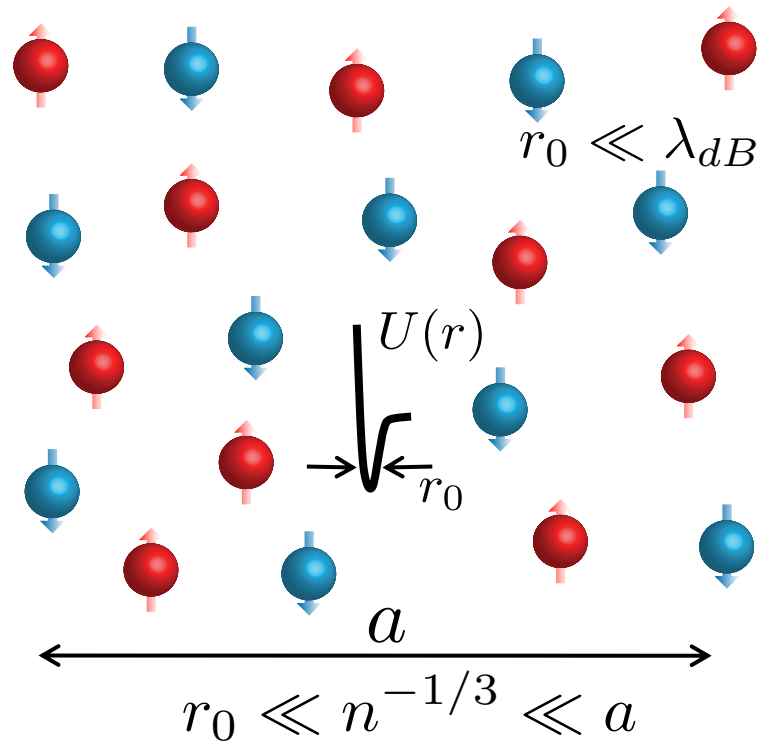
- We study balanced mixtures of cold fermionic ^{6}Li atoms in **two distinct** states
- In dilute Fermi systems, details of short-range potential *U(r)* are not relevant
  ⟹ **universal system** fully specified by *s*-wave scattering length *a*



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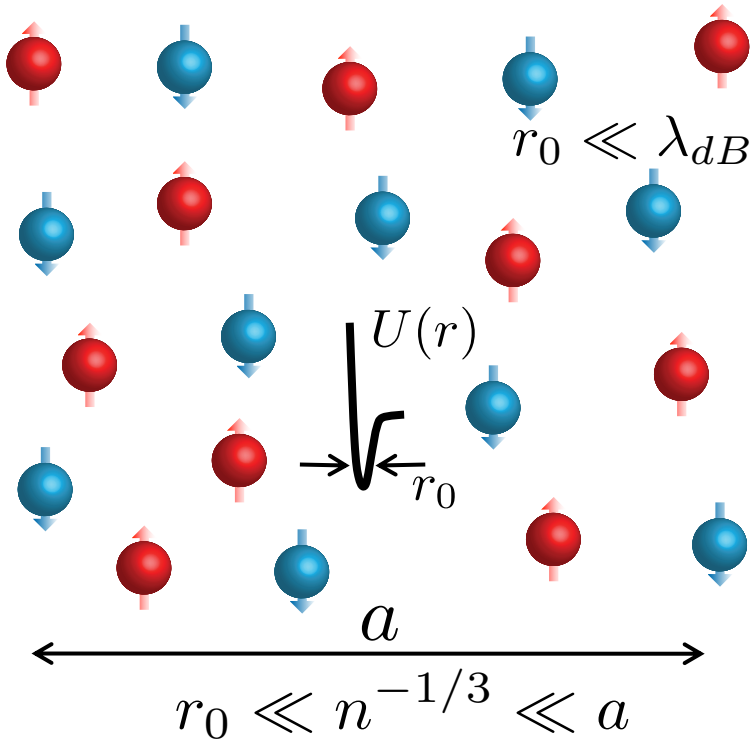
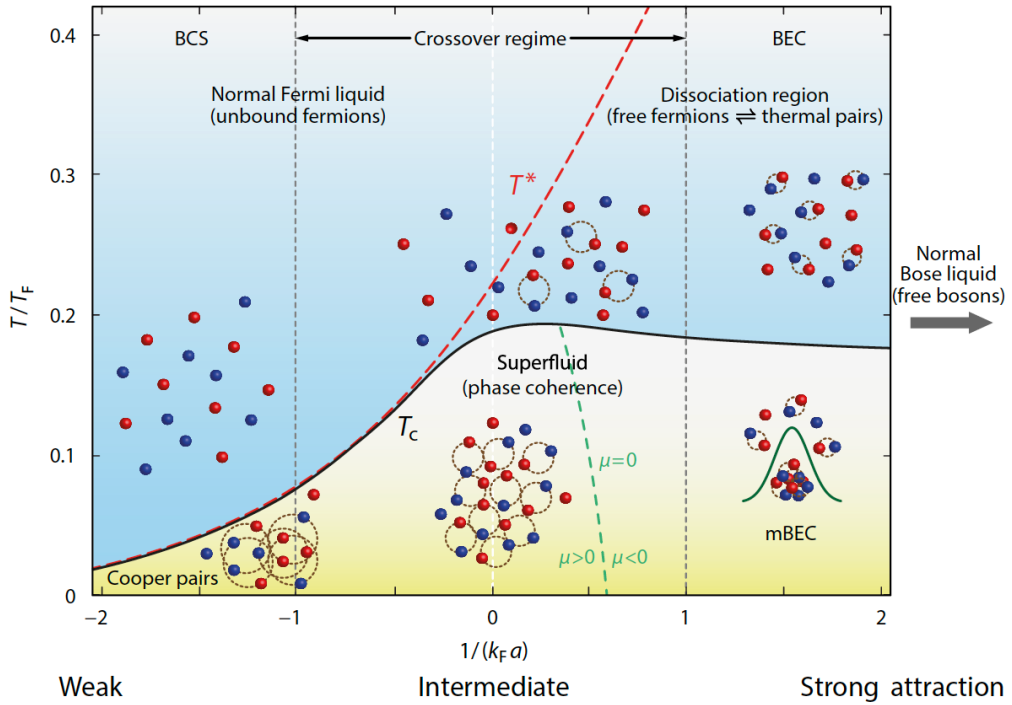
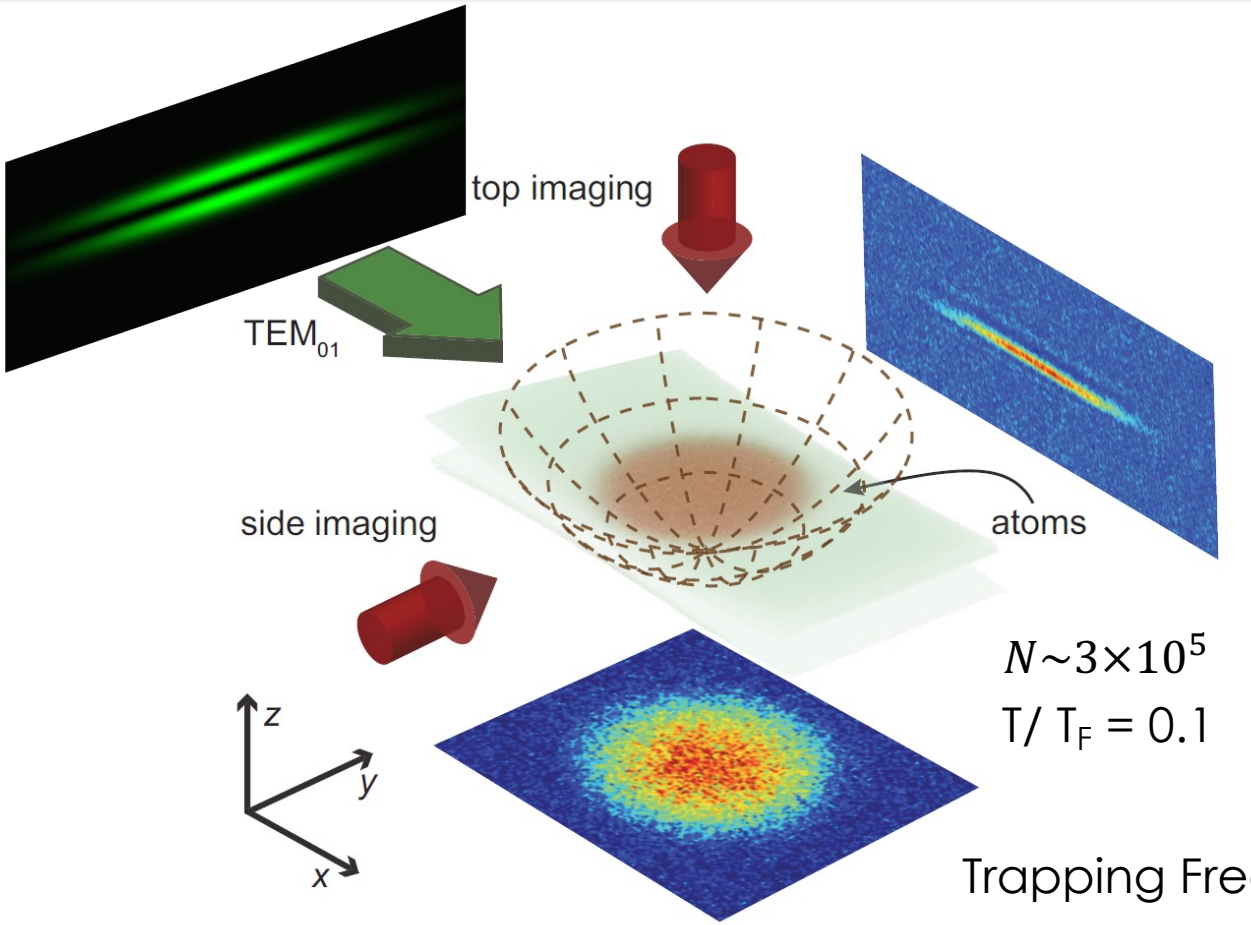
- s-wave interactions tuned via broad Feshbach resonance



S. Hoinka Thesis



Fermi gas preparation



$N \sim 3 \times 10^5$

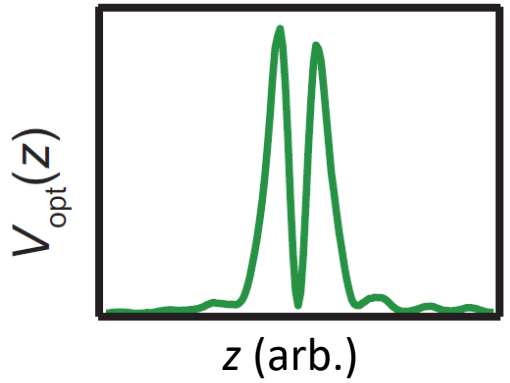
$T/T_F = 0.1$

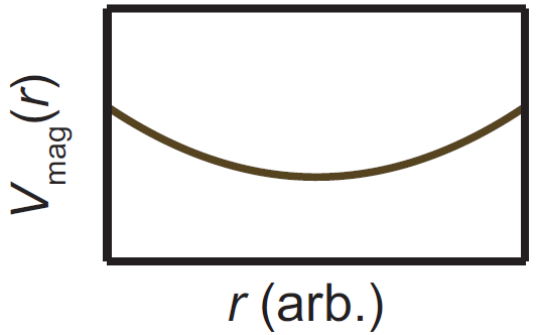
Trapping Frequencies

$$\omega_z/2\pi = 105 \text{ Hz}$$

$$\omega_r/2\pi = 22 \text{ Hz}$$

Transverse profile of the TEM_{01} mode





Harmonic radial trapping potential from residual B field

Continuous Symmetry Breaking

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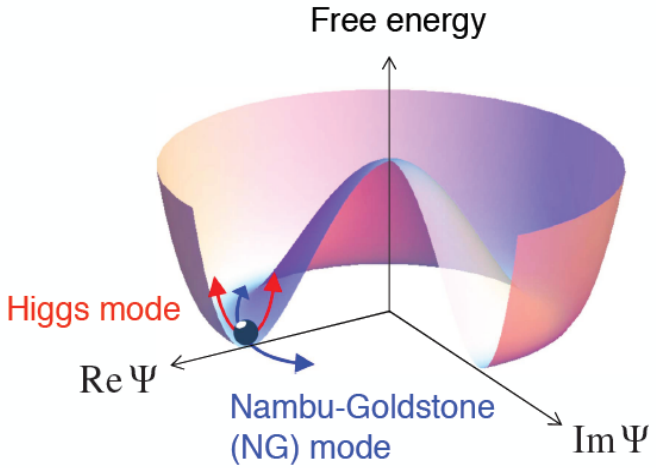

Shimano, Tsuji, Ann. Rev. Cond. Matt. **11**, 103 (2020)

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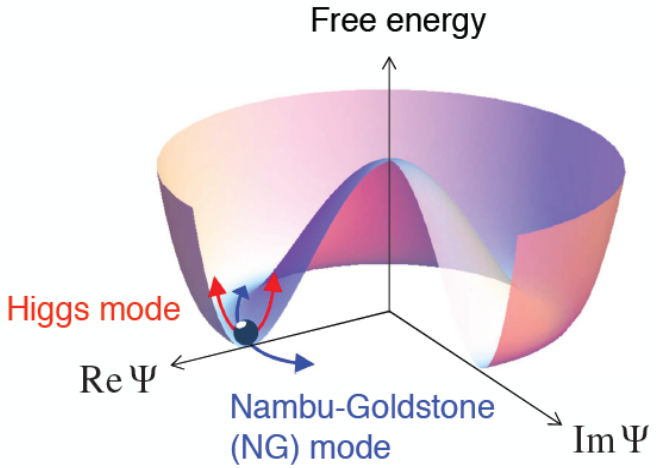

(i) Goldstone mode (gapless)

(ii) Higgs mode (gapped)

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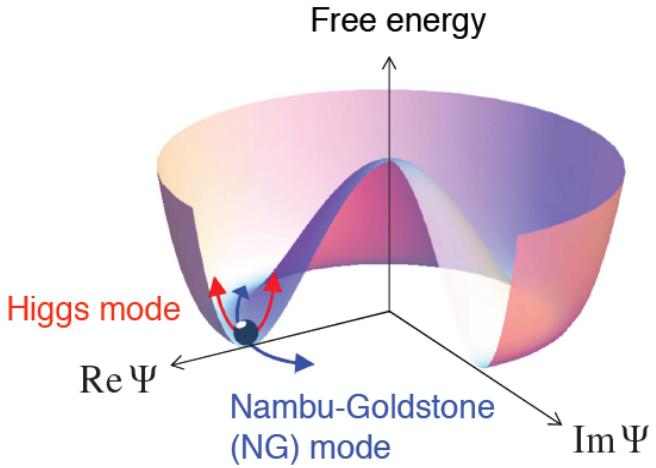

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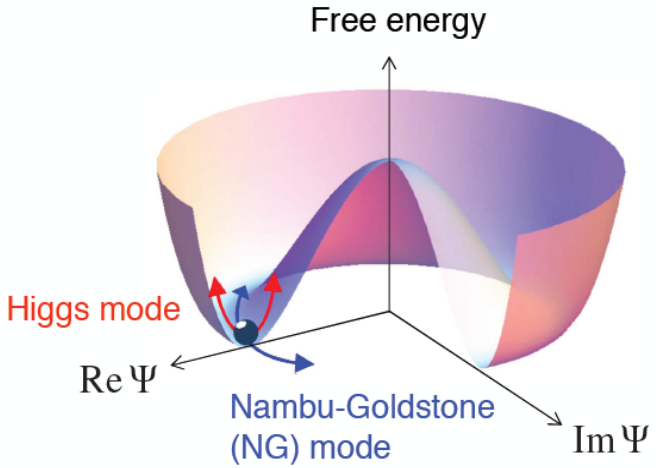

