Research on ultracold few-atomic molecules using ionization detection

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Clusters & Hierarchies

Outline

Background

・Researches on Efimov state using ultracold atom

Our plan

・Direct observation of Efimov state using ionization

・Fast and low-loss cooling method with cavity enhanced optical cavity

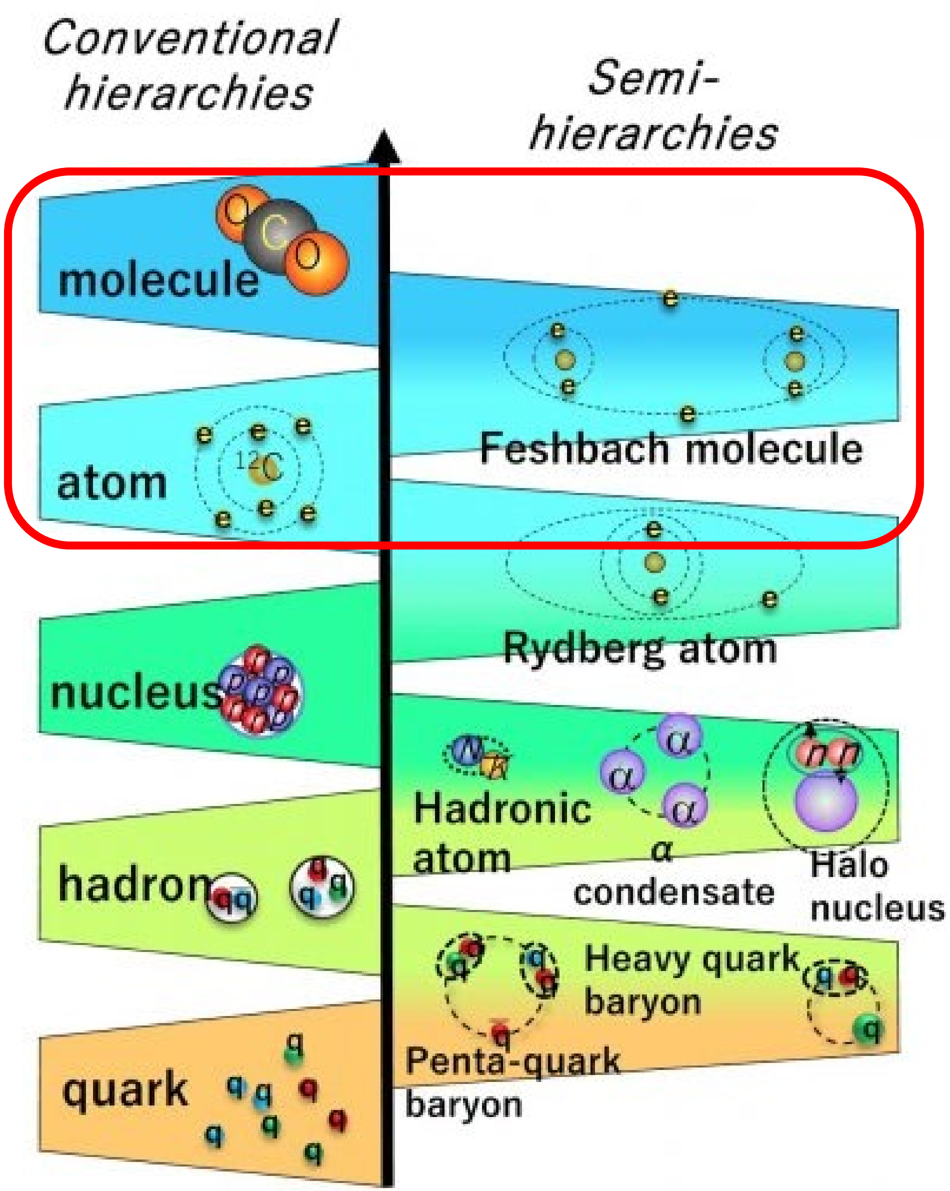
Current status of our experiment

・Atom trapping in 3D Cavity-enhanced optical lattice

・Laser cooling of atoms by Raman sideband cooling

