Clusters & Hierarchies

8th Cluster Workshop

Quantum Simulation of Three-Body Forces in an Optical Lattice Using Feshbach Resonance

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Outline

- **Introduction :**
  - Three-body forces appearing in various hierarchies
  - Optical lattice system as a quantum simulator
- **Methods :**
  - High-resolution spectroscopy
  - Control of the interaction strength by a Feshbach resonance
- **Results :**
  - Magnetic field dependence of resonance frequency shift
  - Quantitative comparison with numerical calculation results
- **Summary & Outlook**

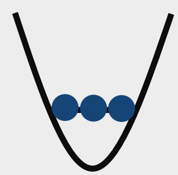
Quantum few-body systems

Importance of physics in quantum few-body systems :

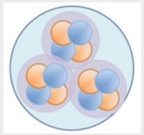
Existence of phenomena with universality that across hierarchies

Among these…
Three-body forces have been intensively studied.

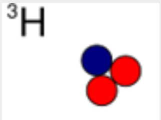
Atoms in a harmonic trap



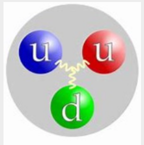
Hoyle state

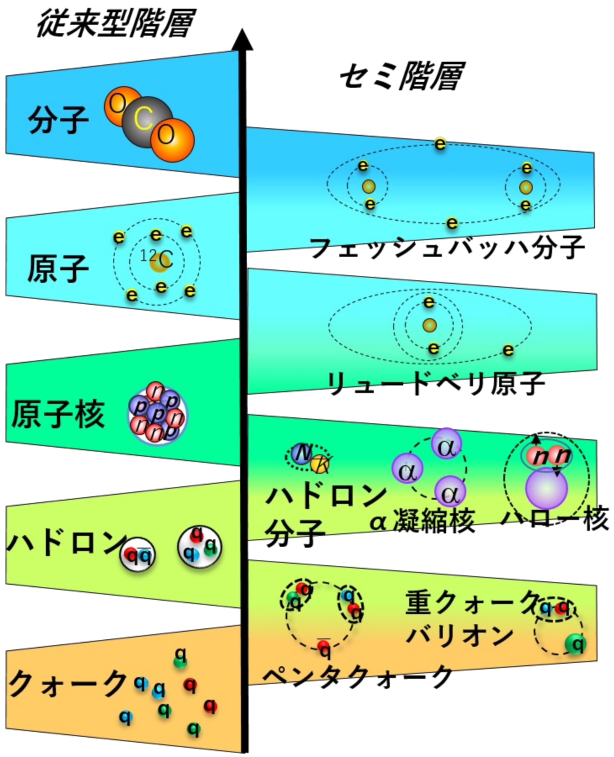


Tritium



Quarks



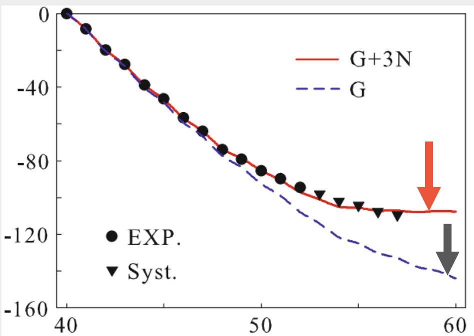


http://be.nucl.ap.titech.ac.jp/cluster/kenkyu.html

Three-body forces in the hadron hierarchy

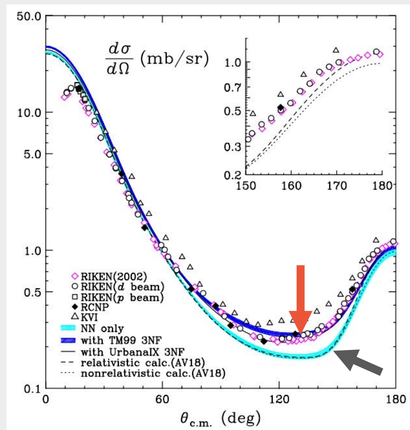
Examples of three-body forces
in the hadron hierarchy

Ground-state energy of Ca isotopes



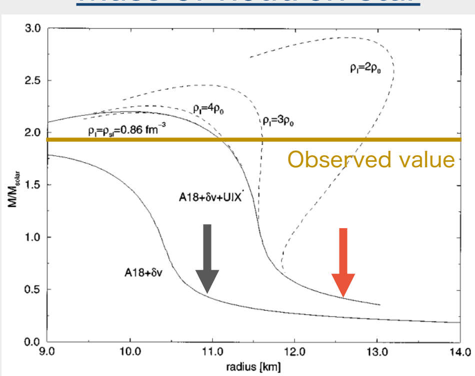
T. Otsuka *et al.*,
Few-Body Syst **54**, 891(2013).