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- Rapid interaction quenches in the superfluid regime allow measurements of the gap frequency.
  Stringari PRA 2012

Higgs Mode in Cold Atoms

PRL 106, 205303 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

Detecting the Amplitude Mode of Strongly Interacting Lattice Bosons by Bragg Scattering

Ulf Bissbort,[1] Sören Götze,[2] Yongqiang Li,[1,3] Jannes Heinze,[2] Jasper S. Krauser,[2] Malte Weinberg,[2] Christoph Becker,[2] Klaus Sengstock,[2] and Walter Hofstetter[1]

[1]*Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, 60438 Frankfurt/Main, Germany*
[2]*Institut für Laser-Physik, Universität Hamburg, 22761 Hamburg, Germany*
[3]*Department of Physics, National University of Defense Technology, Changsha 410073, People's Republic of China*
(Received 12 October 2010; published 20 May 2011)

LETTER doi:10.1038/nature11255

The 'Higgs' amplitude mode at the two-dimensional superfluid/Mott insulator transition

Manuel Endres[1], Takeshi Fukuhara[1], David Pekker[2], Marc Cheneau[1], Peter Schauß[1], Christian Gross[1], Eugene Demler[3], Stefan Kuhr[1,4] & Immanuel Bloch[1,5]

Monitoring and manipulating Higgs and Goldstone modes in a supersolid quantum gas

Julian Léonard, Andrea Morales, Philip Zupancic, Tobias Donner,* Tilman Esslinger

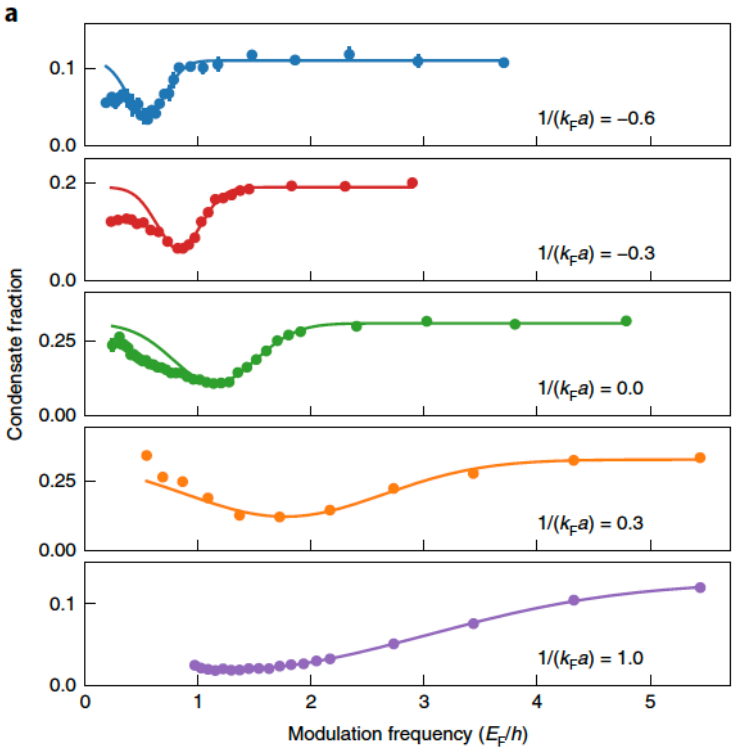
Science **358**, 1415–1418 (2017)

Dipolar gases: Pfau, Ferlaino, Modugno

nature physics LETTERS https://doi.org/10.1038/s41567-018-0128-6

Higgs mode in a strongly interacting fermionic superfluid

A. Behrle[1,3], T. Harrison[1,3], J. Kombe[2], K. Gao[1*], M. Link[1], J.-S. Bernier[2], C. Kollath[2] and M. Köhl[1*]



Kickstarting the Higgs mode

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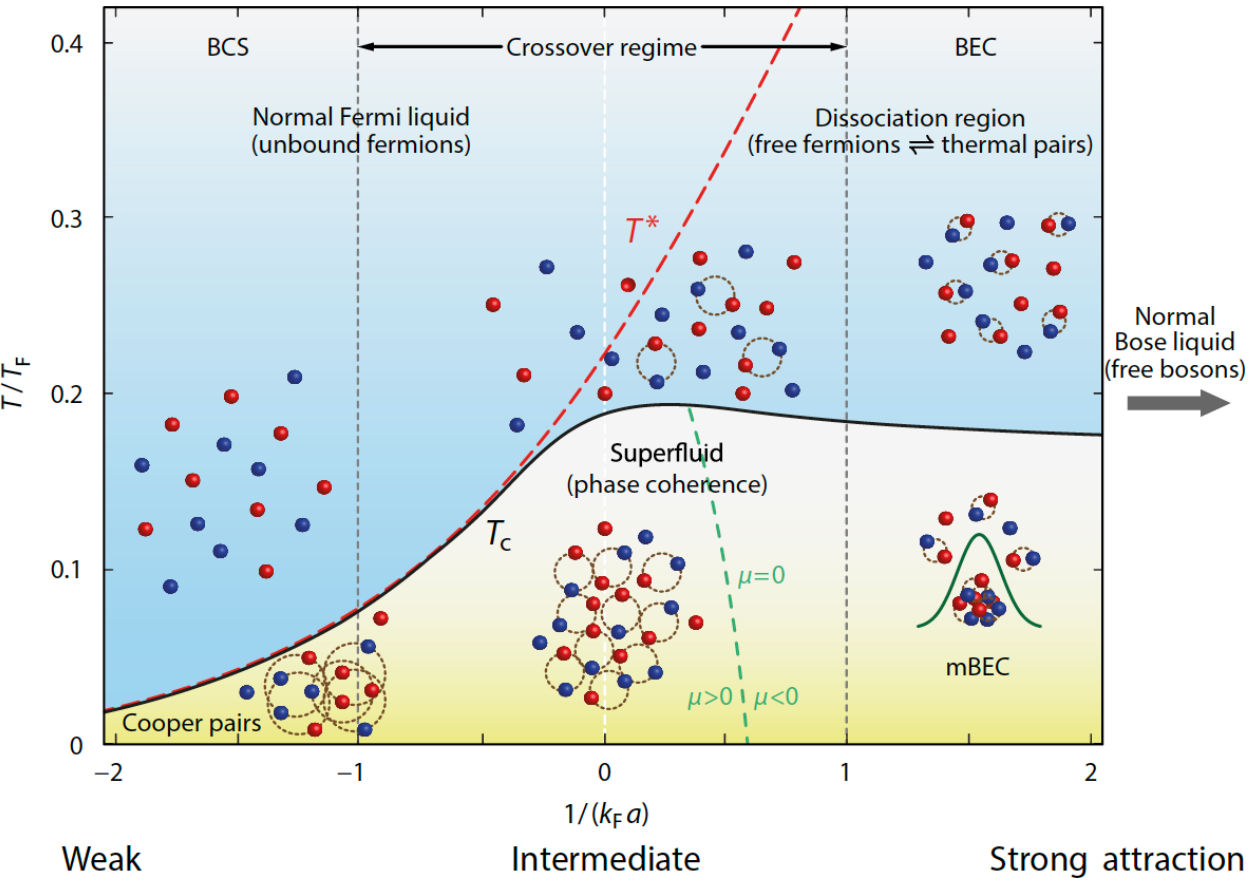

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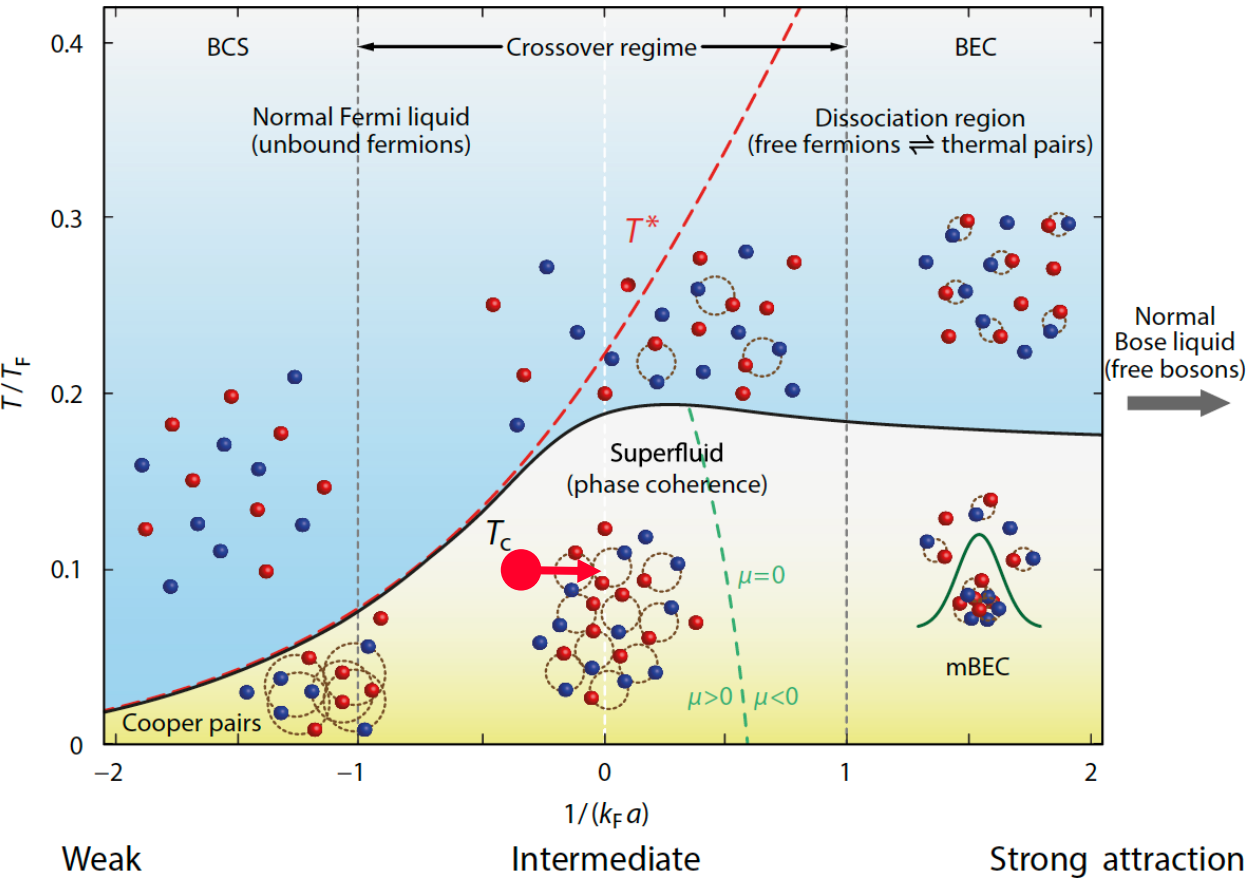