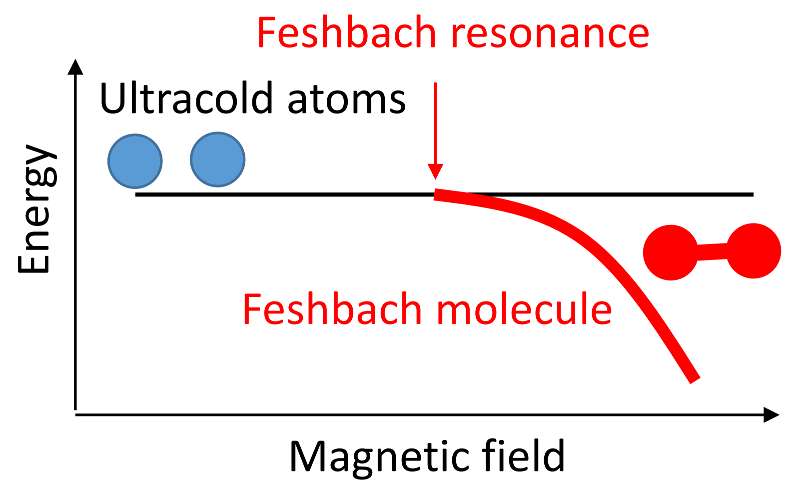
Summary & outlook

Background : Hierarchical structure of matter



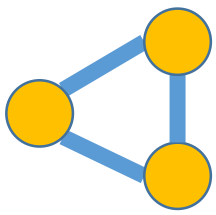
Feshbach molecule

: Most loosely bound di-atomic molecule

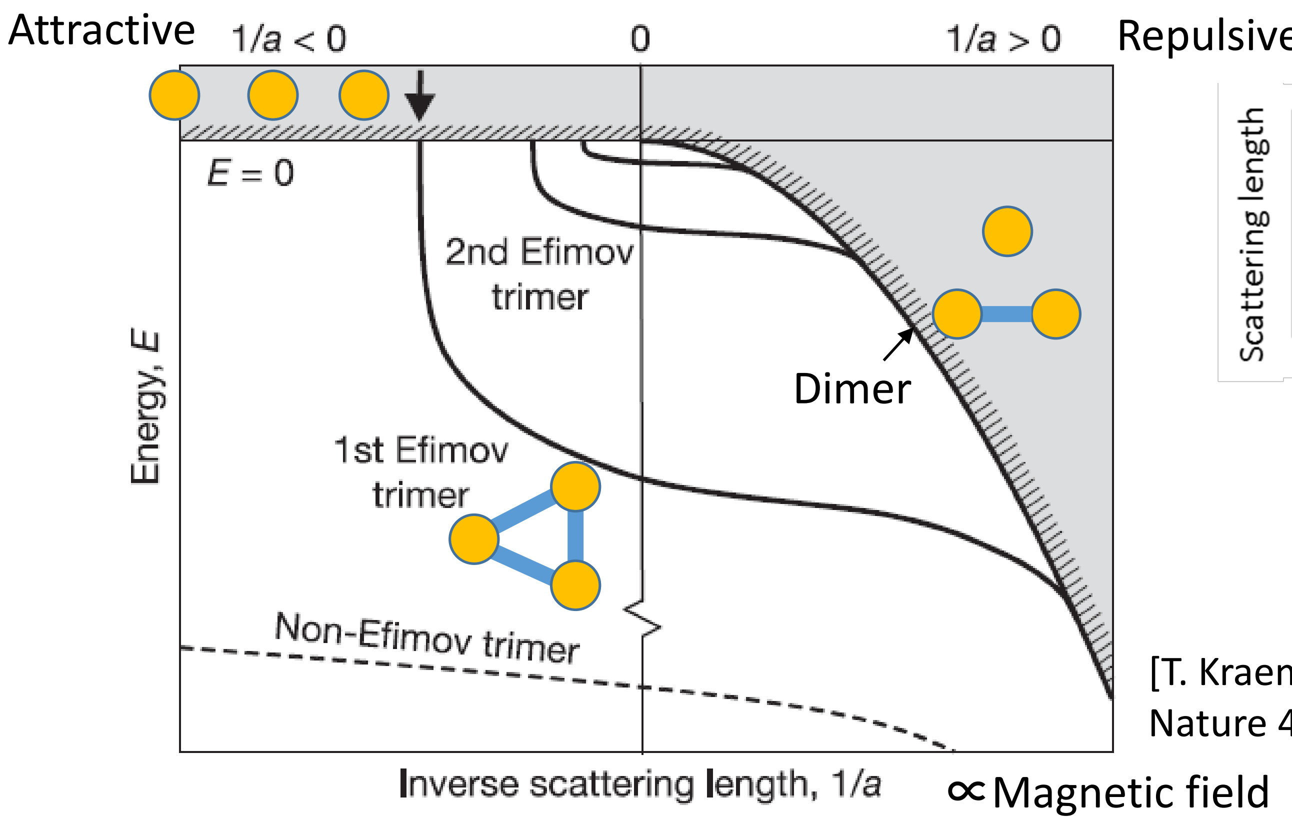


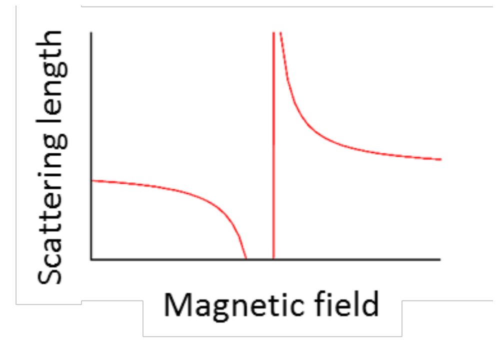
Efimov state

: Most loosely bound Tri-atomic molecule



Efimov states





[T. Kraemer et al., Nature 440 315 (2006)]

Arbitral particles with short range interactions

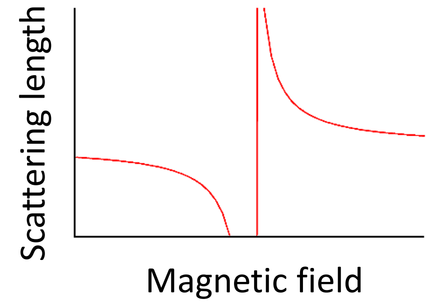
Efimov states are “Universal”.