Deuteron-proton scattering cross section



K. Sekiguchi *et al.*,
PRL **95**, 162301(2005).

Mass of neutron star

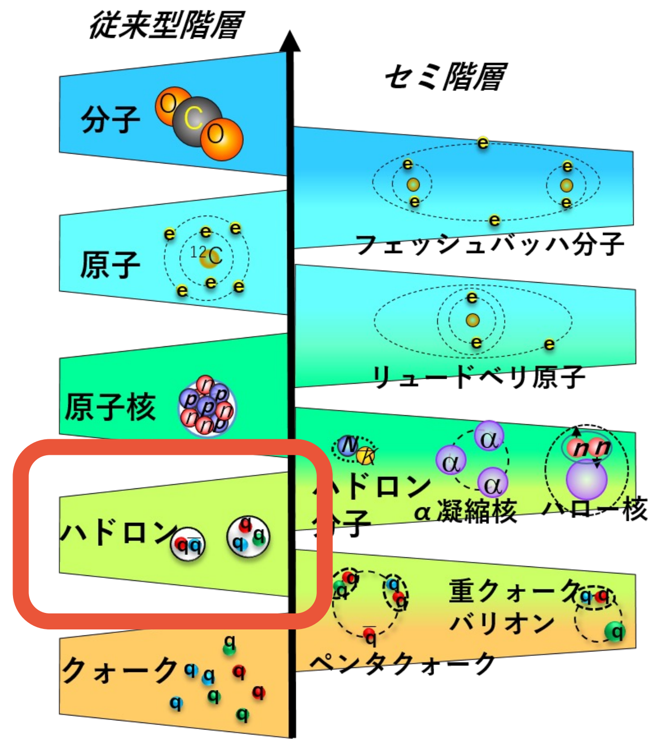


A. Akmal *et al.*, PRC **58**, 3(1998).

Calc. value

↓ w/o 3-body force

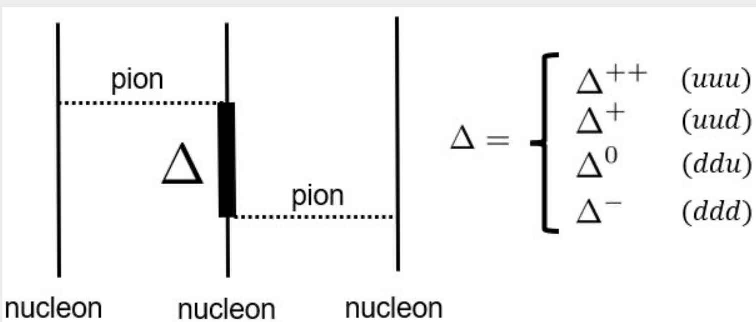
↓ w/ 3-body force



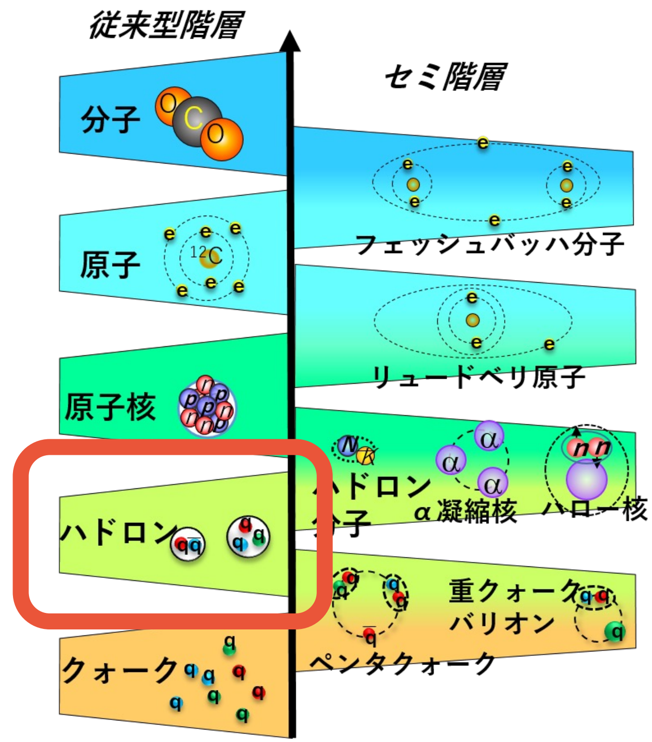
http://be.nucl.ap.titech.ac.jp/cluster/kenkyu.html

Three-body forces in the hadron hierarchy

Mechanism of
three-body forces
↓
Fujita-Miyazawa-type
three-body force



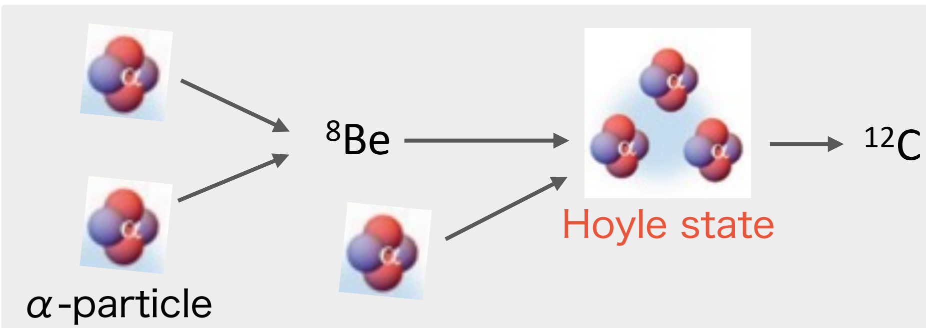
J. Fujita and H. Miyazawa,
Prog. Theor. Phys. **17**, 360 (1957).

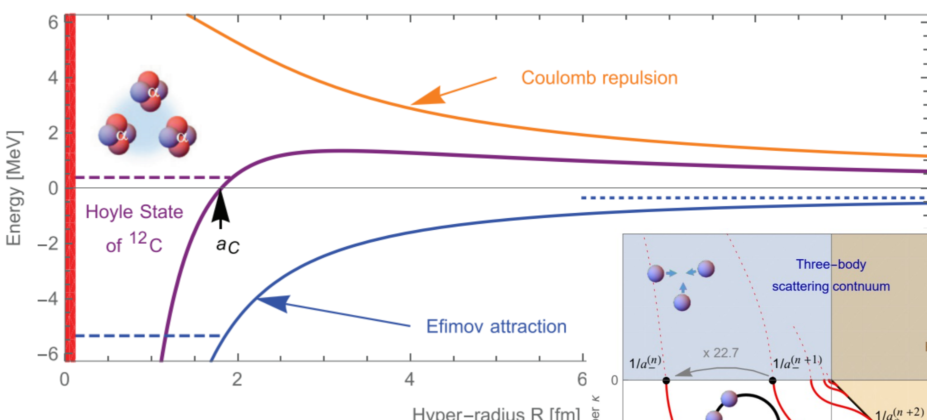


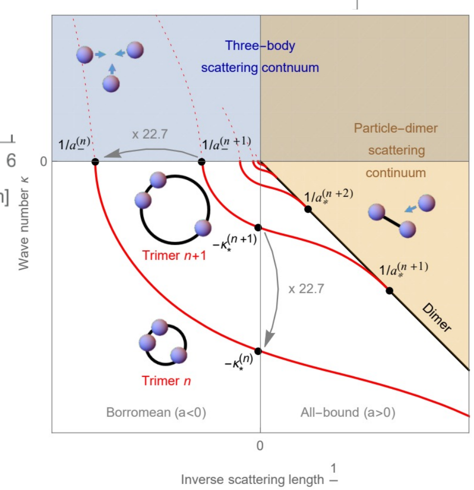
http://be.nucl.ap.titech.ac.jp/cluster/kenkyu.html

Three-body forces in the nuclear hierarchy

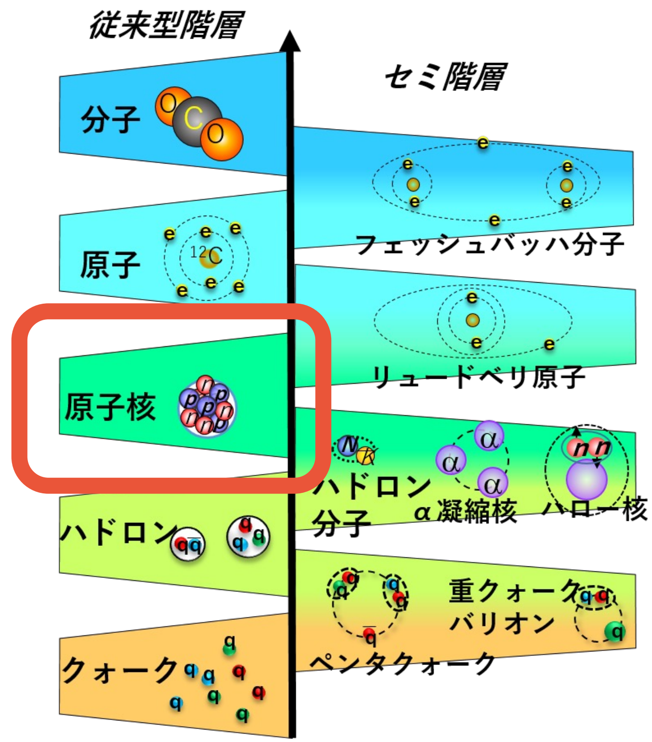
Example of three-body force
in the nuclear hierarchy