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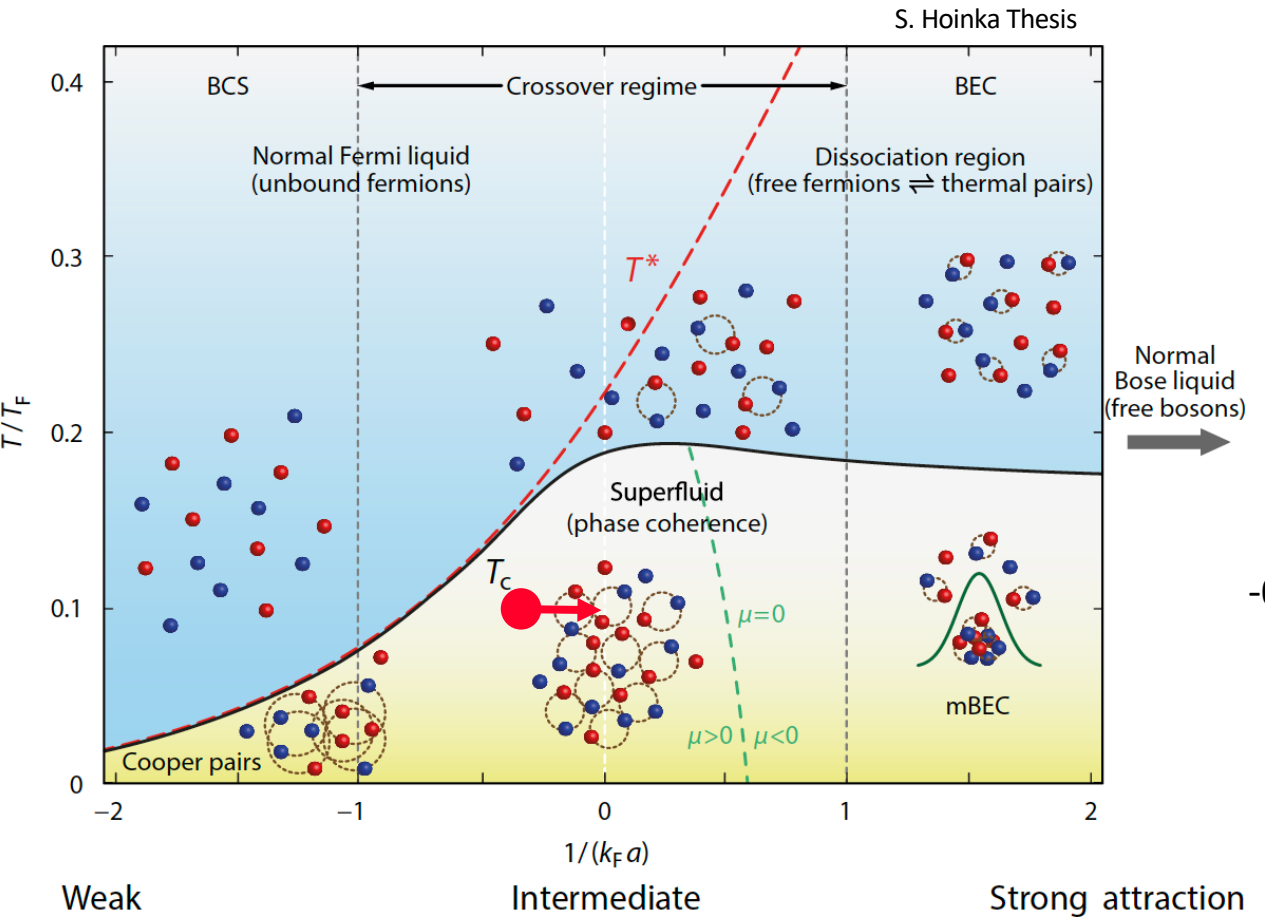
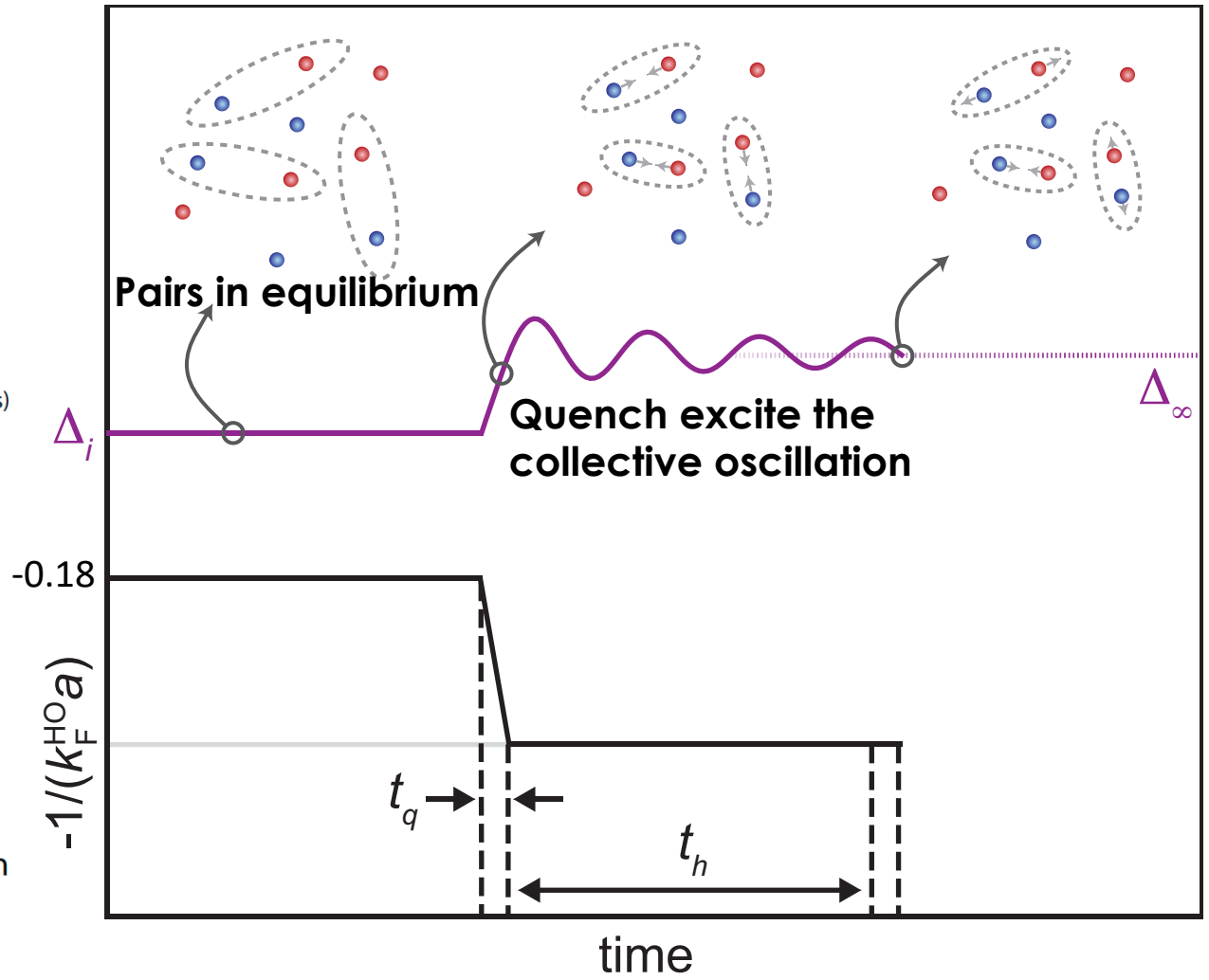
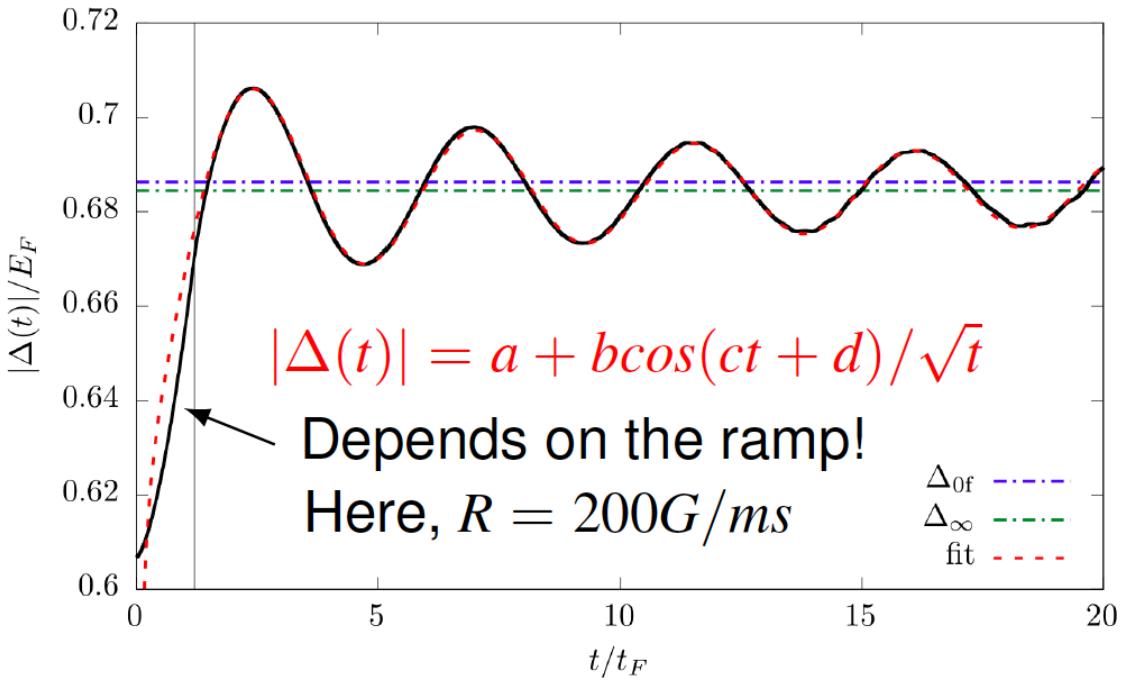




Higgs Mode

Simulations (@ TU/E) suggest we expect Higgs oscillations



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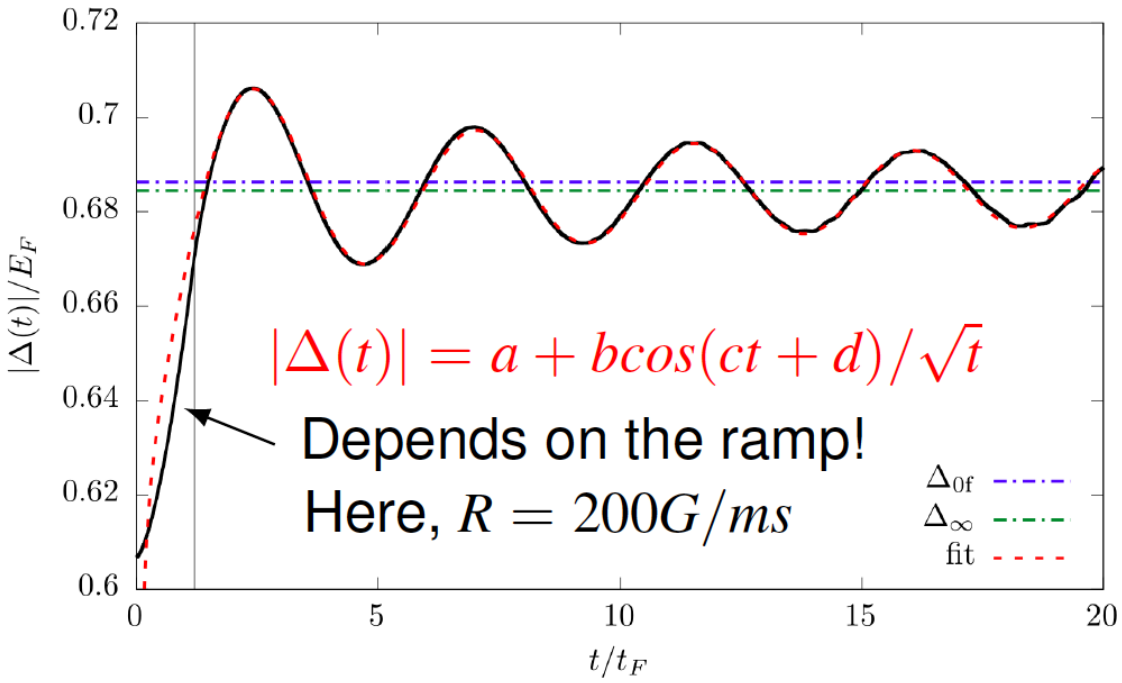
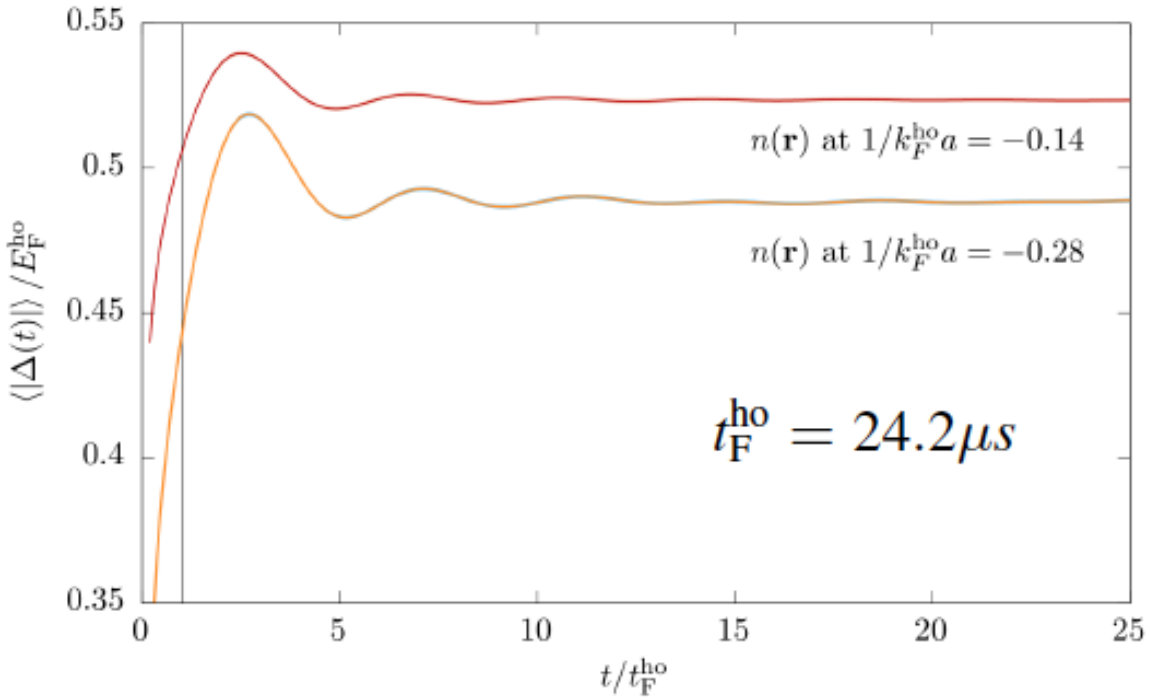


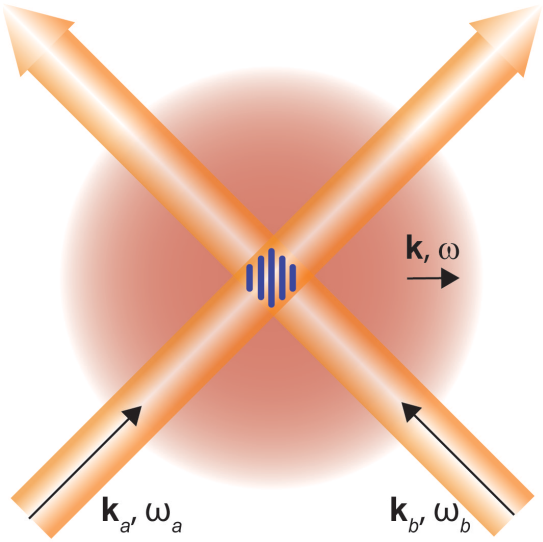
Musolino, Ahmed-Braun, Collusi, Kokkelmans (2020)

Measurements of N_0/N integrate over full cloud so damp rapidly



Probing the Higgs Mode

- The Bragg excitation is achieved with focused Bragg beams.



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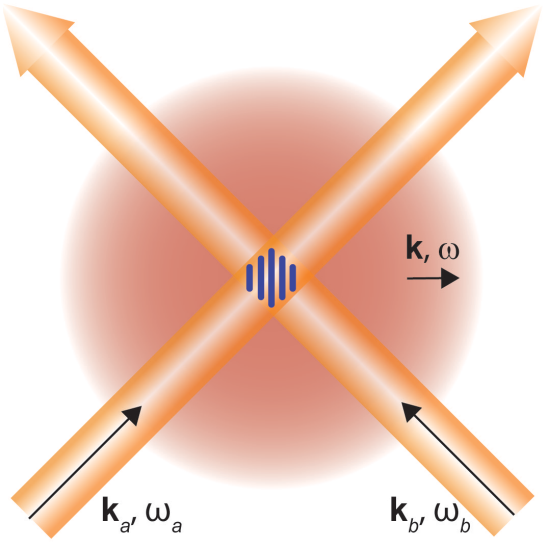

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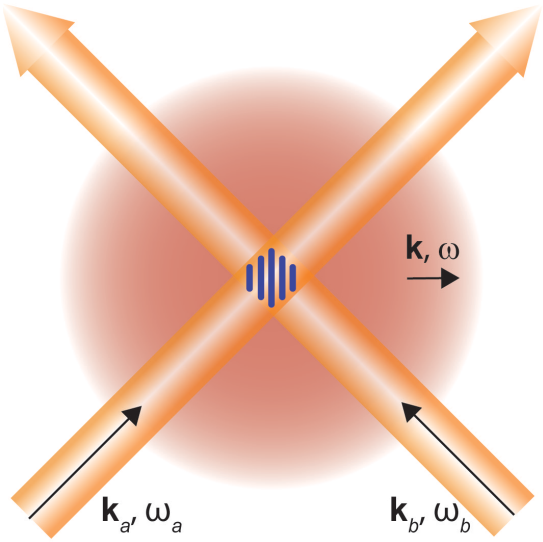
$$\omega_r = \frac{\hbar k^2}{2m}$$



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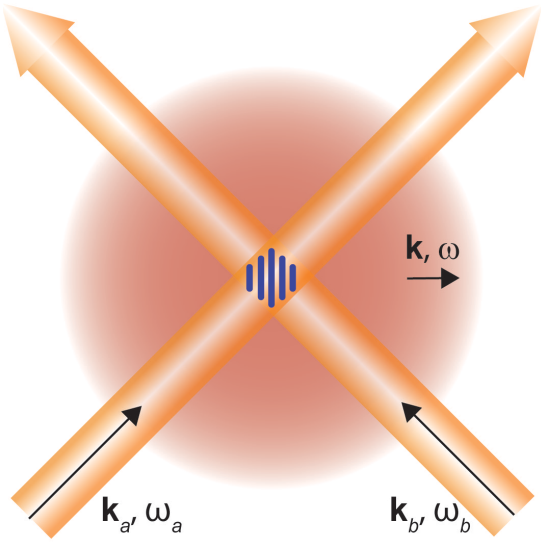