- Ultracold atom
- Helium
- Nuclear
- Electron + atom
- ⋮

⇨ Connect the different hierarchies

Study on Efimov state with ultracold atoms

Ultracold atoms
- Precise control of the scattering length
- Many atomic species



Single specie

Bosons

^{133}Cs - ^{133}Cs - ^{133}Cs

^{85}Rb - ^{85}Rb - ^{85}Rb

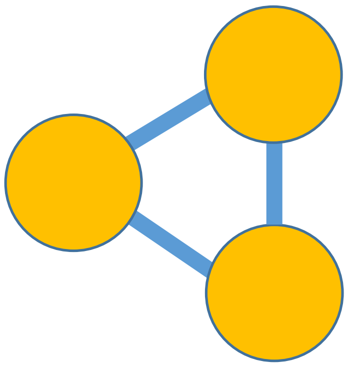
^{39}K - ^{39}K - ^{39}K

^{7}Li - ^{7}Li - ^{7}Li

Fermions

^{6}Li - ^{6}Li - ^{6}Li

in three spin states



Mixture of two species

Boson - Boson

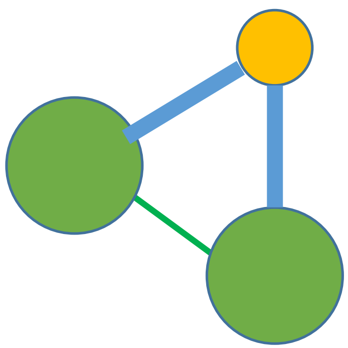
^{87}Rb - ^{87}Rb - ^{41}K

^{87}Rb - ^{87}Rb - ^{7}Li

Boson - Fermion

^{87}Rb - ^{87}Rb - ^{40}K

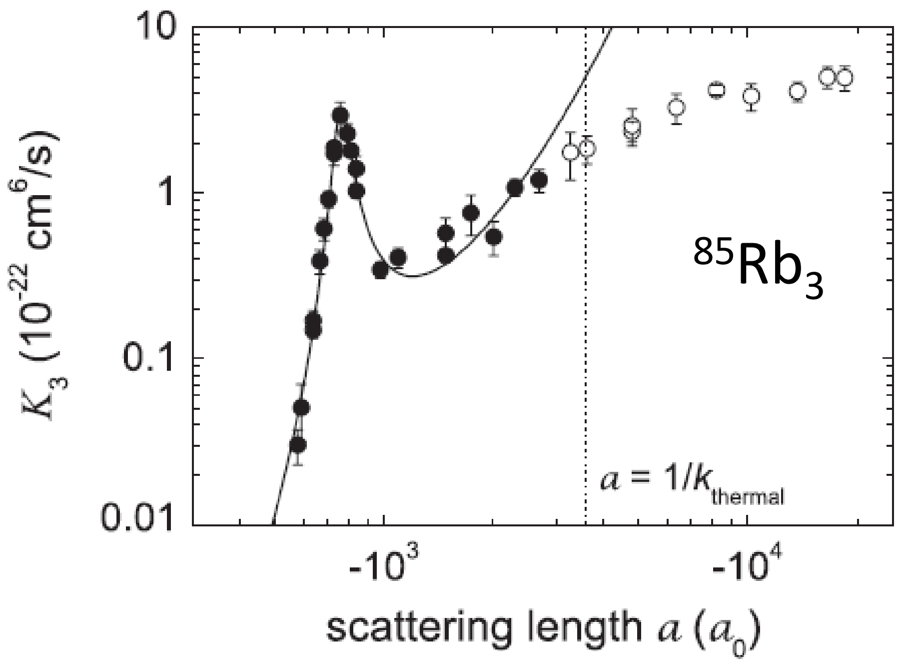
^{133}Cs - ^{133}Cs - ^{6}Li

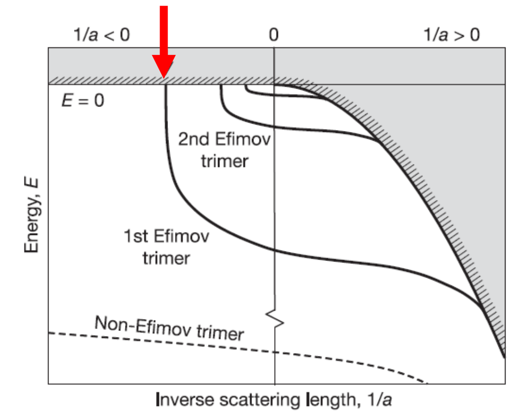


Typical data of Efimov resonance

[R.J. Wild et al., PRL 108 145305 (2012)]

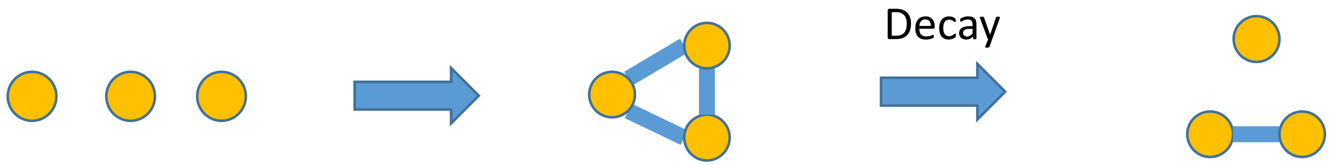
Three body loss coefficients





Efimov Trimer

Deeply bound dimer (not FB molecule)