P. Naidon and S. Endo, Rep. Prog. Phys. **80**, 056001(2017).

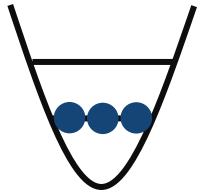


http://be.nucl.ap.titech.ac.jp/cluster/kenkyu.html

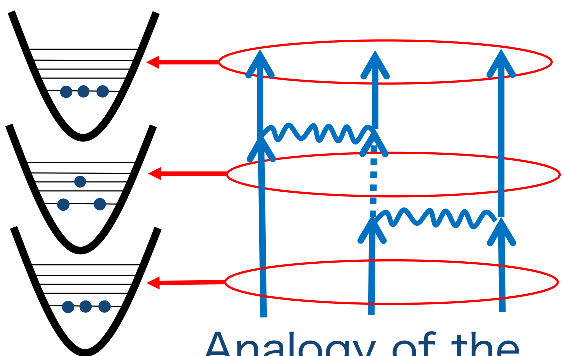
Three-body forces in the atom hierarchy

Example of three-body force
in the atom hierarchy

Three-body force between
atoms in a harmonic trap



- Weak interaction region



Analogy of the
Fujita-Miyazawa-type
three-body force

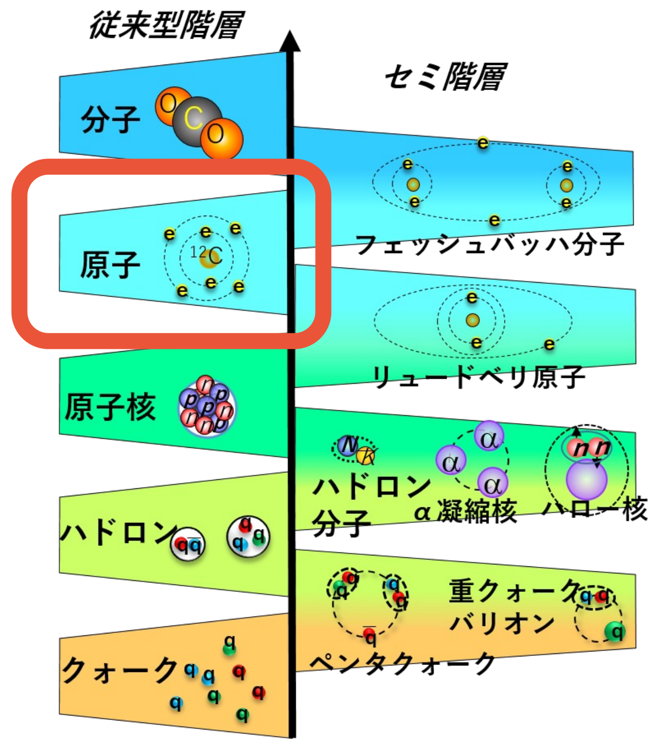
P. R. Johnson *et al.*, New. J. Phys. **11**, 093022 (2009).

- Strong interaction region

Theoretical work on the formation of
Efimov states in a harmonic trap:

D. Blume *et al.*, PRA. **97**, 033621 (2018).

→ Research subjects in this study



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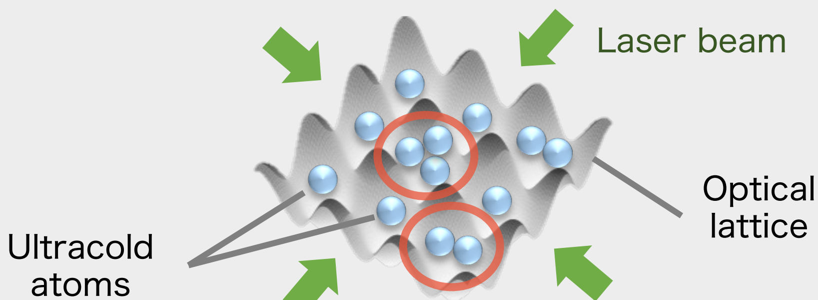
Optical lattice system as a quantum simulator

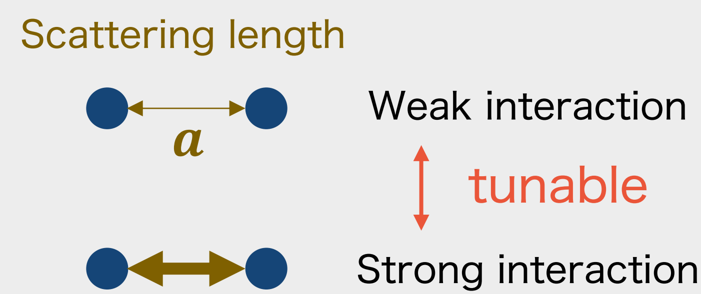
Optical lattice system : Useful platform with high controllability of various parameters of the system

→ Quantum simulator for quantum few-body systems

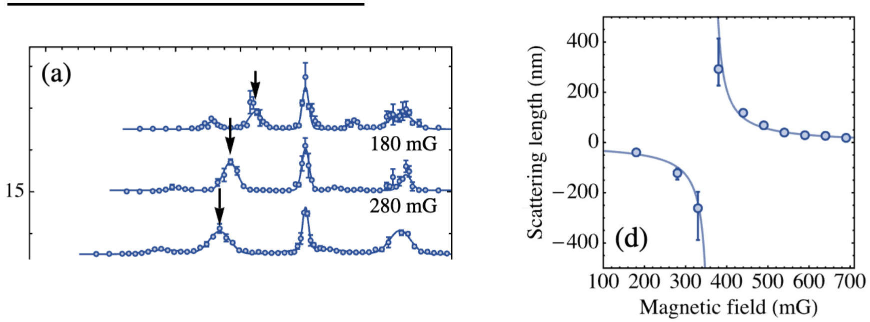
Isolated arrays of quantum few-body systems in a harmonic trap can be created.



Controllability for interactions between atoms by a Feshbach resonance



Previous studies



S. Kato *et al.*, PRL **110**, 173201 (2013).

Taking advantage of the controllability of optical lattice systems, we have studied 2-body interactions.

Optical lattice system as a quantum simulator

Optical lattice system : Useful platform with high controllability
of various parameters of the system

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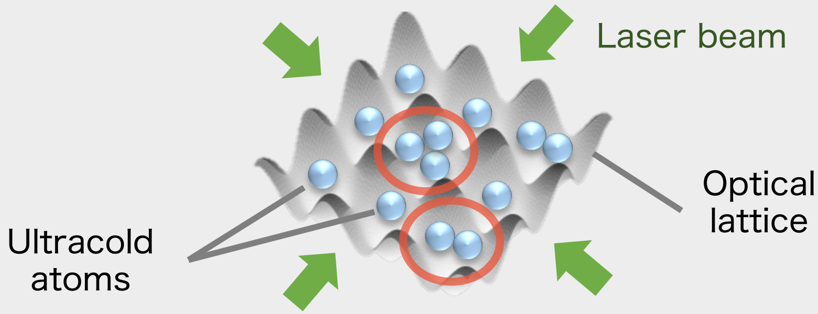
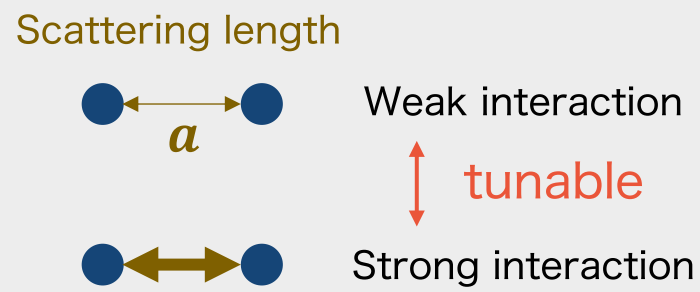
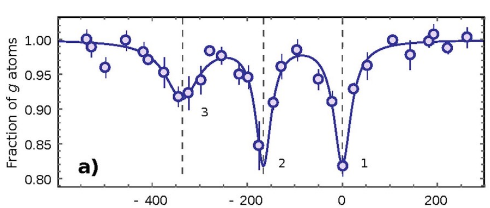
Isolated arrays of quantum few-body systems in a harmonic trap can be created.