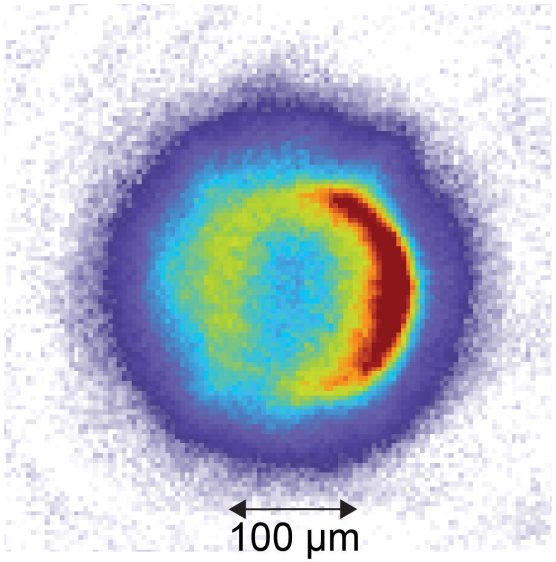

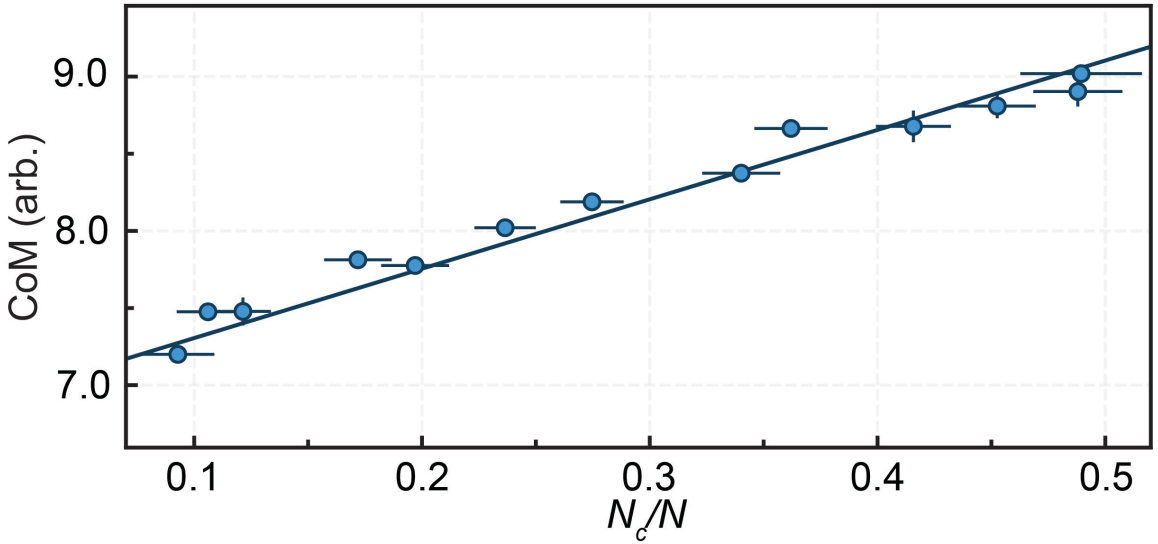

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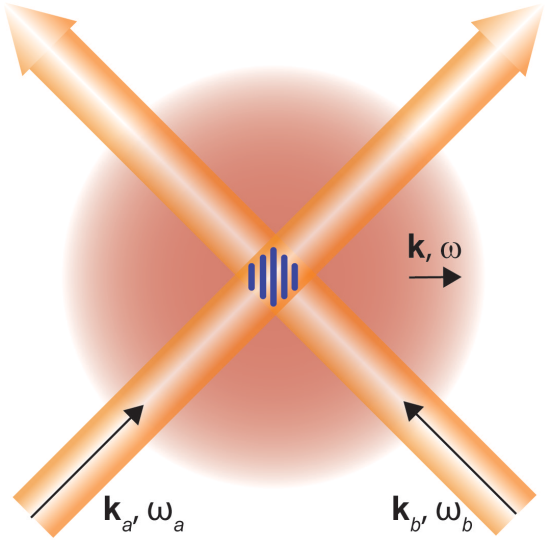

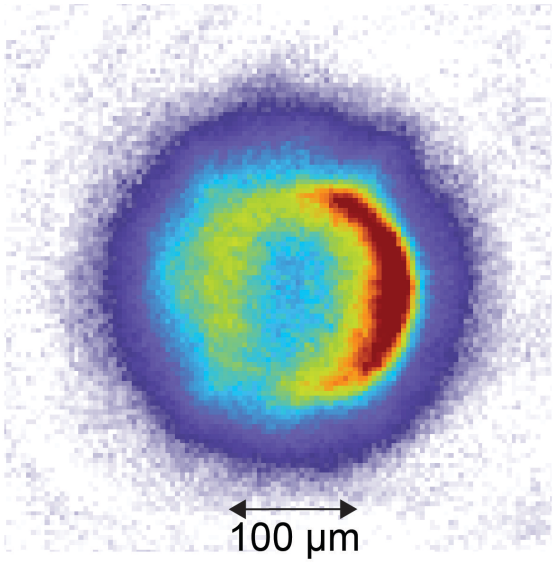

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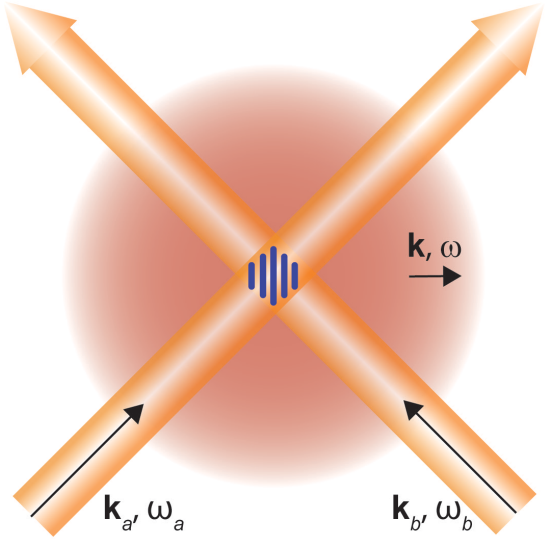

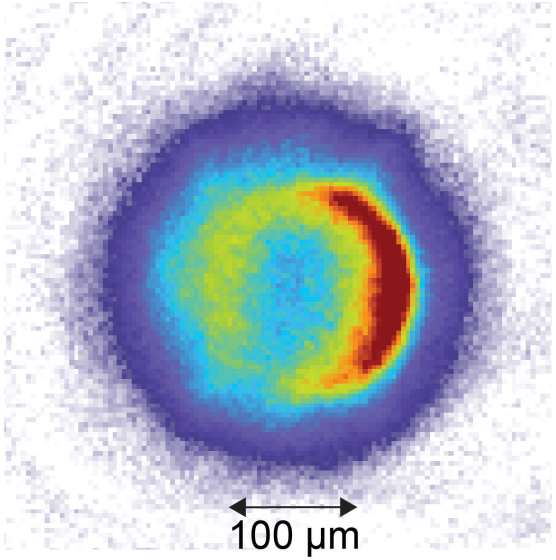

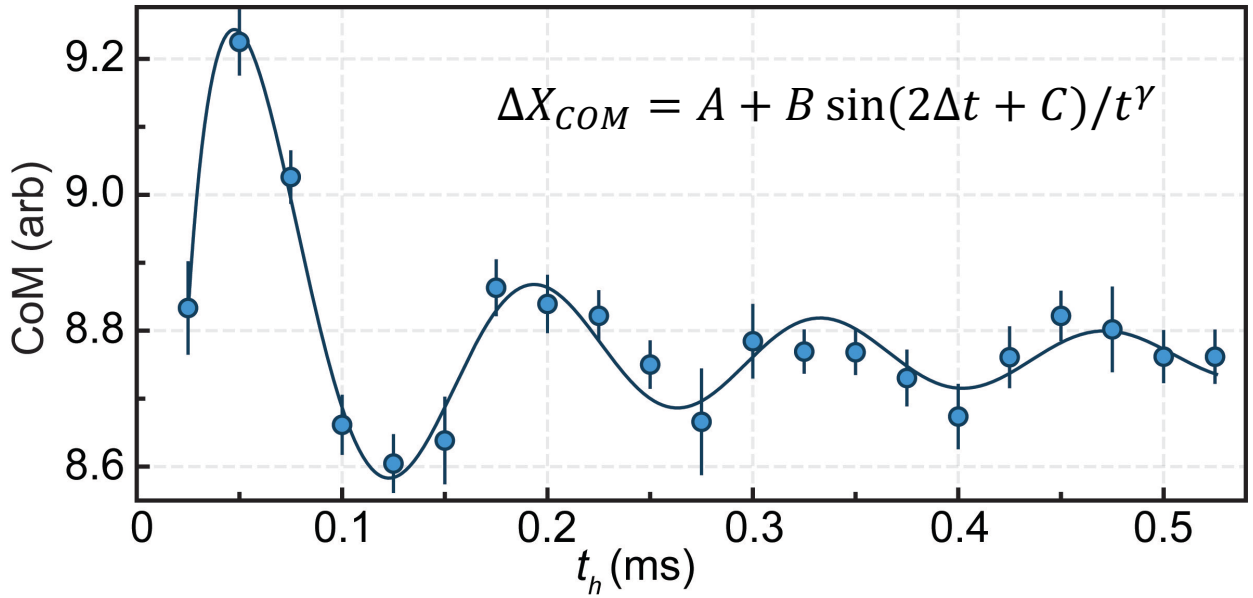

- The **frequency**, **amplitude** and **damping** rate are determined by fitting a **damped sinusoid.**

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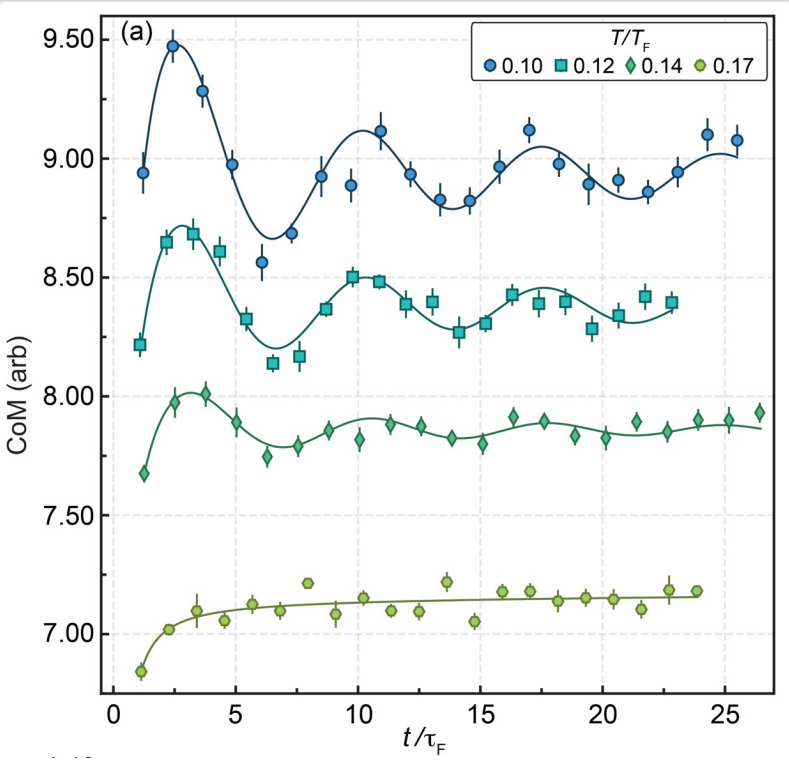

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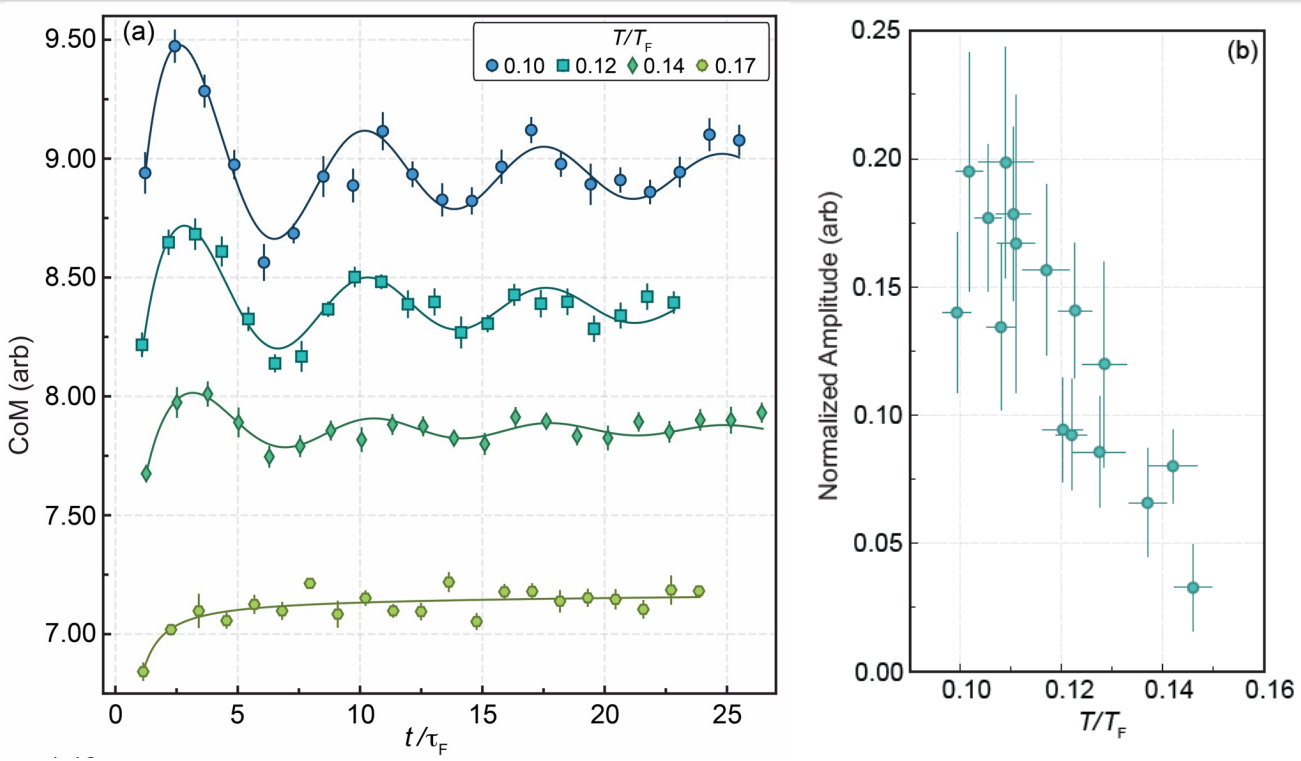

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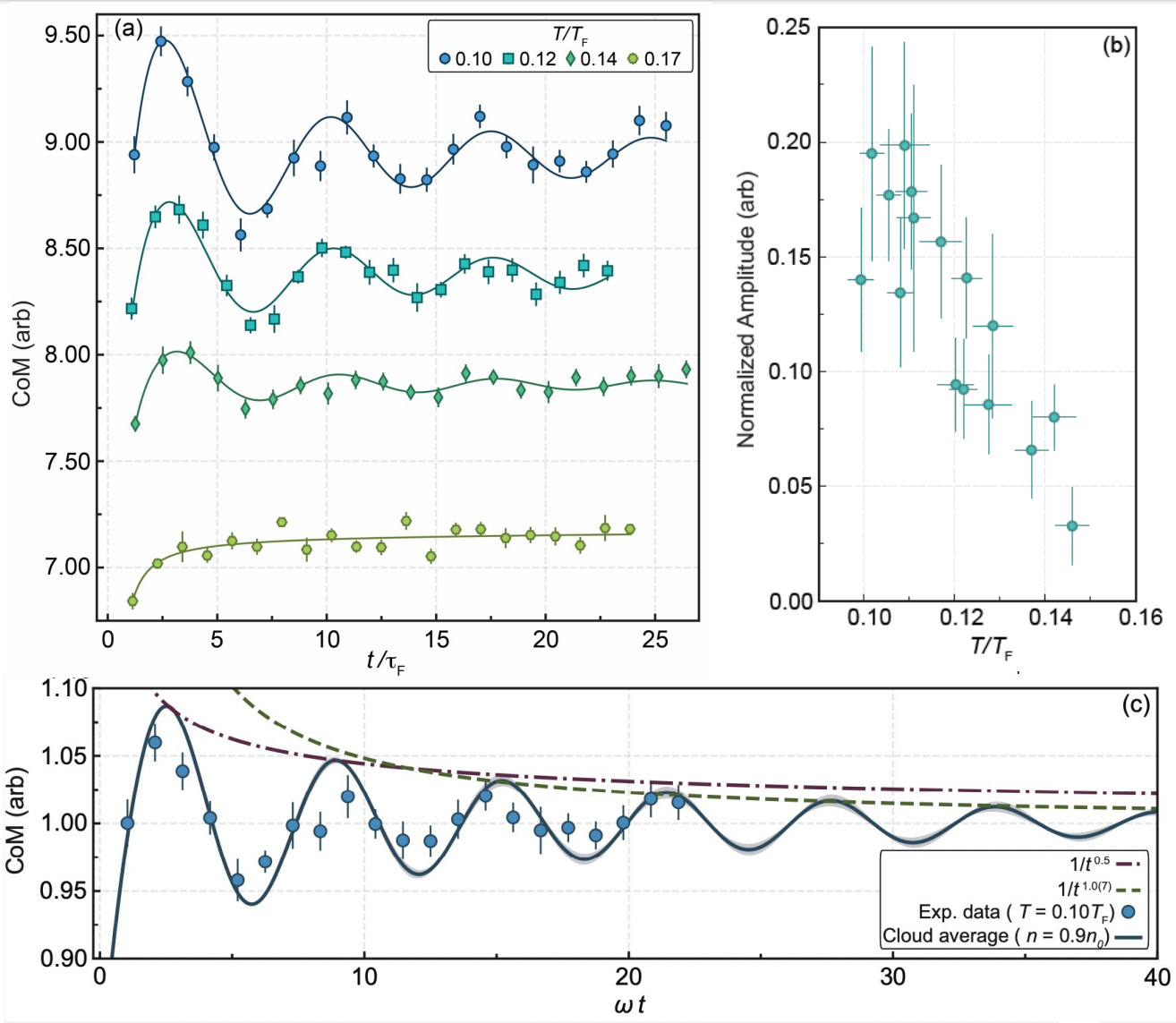