Atomic loss is enhanced

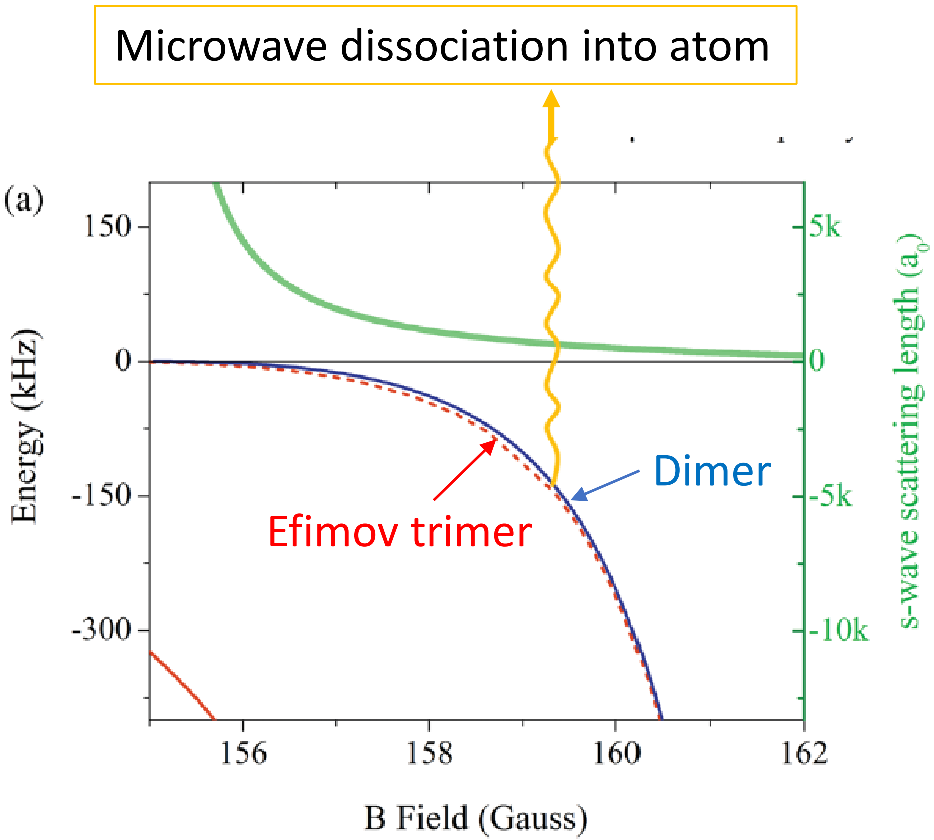
Lifetime ~100us

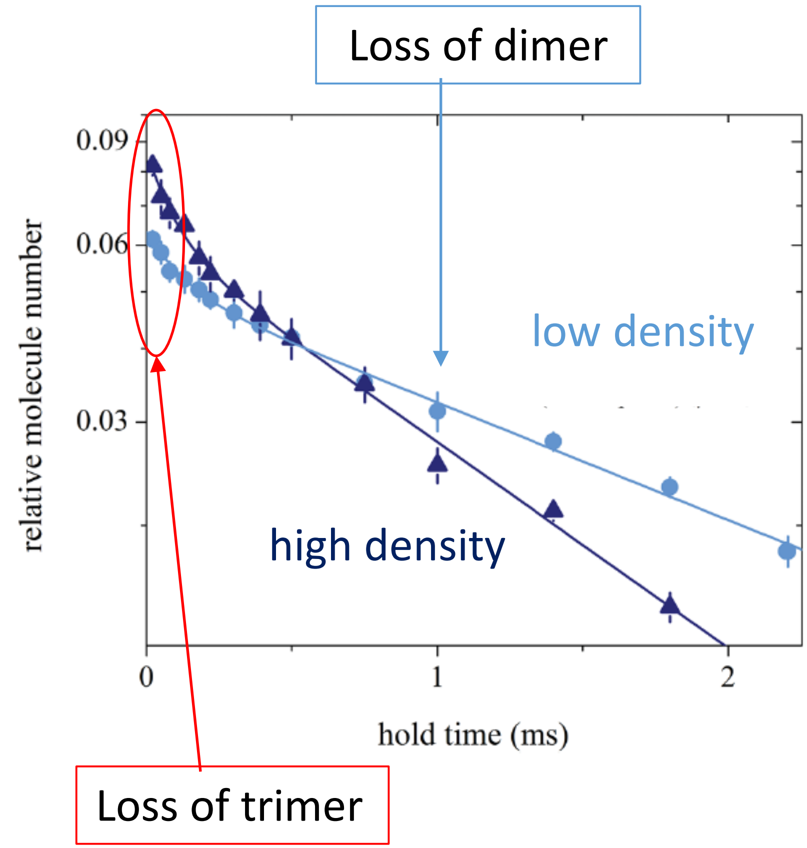
Direct observation is difficult.

Almost all experiments are observations of atomic loss.

Observation of Efimov state

[C. E. Klauss et al., Phys. Rev. Lett 119 143401 (2017)]





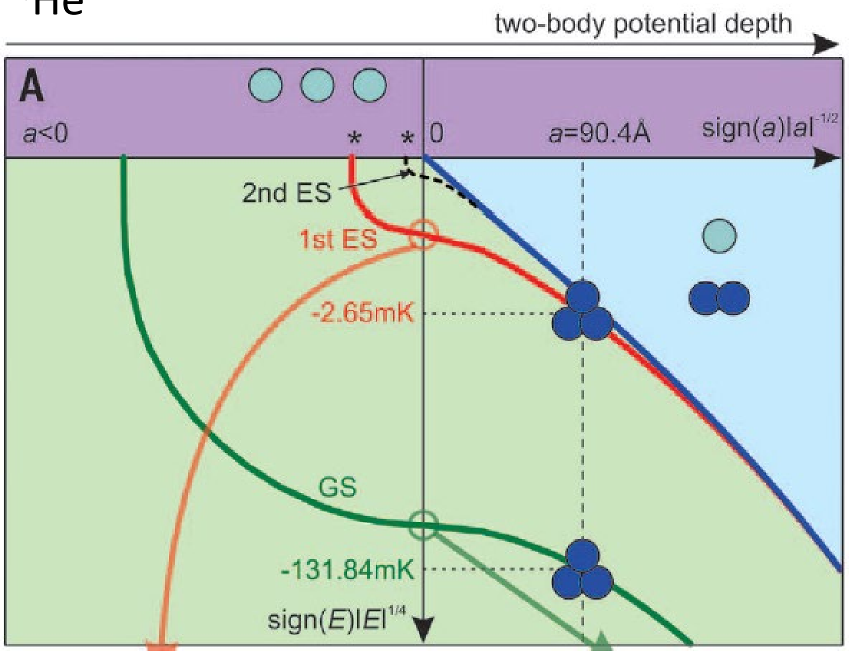
Trimer and dimer cannot be distinguished at the observation process.