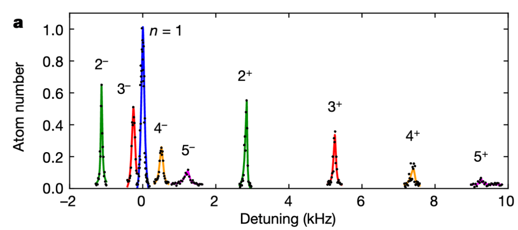
Controllability for interactions between atoms by a Feshbach resonance



Previous studies



L. Franchi *et al.*, New J. Phys. **19**, 103037 (2017).



A. Goban *et al.*, Nature **563**, 369-373 (2018).

In studies of 3-body force, Interaction strength was either fixed or slightly changed.

↓

Studies in a wide range of interaction strength has not been done.

Outline of this study

Research contents

- ✓ Study three-body forces in a harmonic trap
  in an optical lattice system

Purpose

- ✓ Qualitative understanding of three-body forces in
  a harmonic trap in a wide range of interaction strength

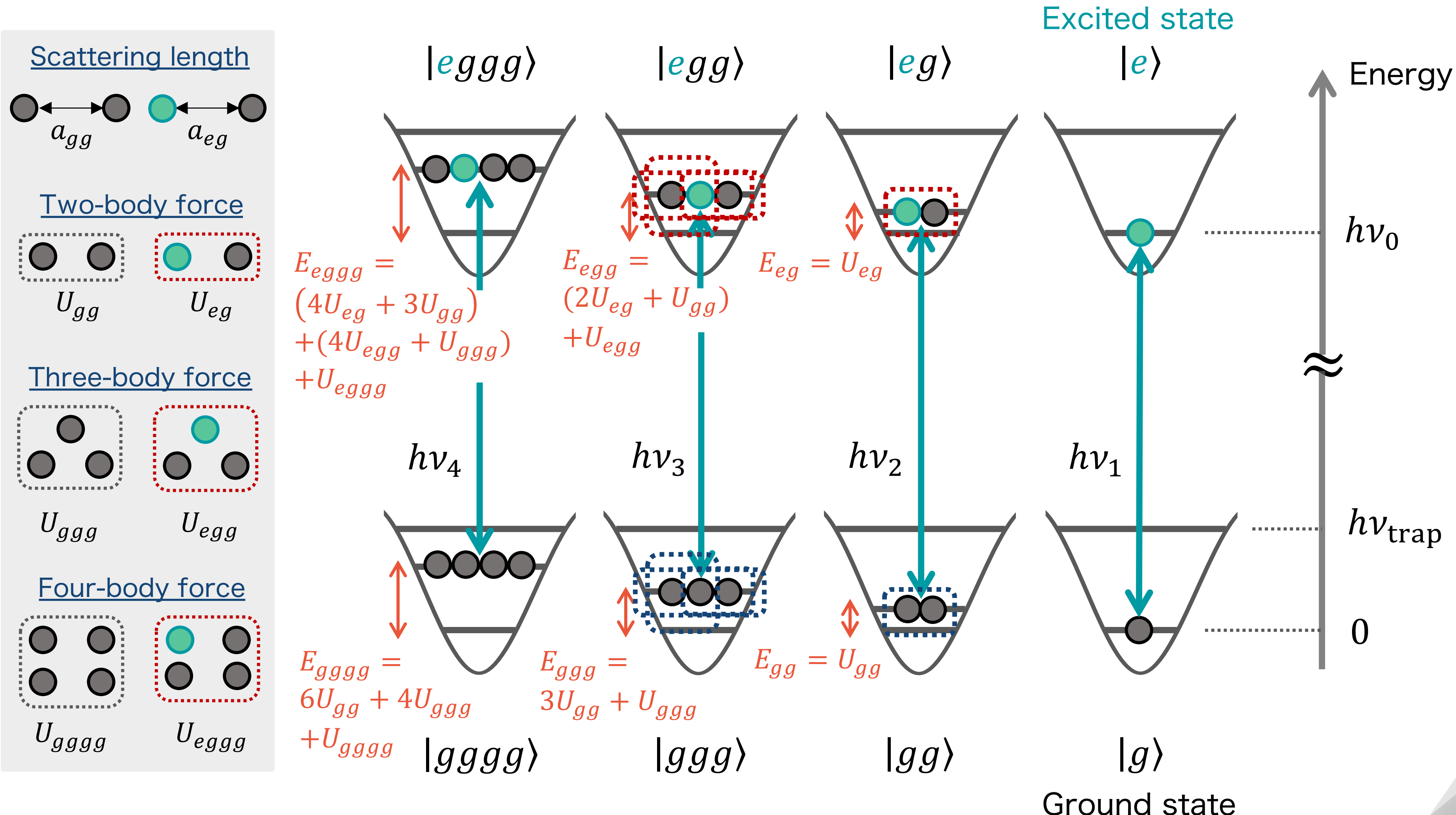
Methods

- ✓ High-resolution laser spectroscopy
- ✓ Control of the interaction strength by a Feshbach resonance