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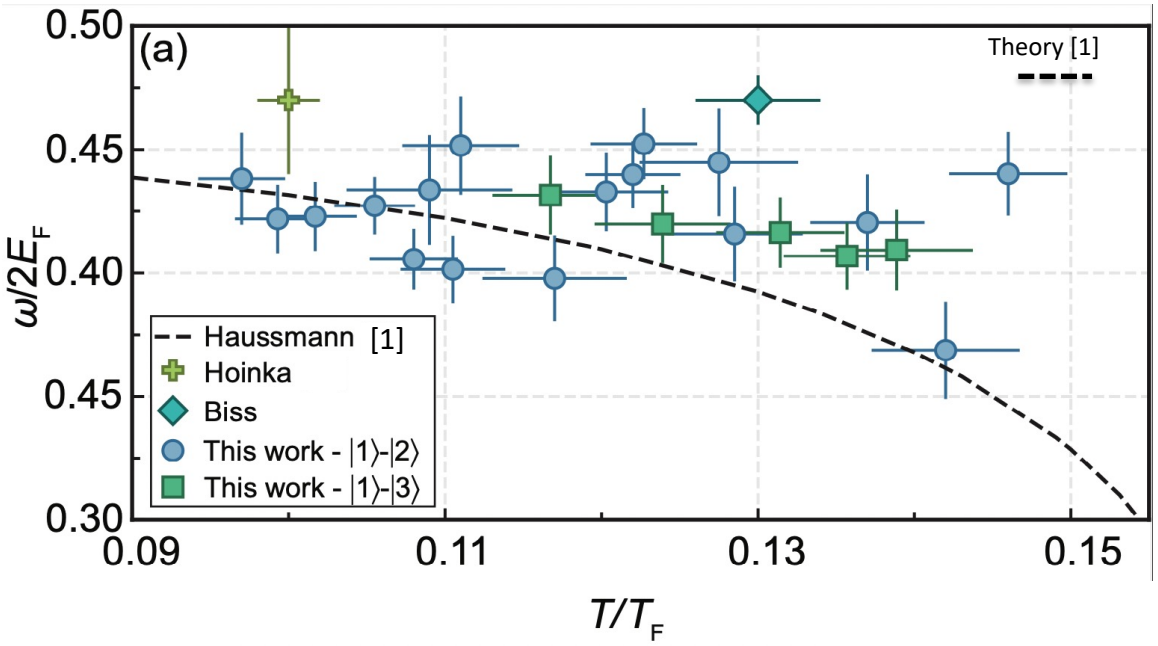
[1] R. Haussmann et al., PRA **75**, 023610 (2007)



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- Beyond $T > 0.15T_F$ the oscillations fall below our sensitivity.
- The expected decay rate in the far BCS and BEC region should be 0.5 and 1.5, respectively, as indicated buy the dashed and dot dash lines.
- The observed decay rate lies approximately midway between the BCS and BEC limits and looks stable as the temperature is increased.

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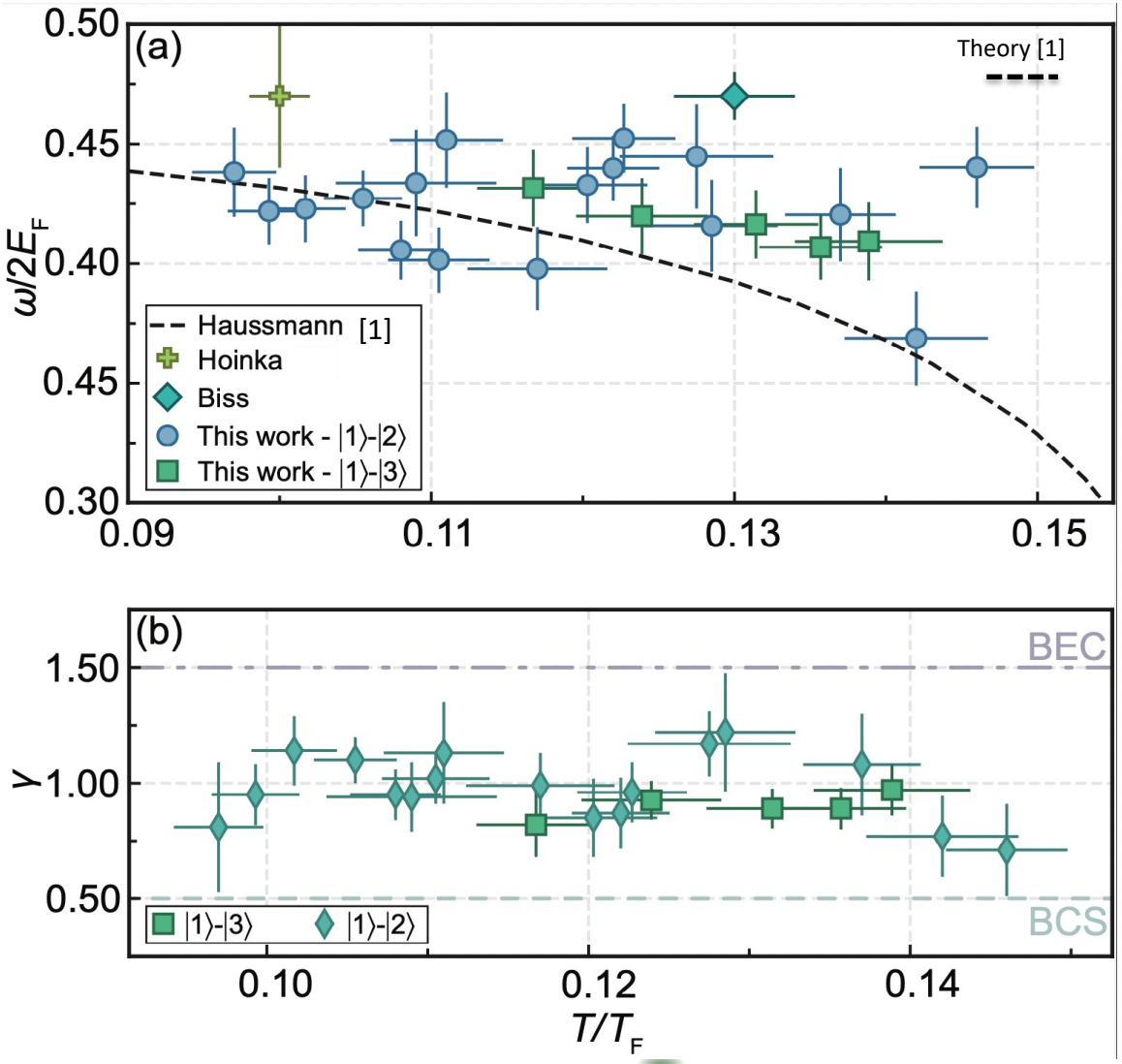
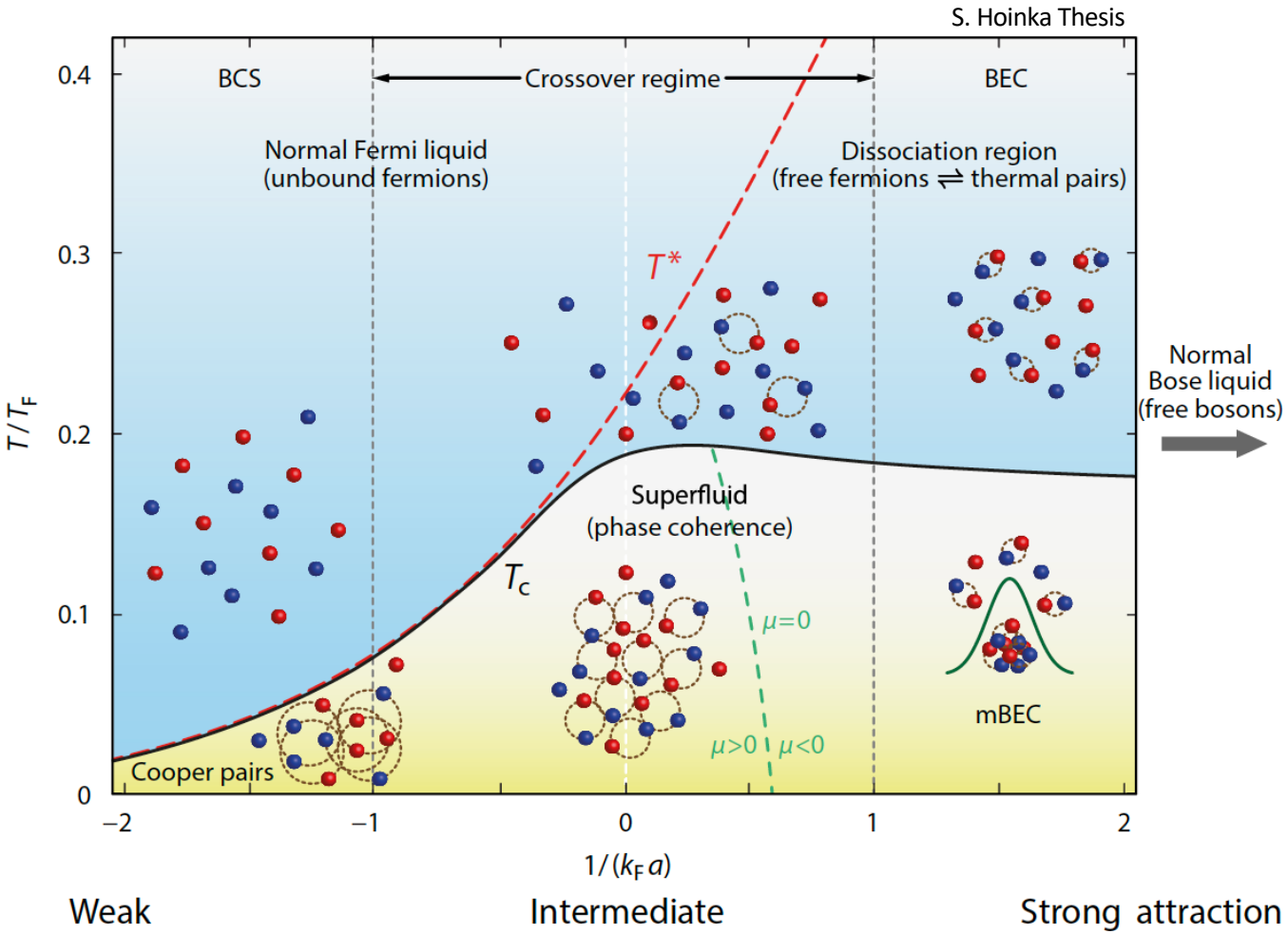


Changing the interactions



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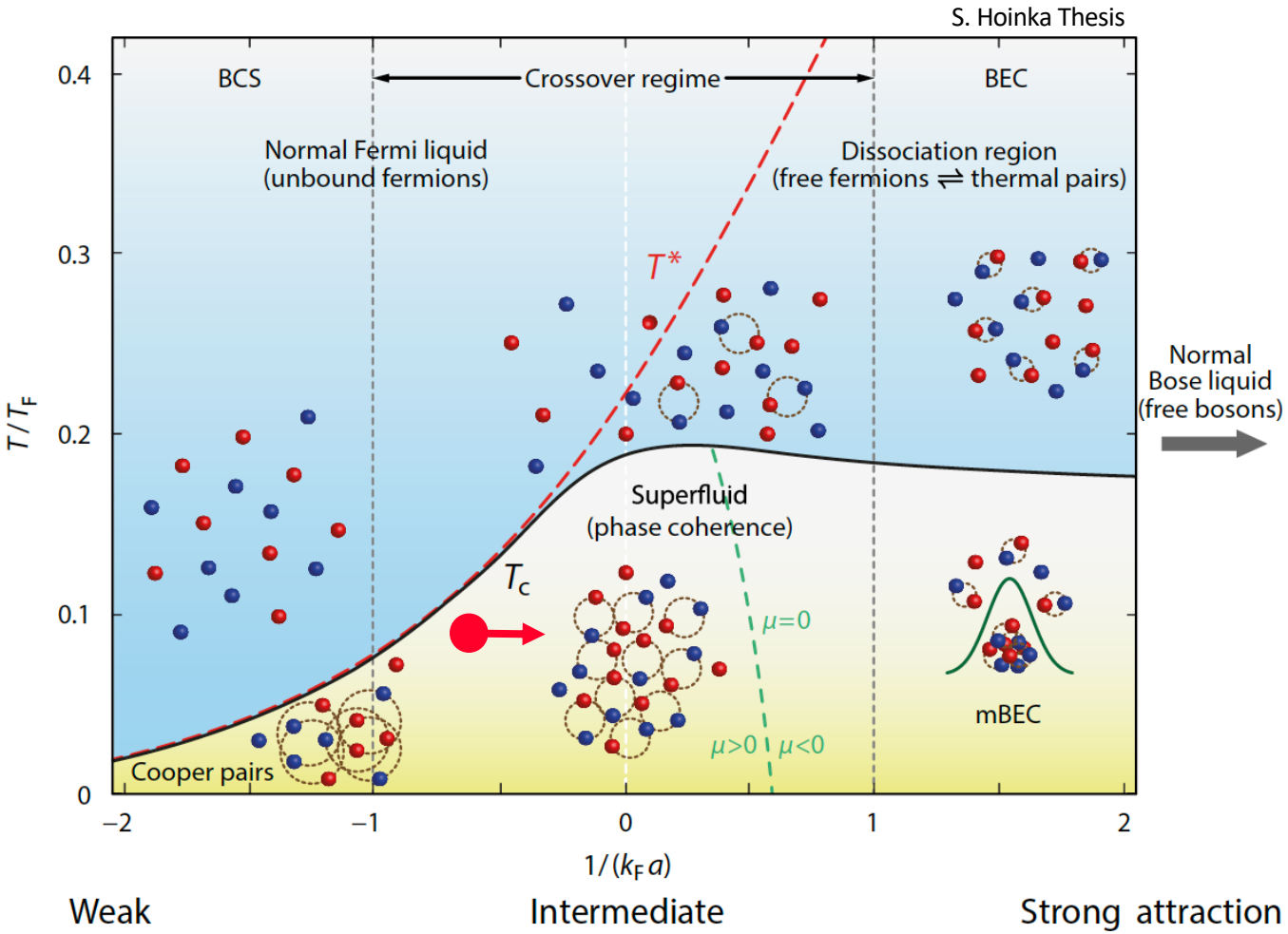