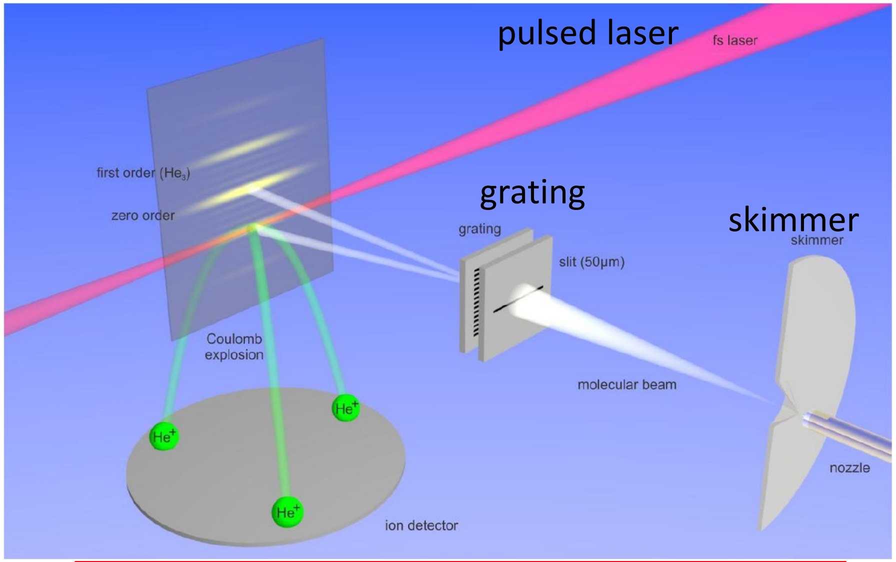
Lifetime ~ 100us

Direct observation of Efimov state (He)

[M. Kunitski et al., Science 348 551 (2015)]

^4He





Efimov states are directly observed by ionization detection

He is very special atom

No dimer states ($^4He_2$) below the trimer

⇩

Efimov trimer ($^4He_3$) is stable.

No Feshbach resonance for He.

⇔

In experiments of ultracold atoms

Lifetime of trimer is very short (~100us)

Direct observation of trimer could be the key technique for further experiments.

Outline

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- Researches on Efimov state using ultracold atom

Our plan

- Direct observation of Efimov state using ionization
- Fast and low-loss cooling method with cavity enhanced optical cavity

Current status of our experiment

- Atom trapping in 3D Cavity-enhanced optical lattice
- Laser cooling of atoms by Raman sideband cooling

Summary & outlook

Our plan: ionization detection of Efimov state

Direct observation of Efimov trimer using ionization detection

- Fast ionization pulse: 5ns << lifetime of trimer
- High sensitivity : >50% (MCP)
- Detect ions separately depending on their mass

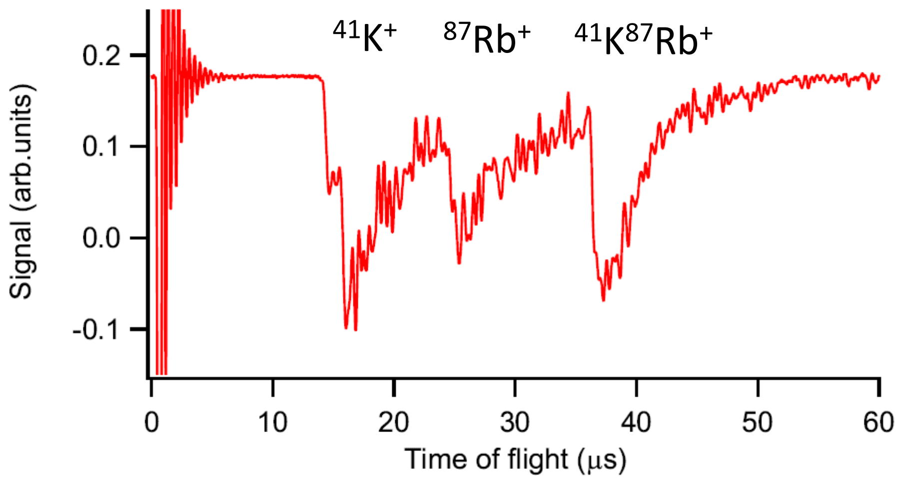
Atom, dimer, and trimer can be clearly distinguished.

⇨ Direct observation of Efimov trimer

⇩

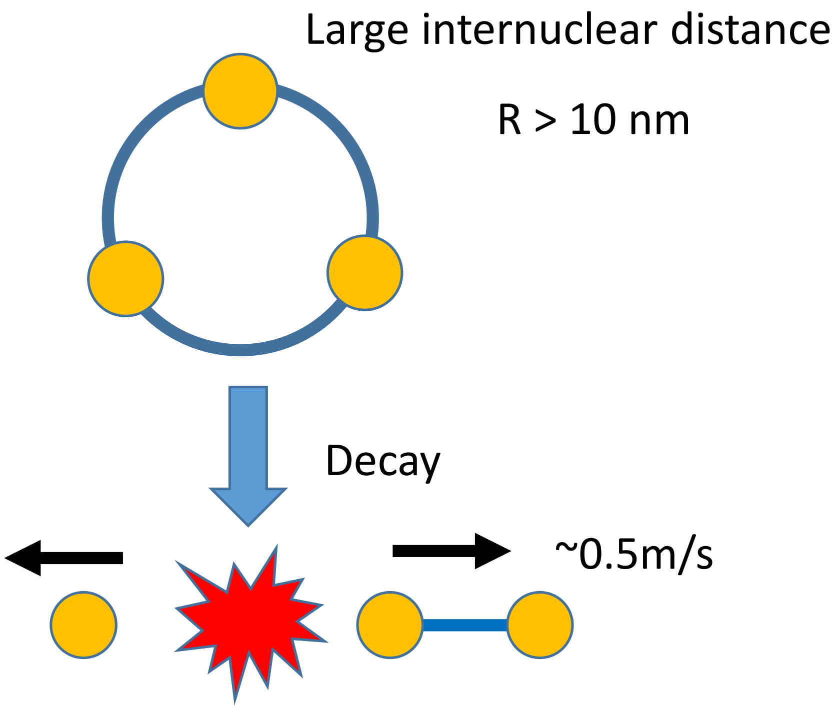
Further study about decay process

Typical ion signal (K, Rb, KRb)