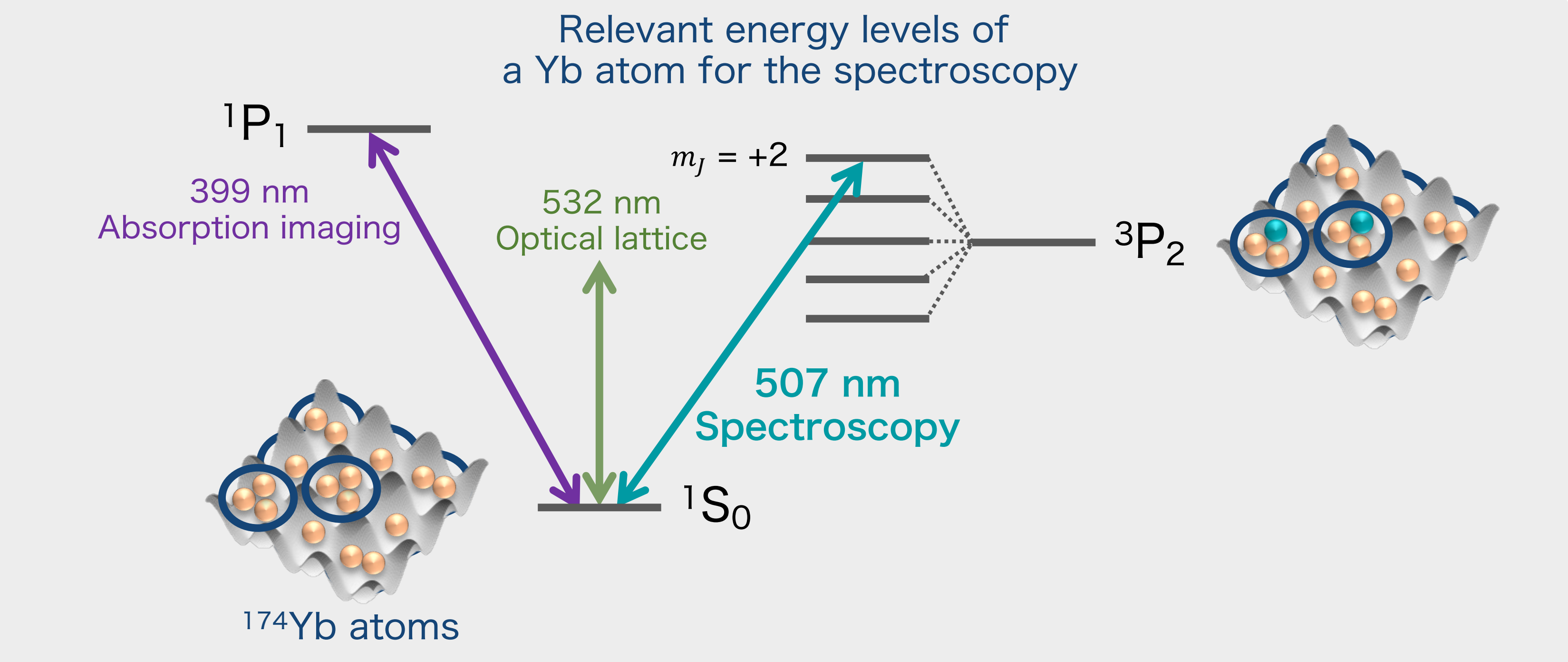
Method：How to study multi-body forces

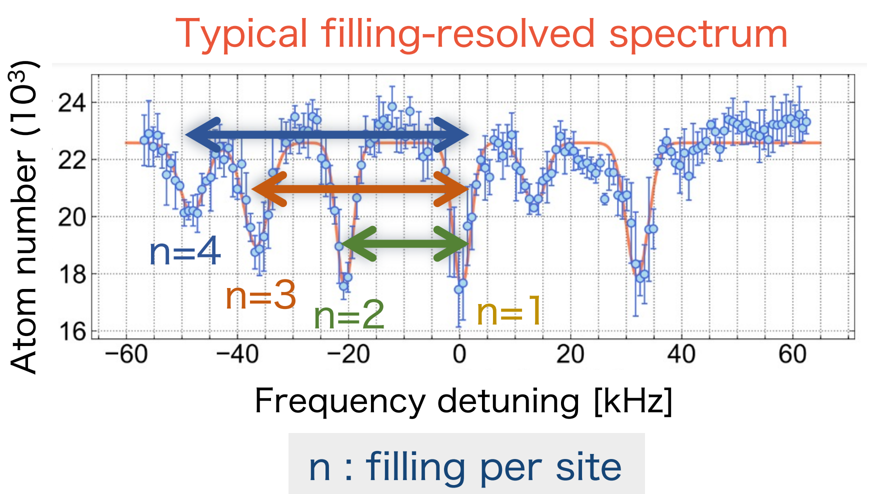
How do we study multi-body forces in a harmonic trap ?

These are revealed by filling-dependent resonance shift in an obtained spectrum.



Method : High-resolution spectroscopy



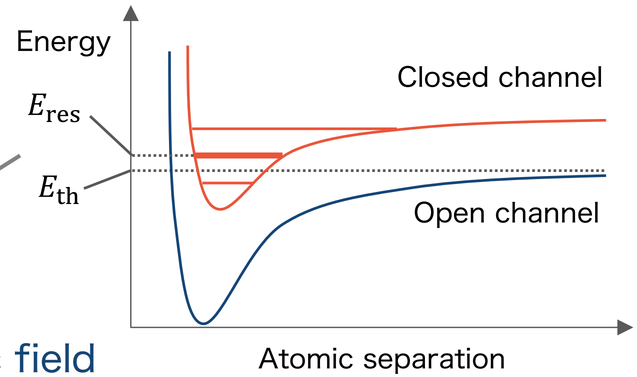


Perform loss spectroscopy to increase the S/N of multiple occupied sites

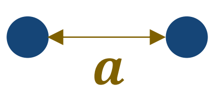
→ We were able to observe up to 'n=4' spectrum.

Method : Control of the interaction strength

Interaction strength between atoms can be controlled by a Feshbach resonance.

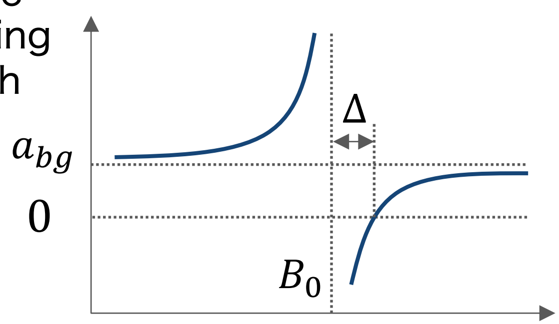


$(E_{res}-E_{th})$ can be controlled by an external magnetic field



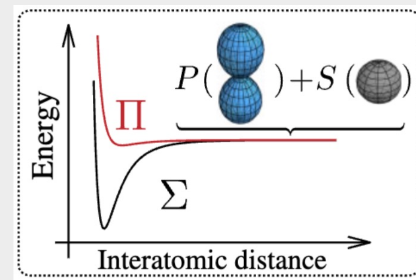
$$a = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