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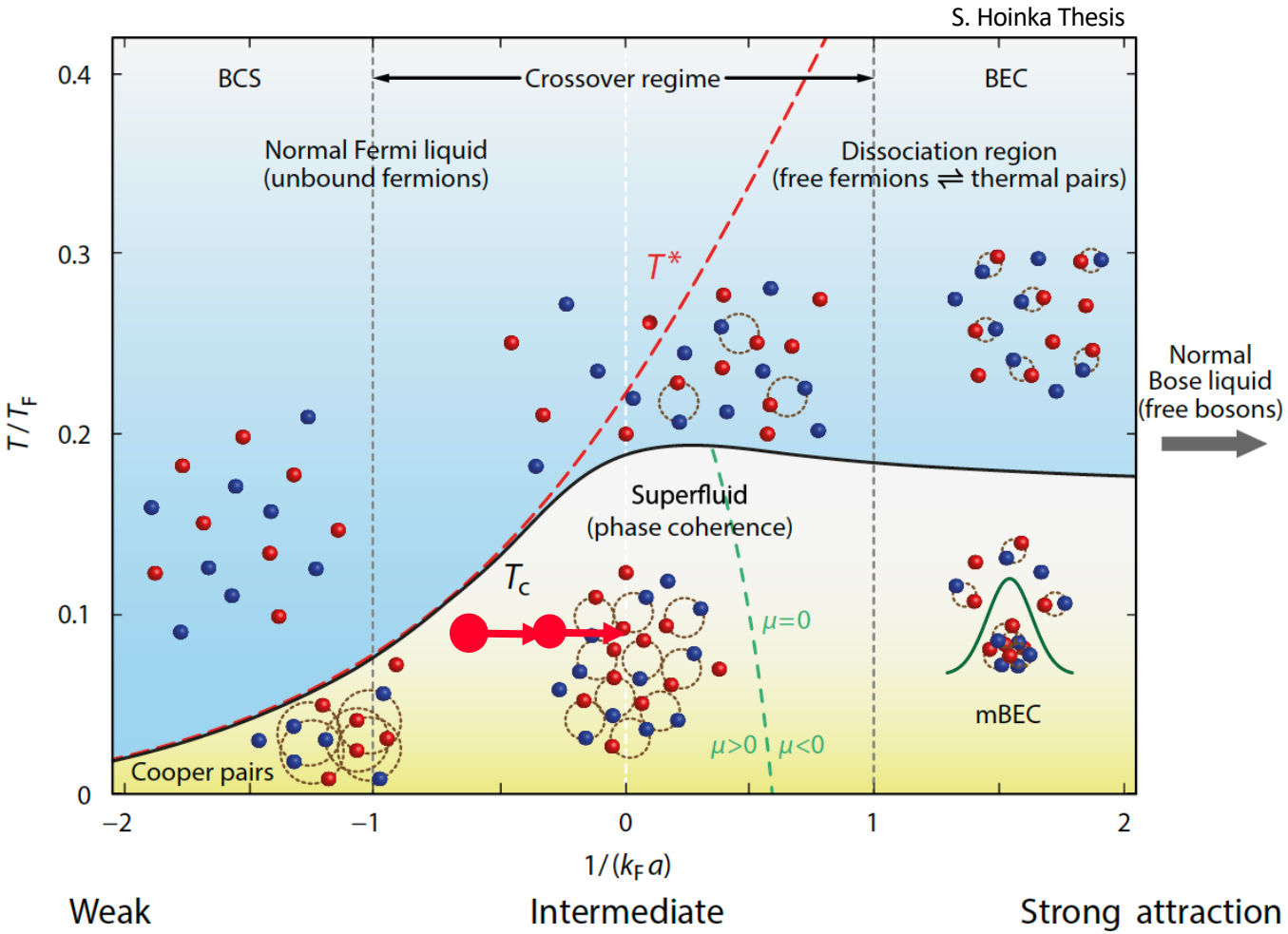
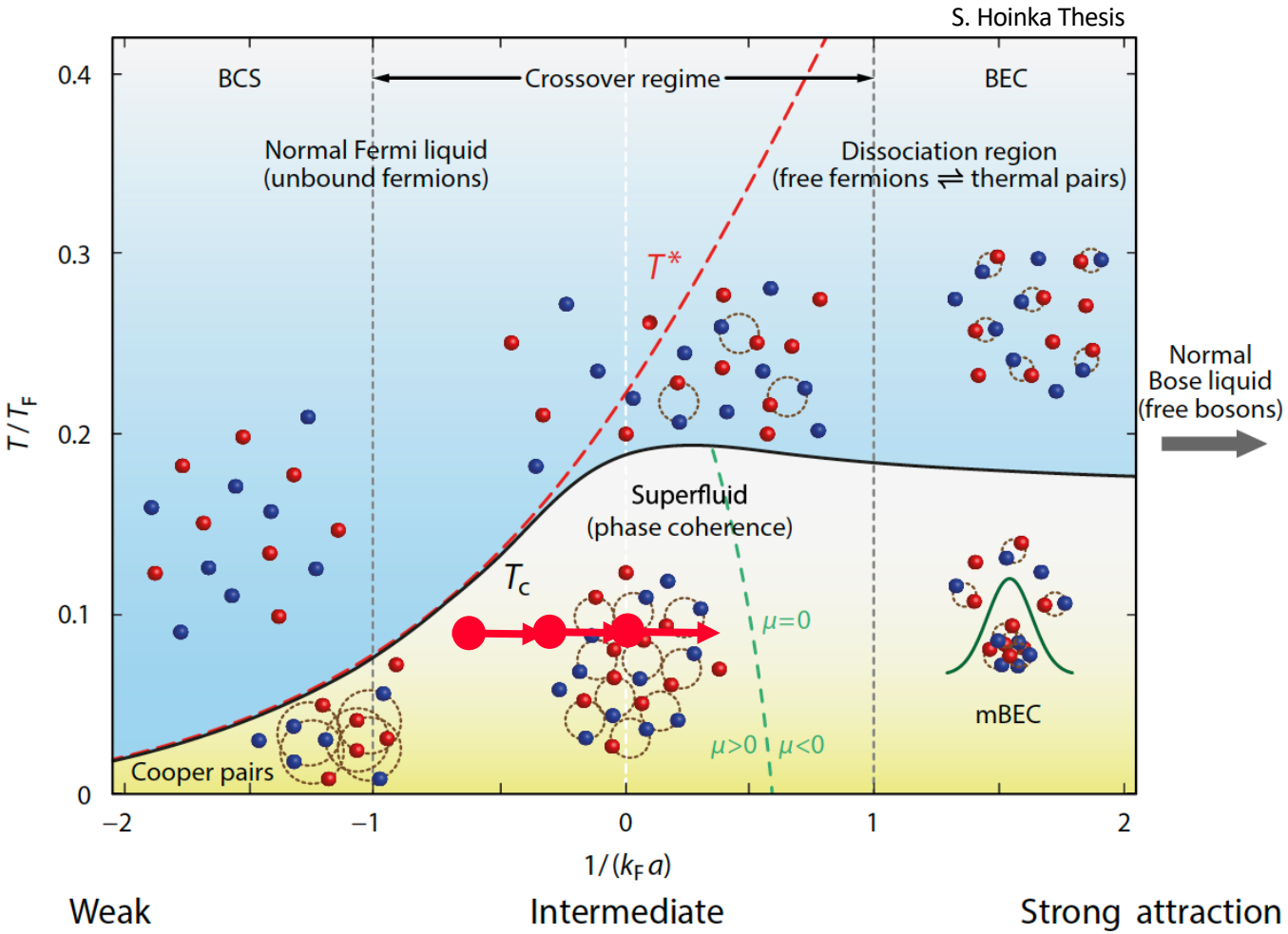
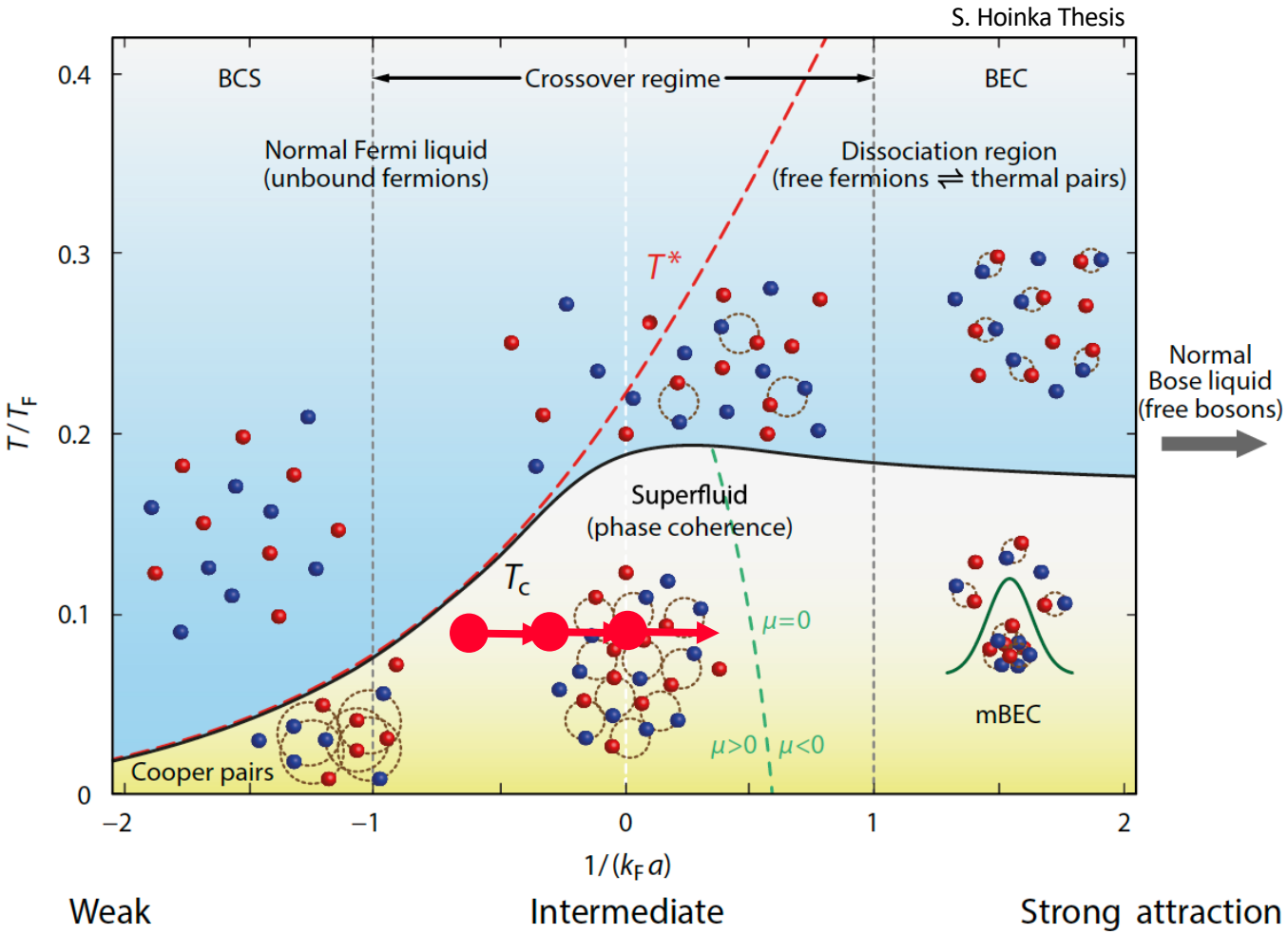


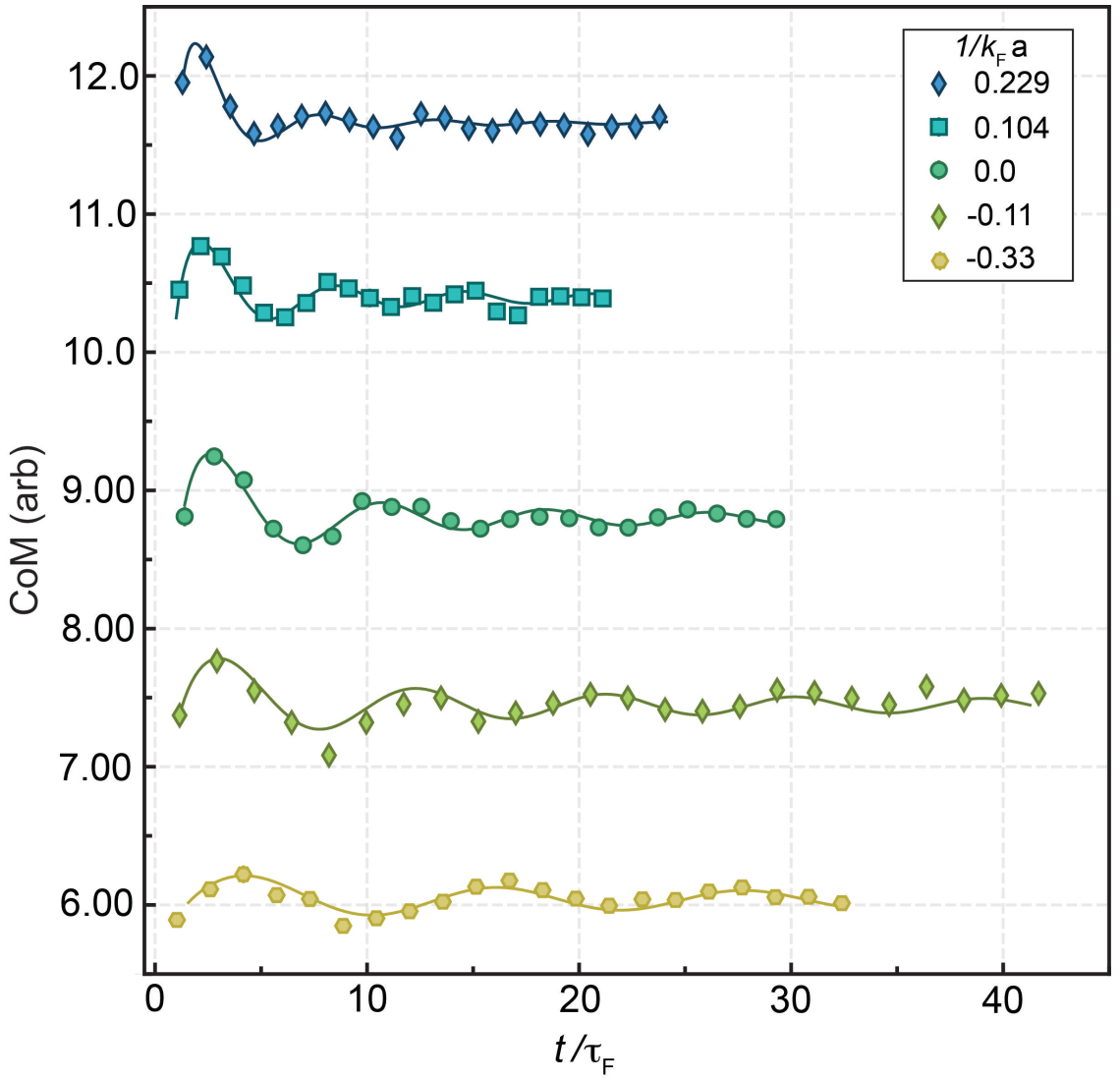
Changing the interactions



Changing the interactions



Normal Bose liquid (free bosons)