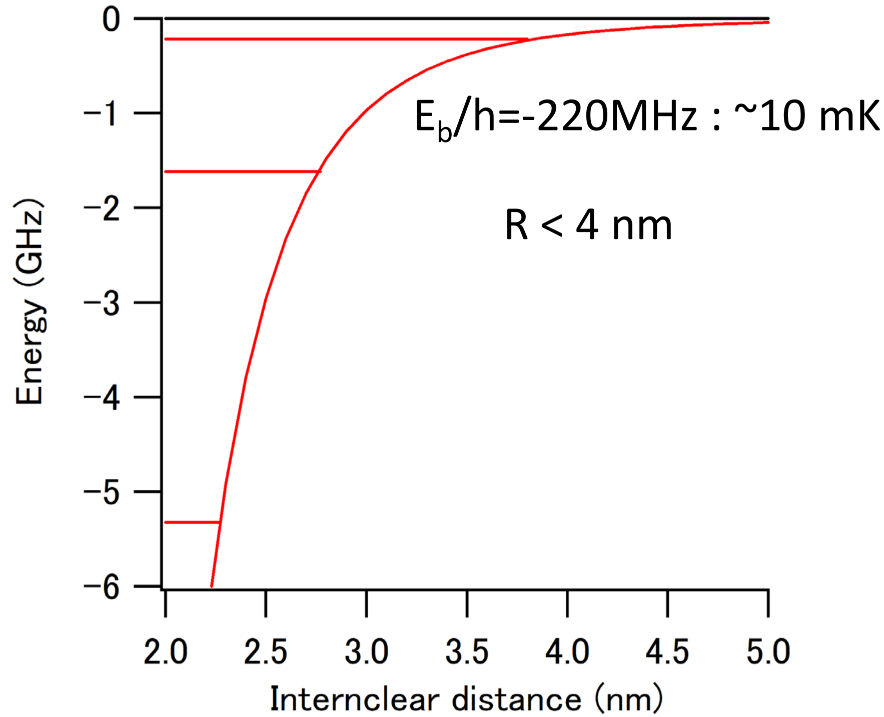
Decay process of Efimov trimer

Efimov state



Binding energy of product molecule gives their kinetic energies.

Bound states of dimer($^{85}Rb_2$)

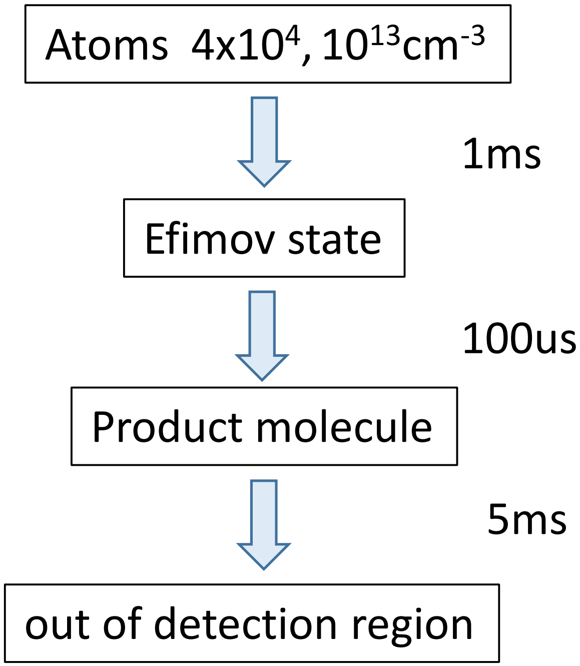


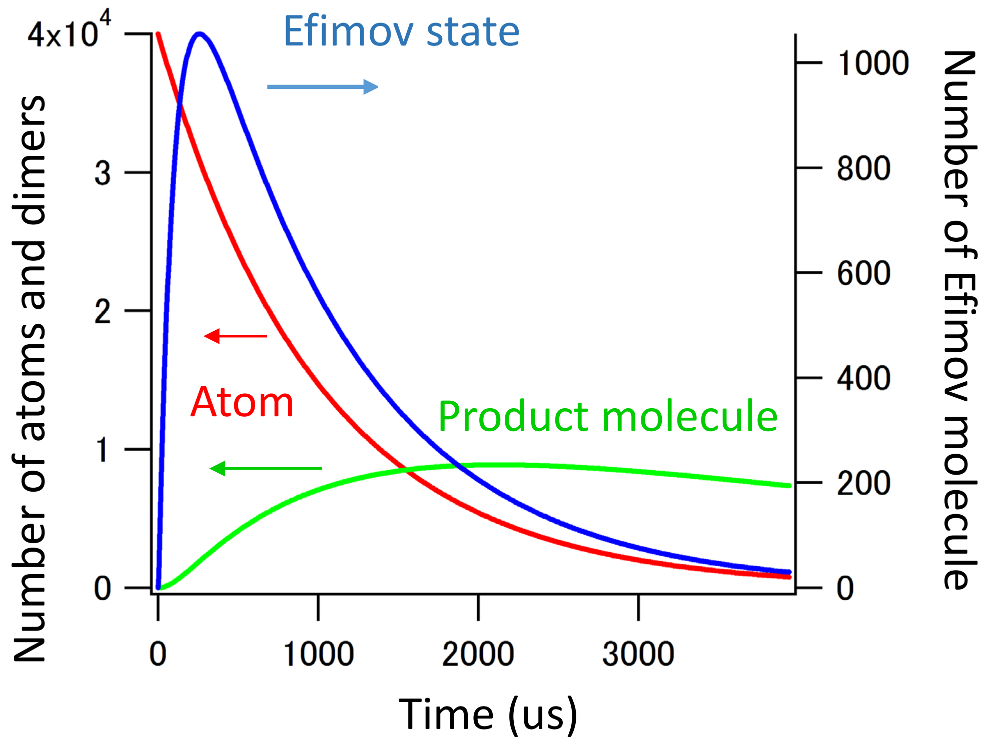
T ~ 10mK?