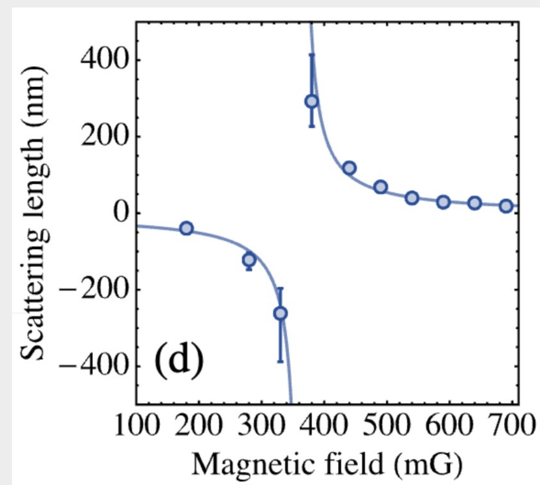
s-wave scattering length



Magnetic field

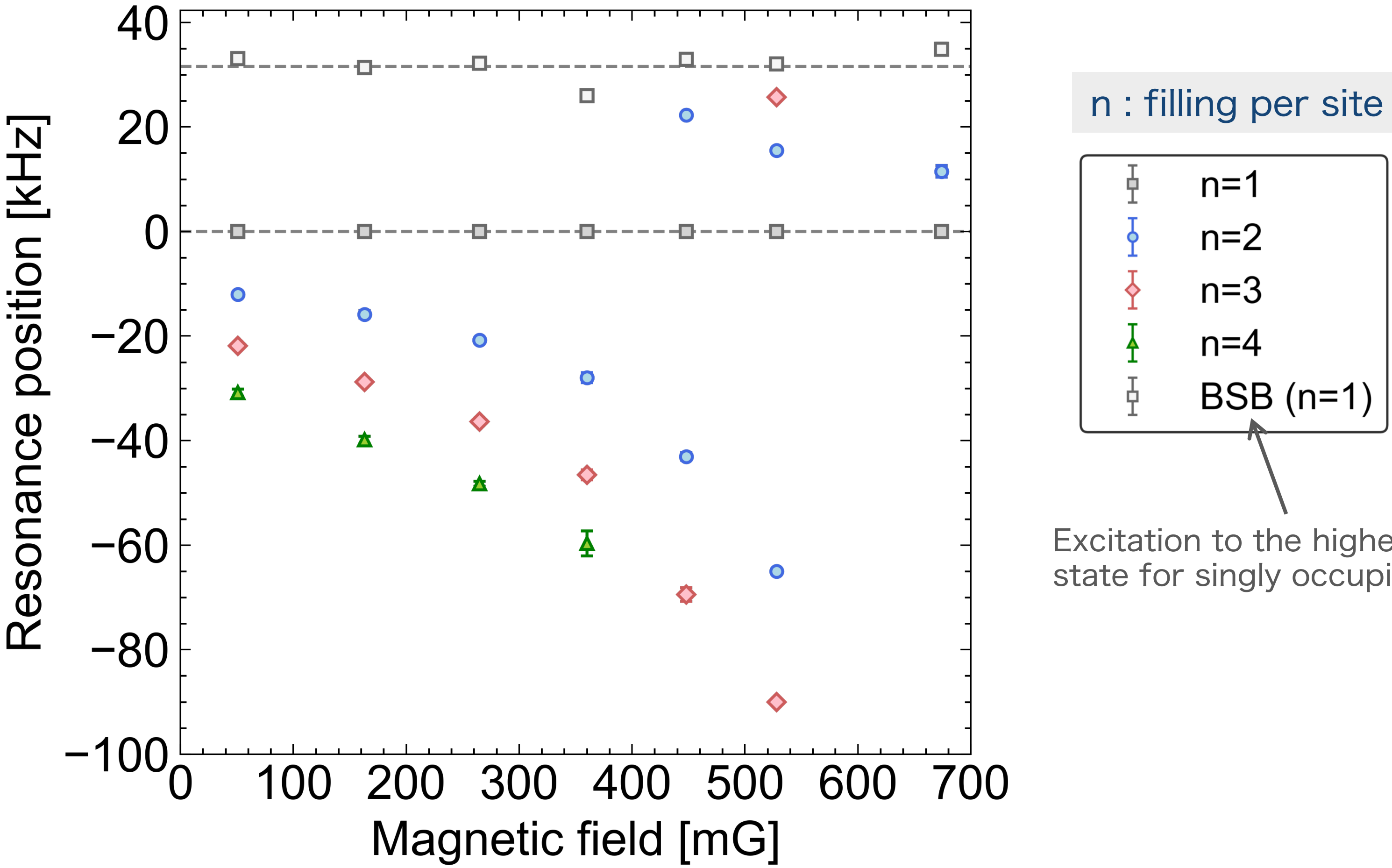
Feshbach resonance used in this study :
Between $^1S_0$ & $^3P_2$ (m_J=+2) states of ^{174}Yb





S. Kato *et al.*, PRL **110**, 173201(2013).

Results：Resonance freq. shift vs. B-field

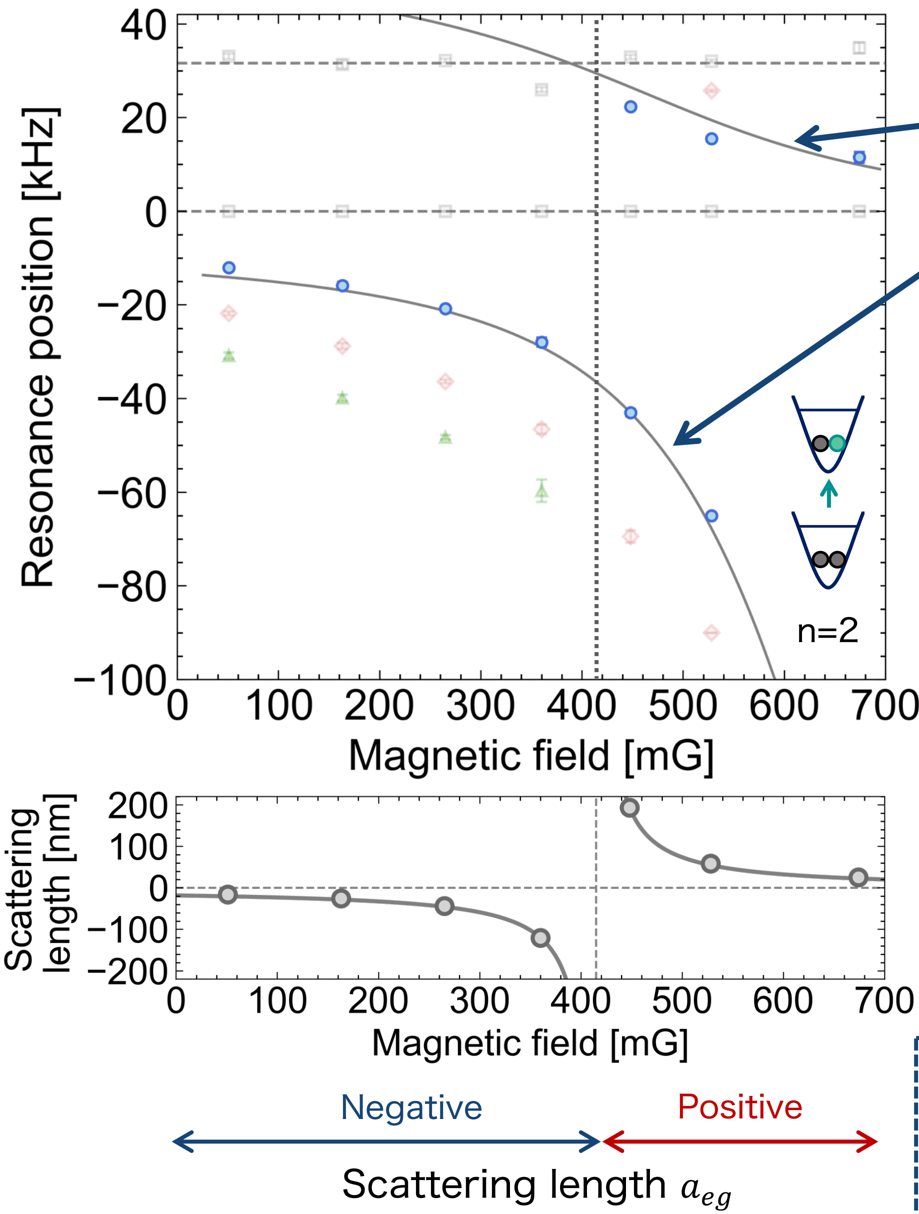


n : filling per site

Excitation to the higher vibrational state for singly occupied sites (n=1)

Filling-dependent frequency shifts were systematically measured over a wide range of interaction strengths.