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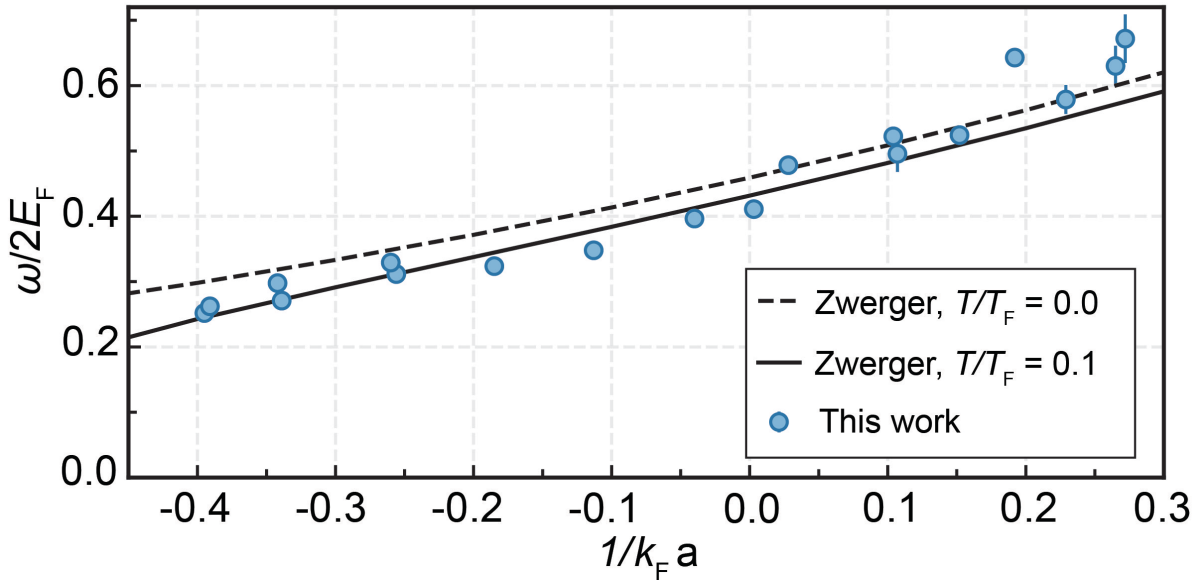
Interactions

- The pairing gap change as a function of the interaction



Interactions

- Damping change as a function of the interaction

Interactions

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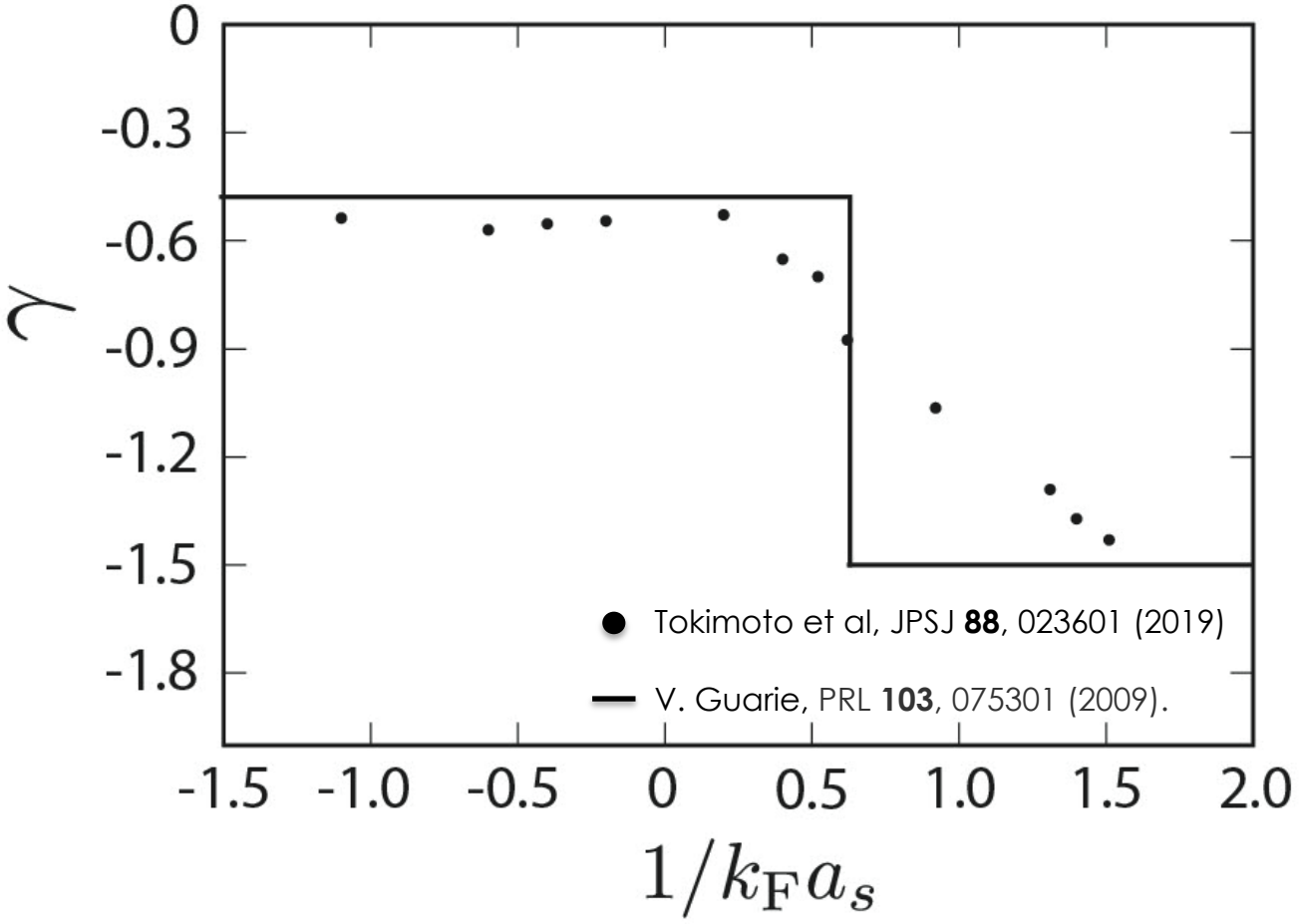
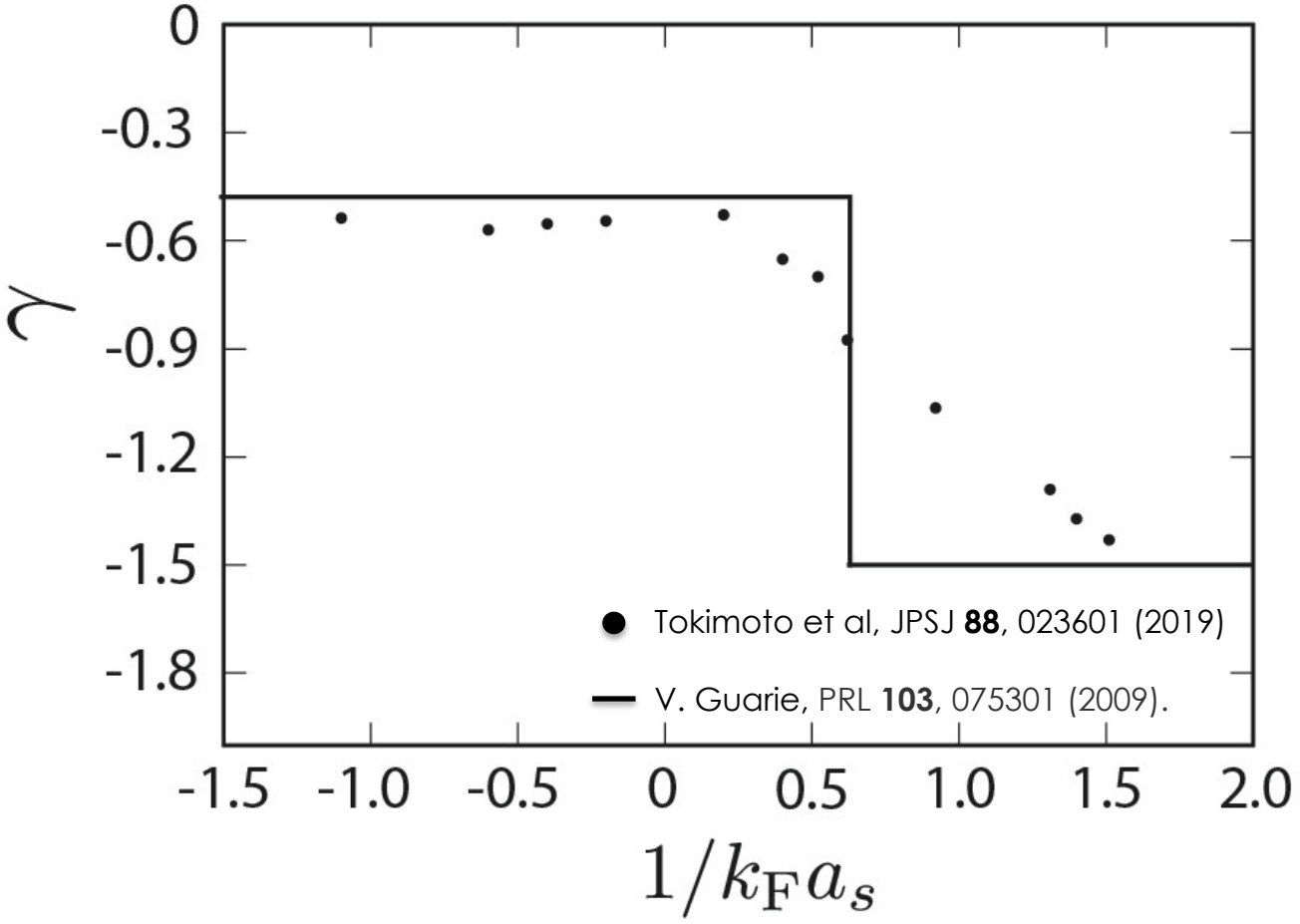
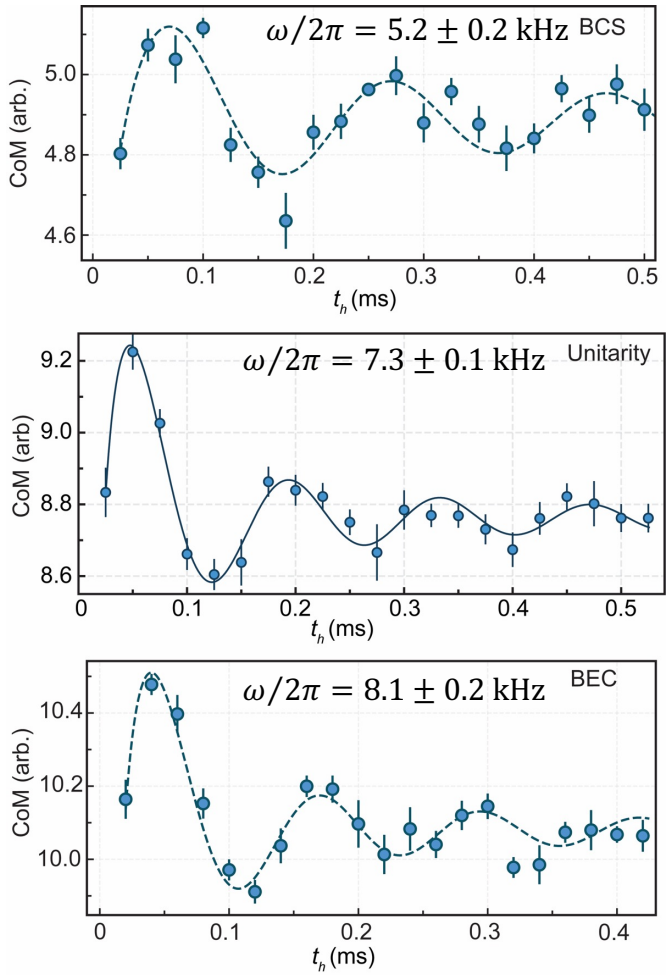


Interactions

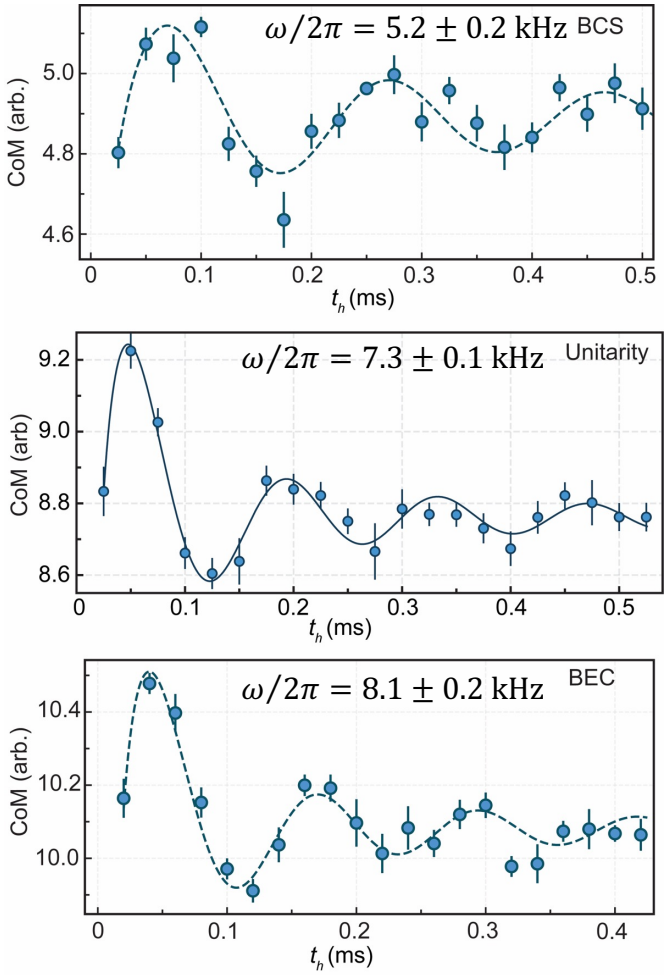
- Damping change as a function of the interaction