Difficult to trap

Possible to detect by ionization

Possibility of the product molecule detection





At maximum

~10^3 Efimov states
~10^4 product molecules

→ Detectable by ionization detection

Detailed study about the decay process will be realized.

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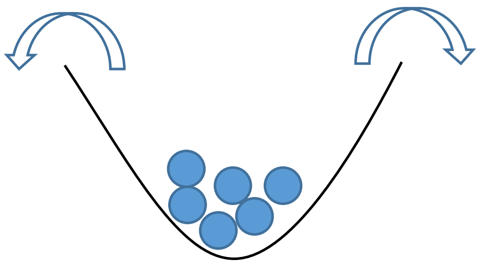
Our plan for Efimov experiment

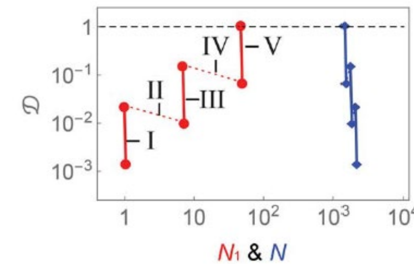
Evaporative cooling

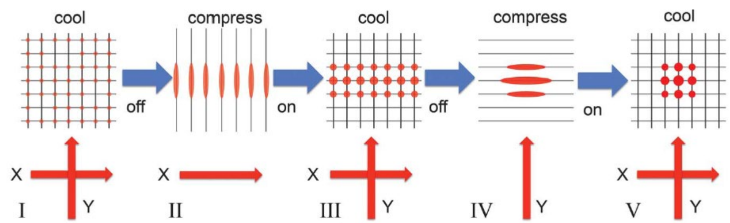
Slow：~10 s
Large loss：~99%



Laser cooling + Compression

Fast : ~300 ms
Small loss ~30％



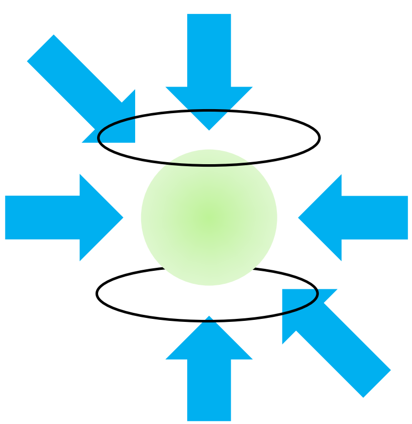


N~10^3

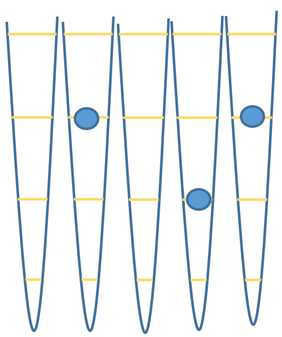
[J. Hu et al., Science 358 1078-1080 (2017)]

Our Plan

MOT

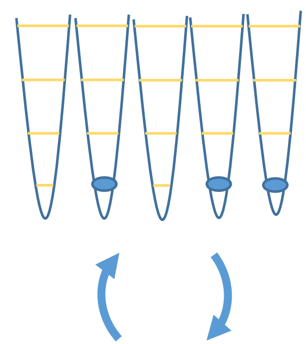


Large and deep lattice



Large number of atoms

Laser cooling in lattice



Compression by
controlling lattice depth

BEC

Feshbach
resonance

Efimov

Detection

Optical lattice enhanced by high-finesse cavity

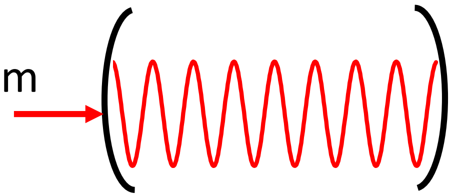
High finesse optical cavity in vacuum chamber