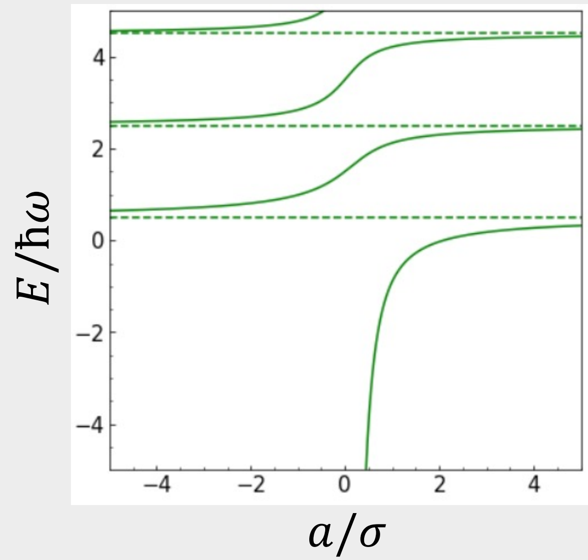
Results : Resonance freq. shift of ‘n=2’



‘Busch’s formula’

$$\sqrt{2}\frac{\Gamma(-E/(2\hbar\omega)+3/4)}{\Gamma(-E/(2\hbar\omega)+1/4)}=\frac{\sigma}{a}$$

- E: interaction energy
- a: scattering length
- σ: harmonic oscillator length ($\sqrt{\hbar/(m\omega)}$)

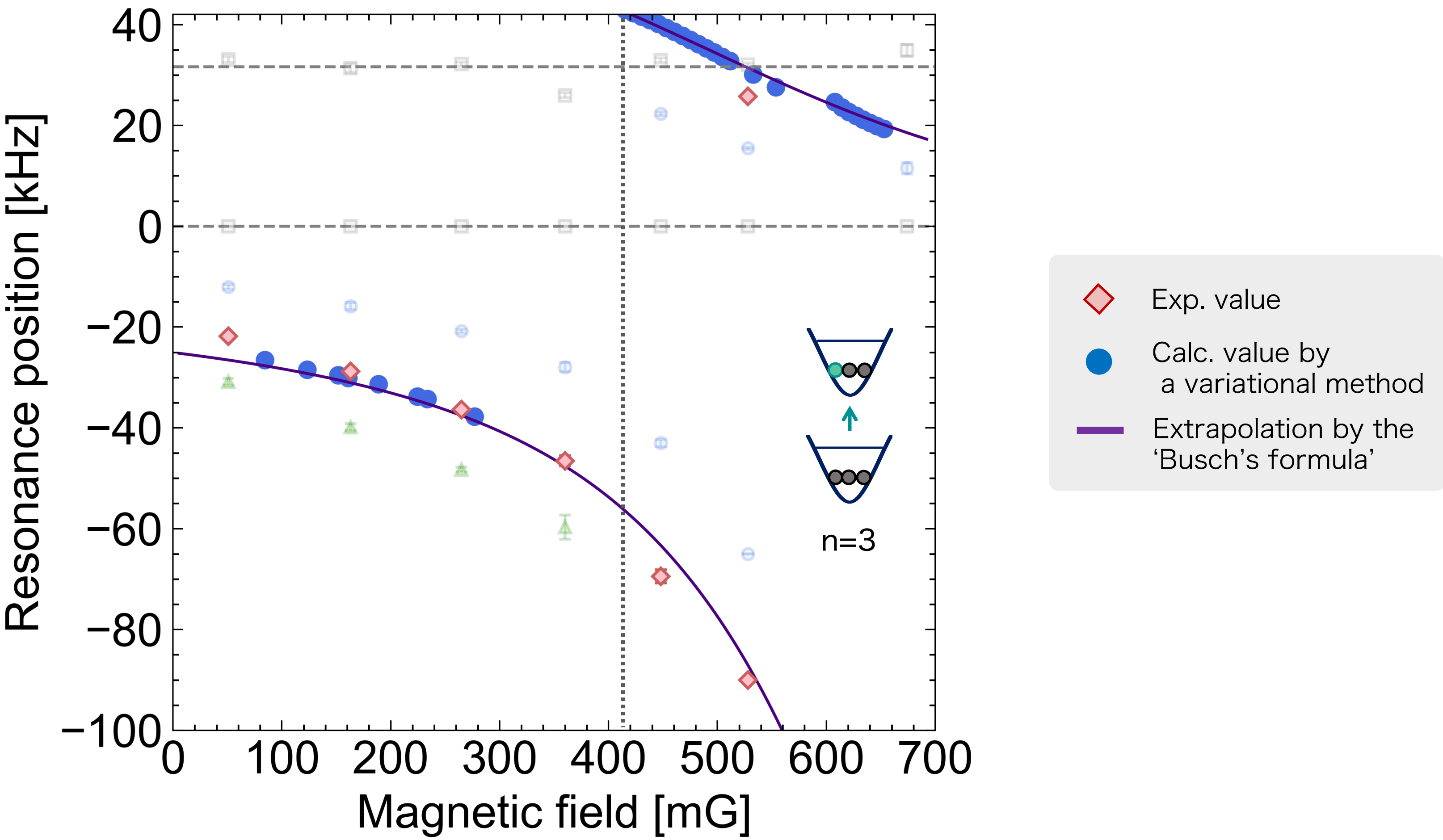


T. Busch *et al.*, Found. Phys. **28**, 549 (1998).

The shifts of ‘n=2’ is in good agreement with the calculated values.

(as in the previous work: S. Kato *et al.* (2013))