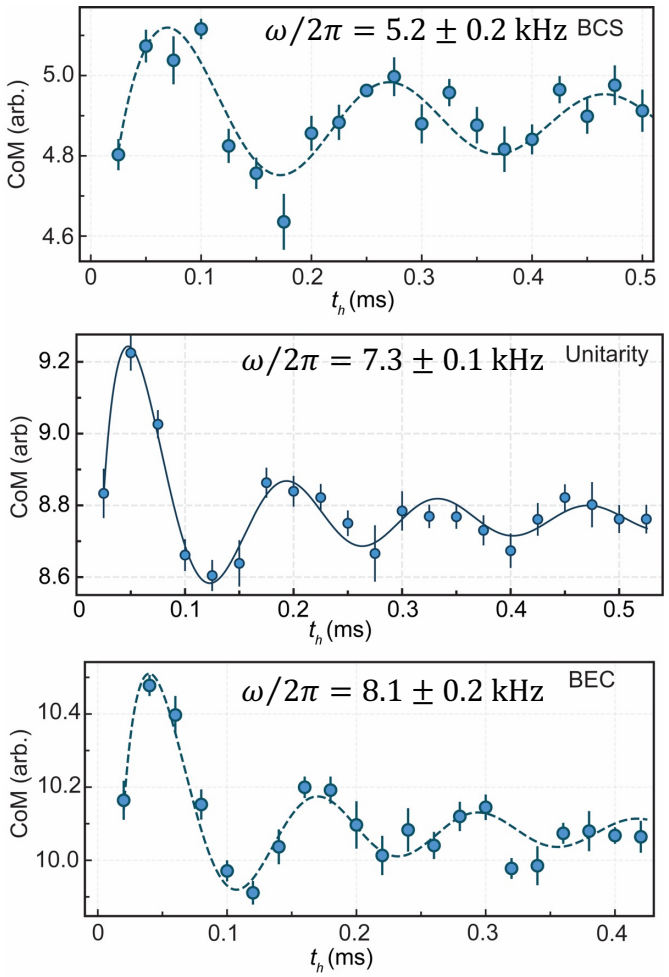
Interactions

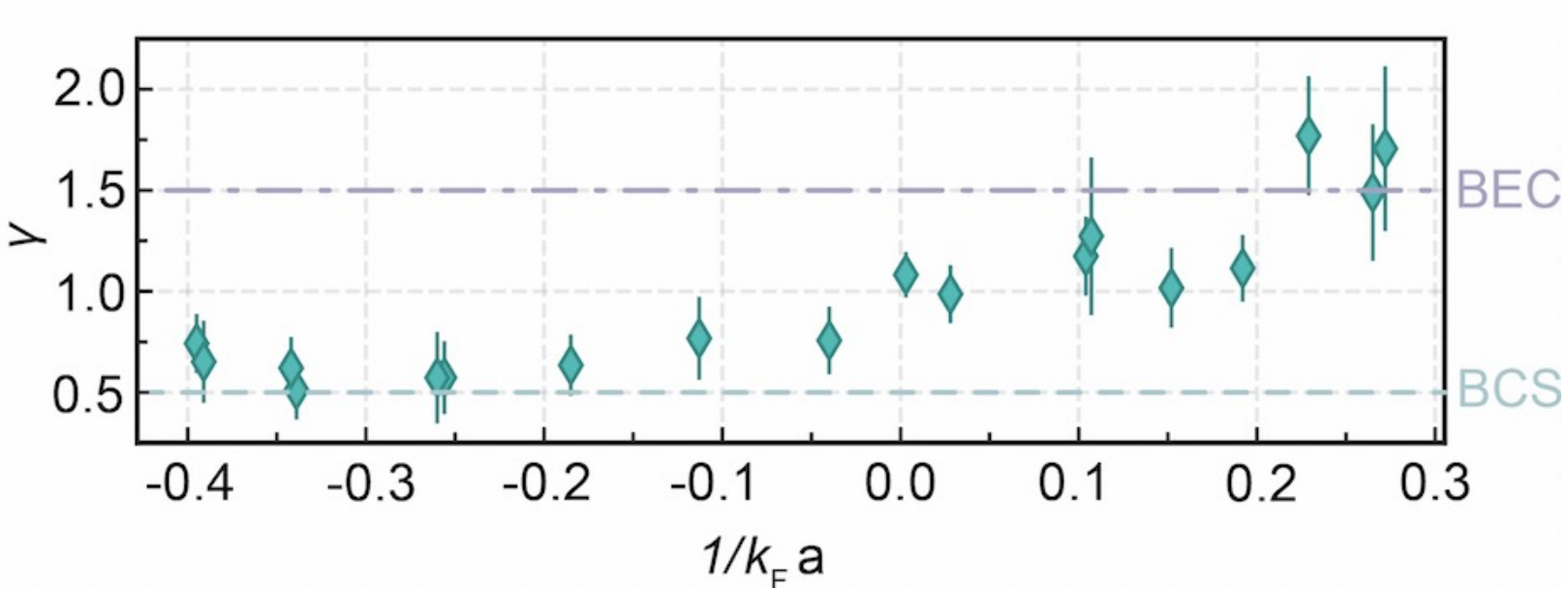
- Damping change as a function of the interaction



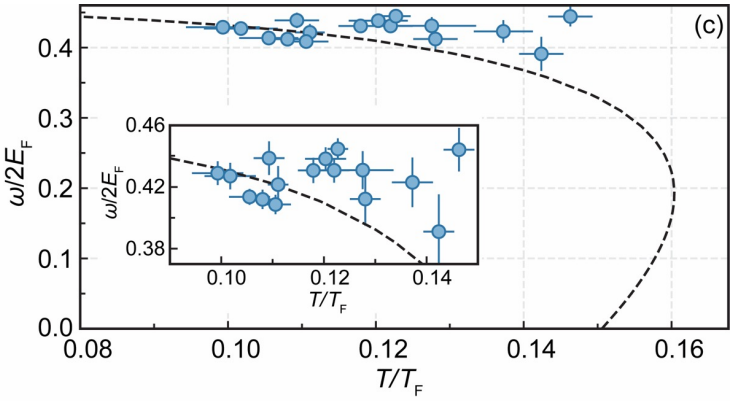
Interactions

- Damping change as a function of the interaction



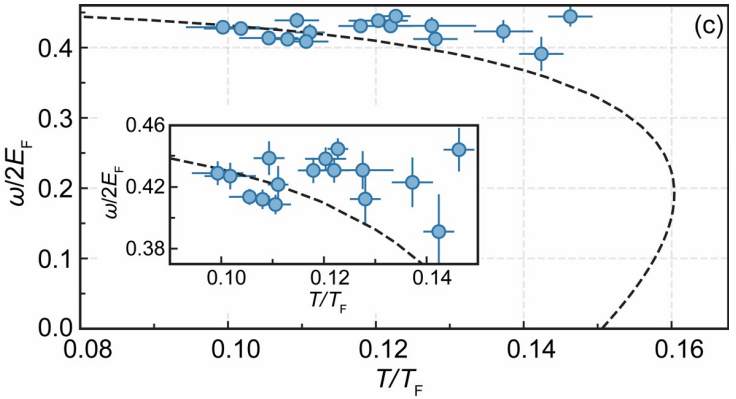


Summary

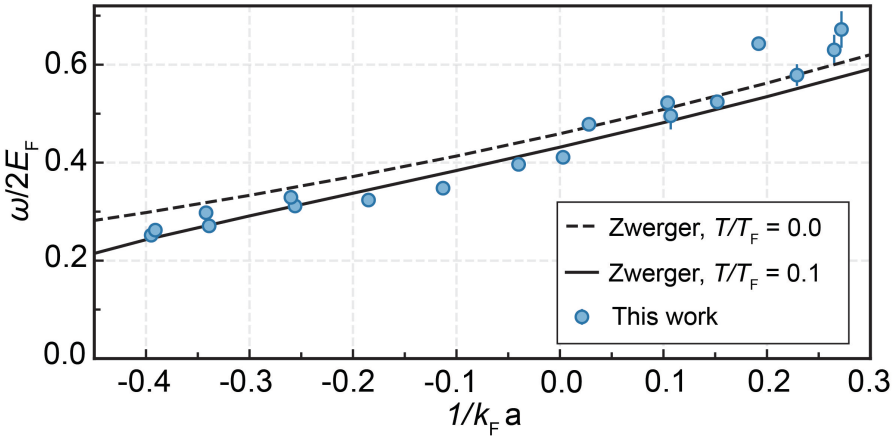


- Pairing gap as a function of temperature

Summary

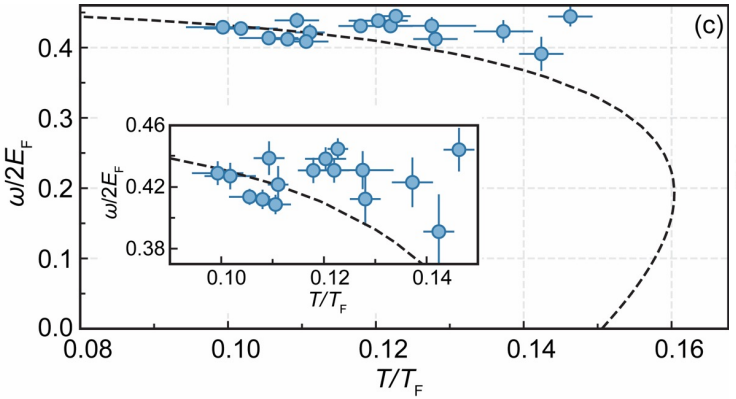


- Pairing gap as a function of temperature



- Pairing gap as a function of interactions

Summary



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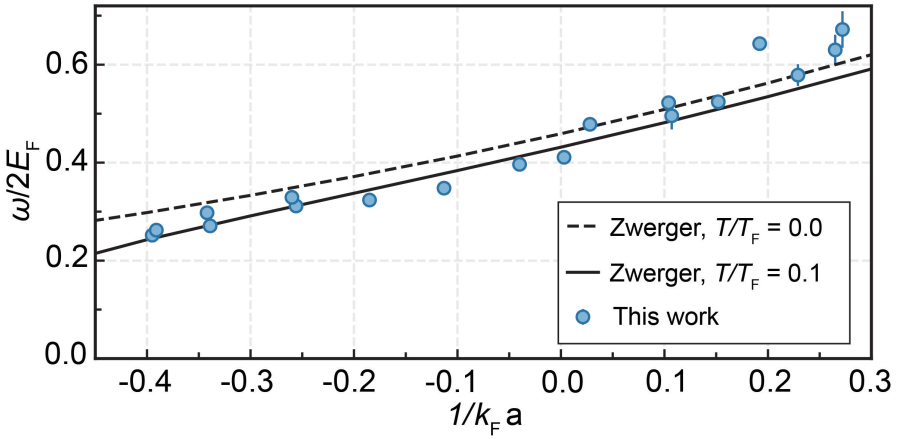
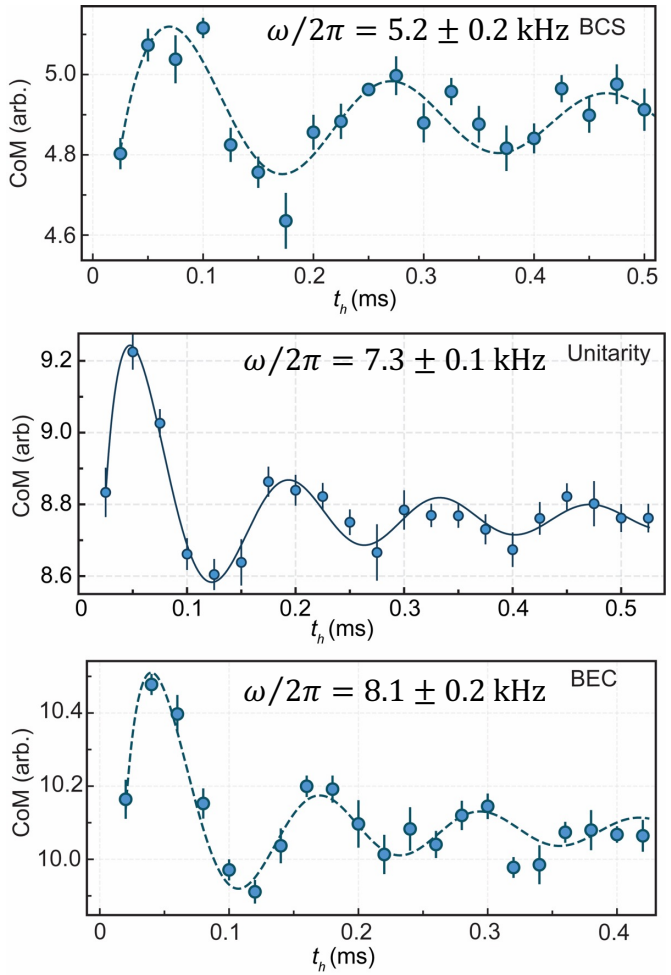
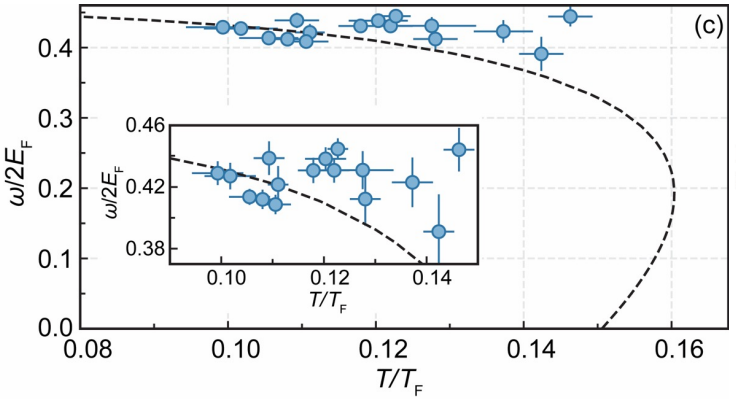


- Pairing gap as a function of interactions

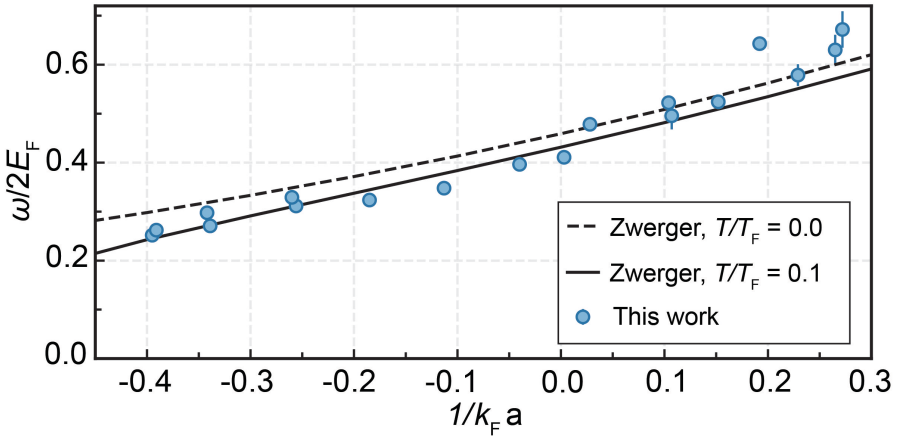


- Damping changes as a function of interactions

Summary



- Pairing gap as a function of temperature



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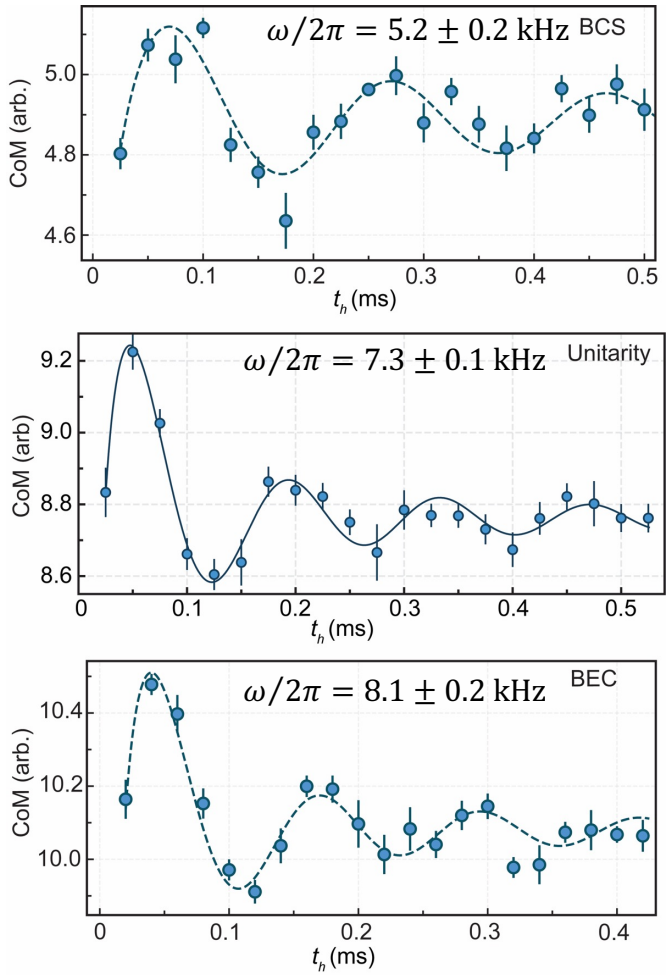

- Damping changes as a function of interactions

Thanks for listening