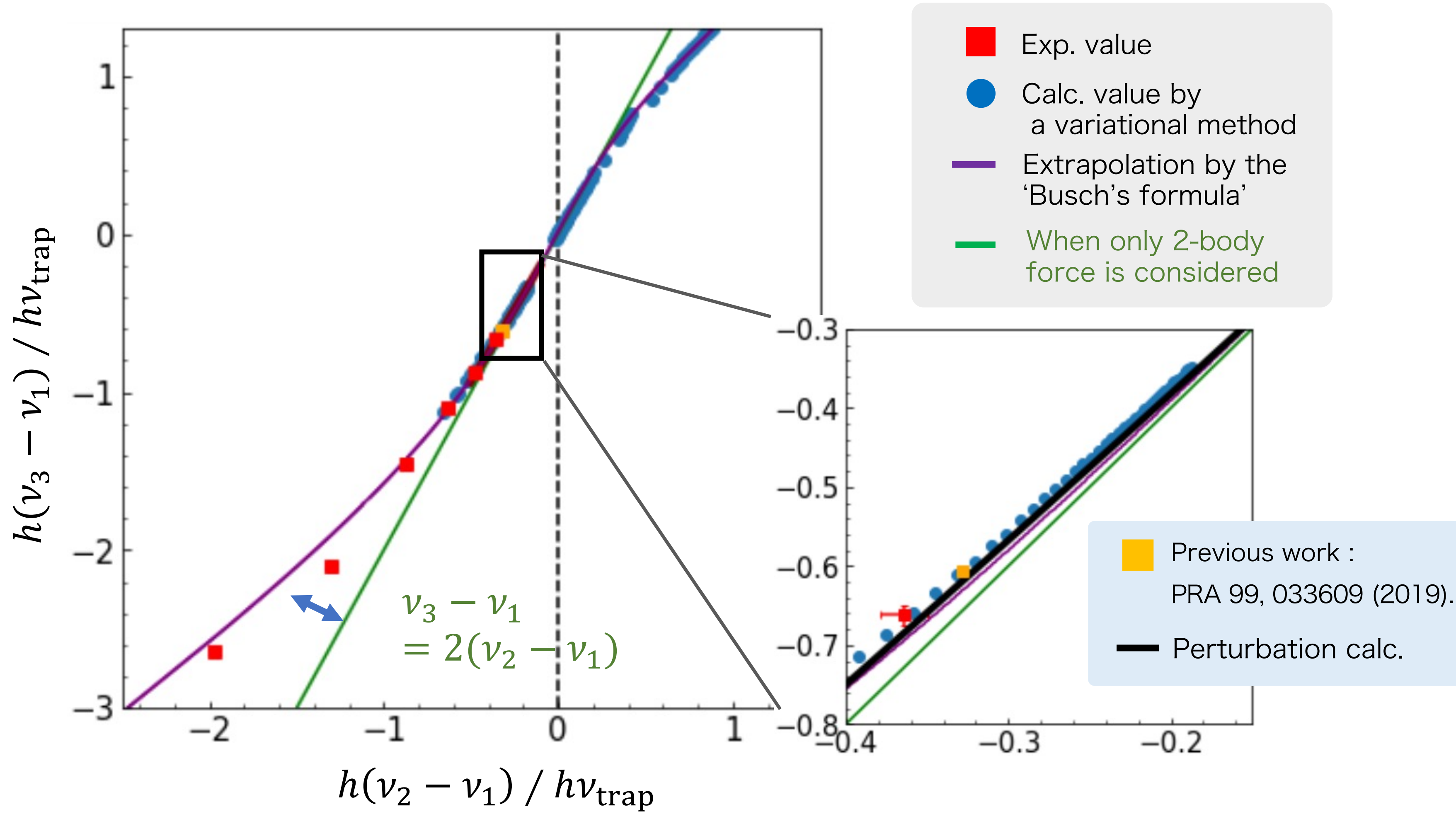
Results：Resonance freq. shift of ‘n=3’



※ Details of calc. were reported by Y. Haruna @7th cluster WS (2021) & EMMI WS (2022).
Ref.: D. Blume *et al.*, PRA **97**, 033621 (2018).

The shifts of ‘n=3’ is also in good agreement with the calculated values.

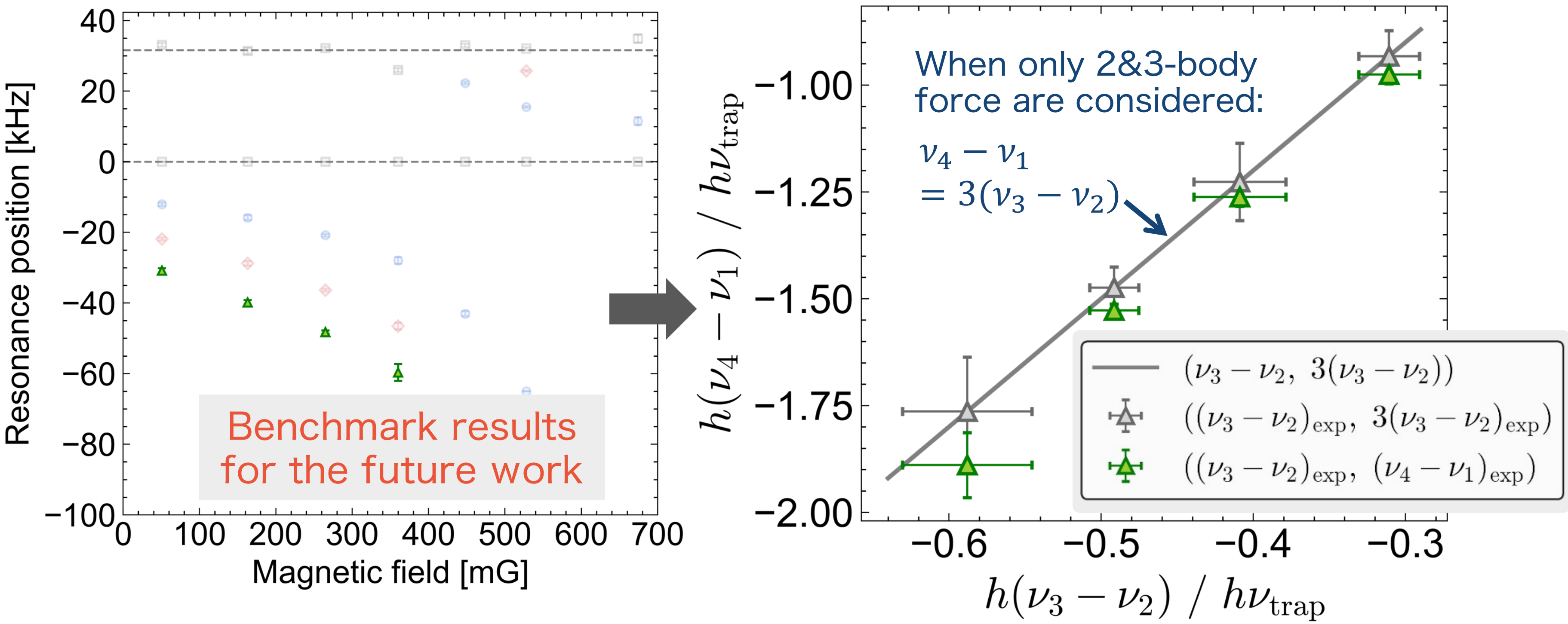
Results：Resonance freq. shift of ‘n=3’

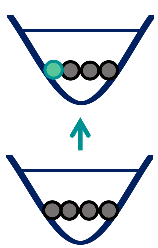


※ Details of calc. were reported by Y. Haruna @7th cluster WS (2021) & EMMI WS (2022).
Ref.: D. Blume *et al.*, PRA **97**, 033621 (2018).

The shifts of ‘n=3’ is also in good agreement with the calculated values.

Results：Resonance freq. shift of ‘n=4’





n=4

- The evidence of four-body force was not found within the accuracy of this measurement.
- All plots show a similar trend of deviation from the calculated values.

Summary & Outlook

- ✓ Study three-body forces in a harmonic trap in an optical lattice system
- ✓ Determine the binding energy in a wide range of interaction strength by a Feshbach resonance beyond perturbative regime
- ✓ Resonance freq. shift of n=3 shows good quantitative agreement with calc. results.
- ✓ The evidence of four-body force was not found within the accuracy of this measurement.
  → Benchmark results for the future work