Finesse：~7x10^4

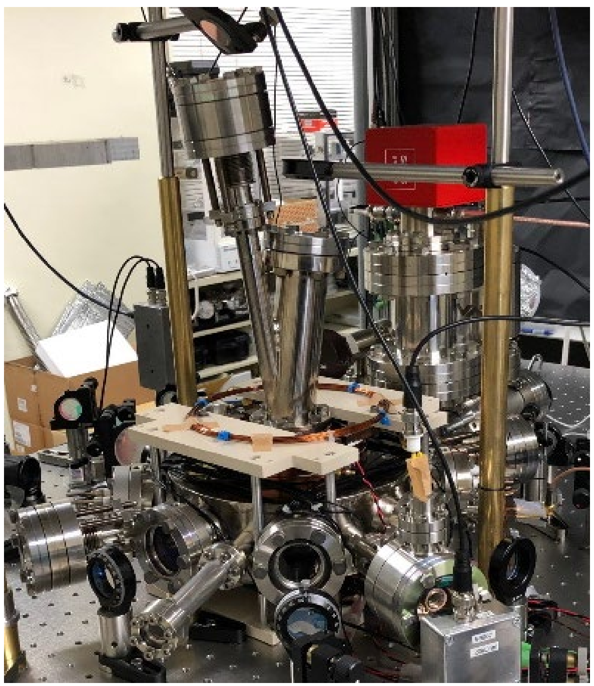
Enhancement：~2x10^4

In cavity
P ~200W

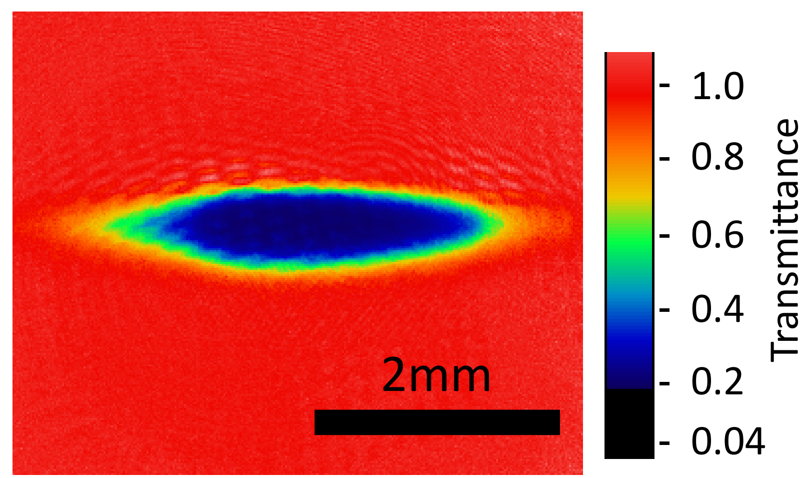
Wavelength λ=1038nm
Input P ~10mW



Diameter~1mm, Depth U~300uK



Absorption imaging



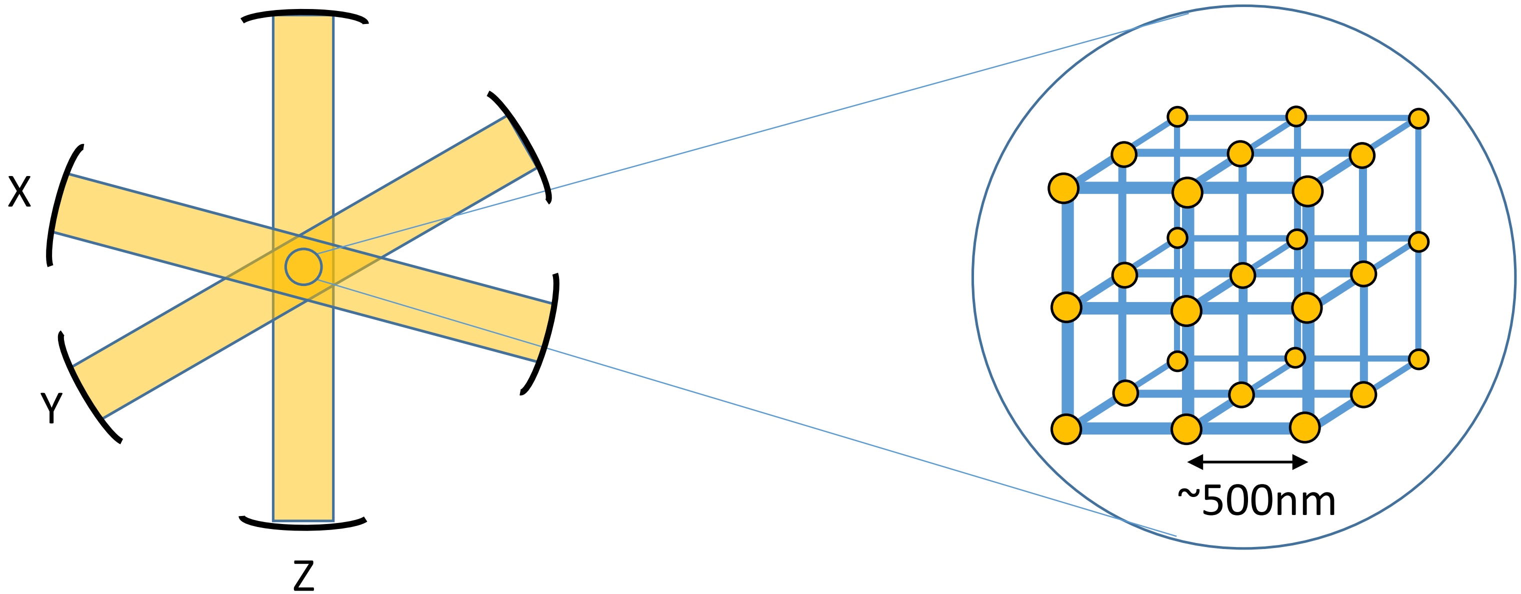
Rb

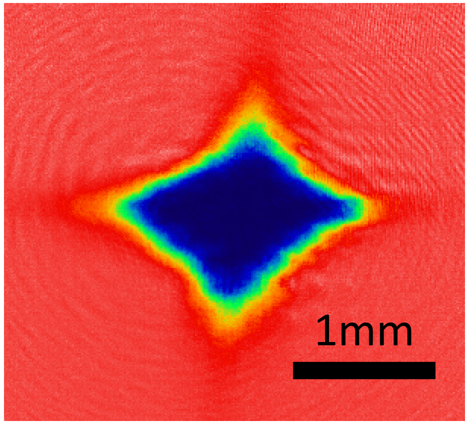
N = 2 x 10^7

T ~60 μK

Lifetime ~3s

Cavity-enhanced 3D optical lattice



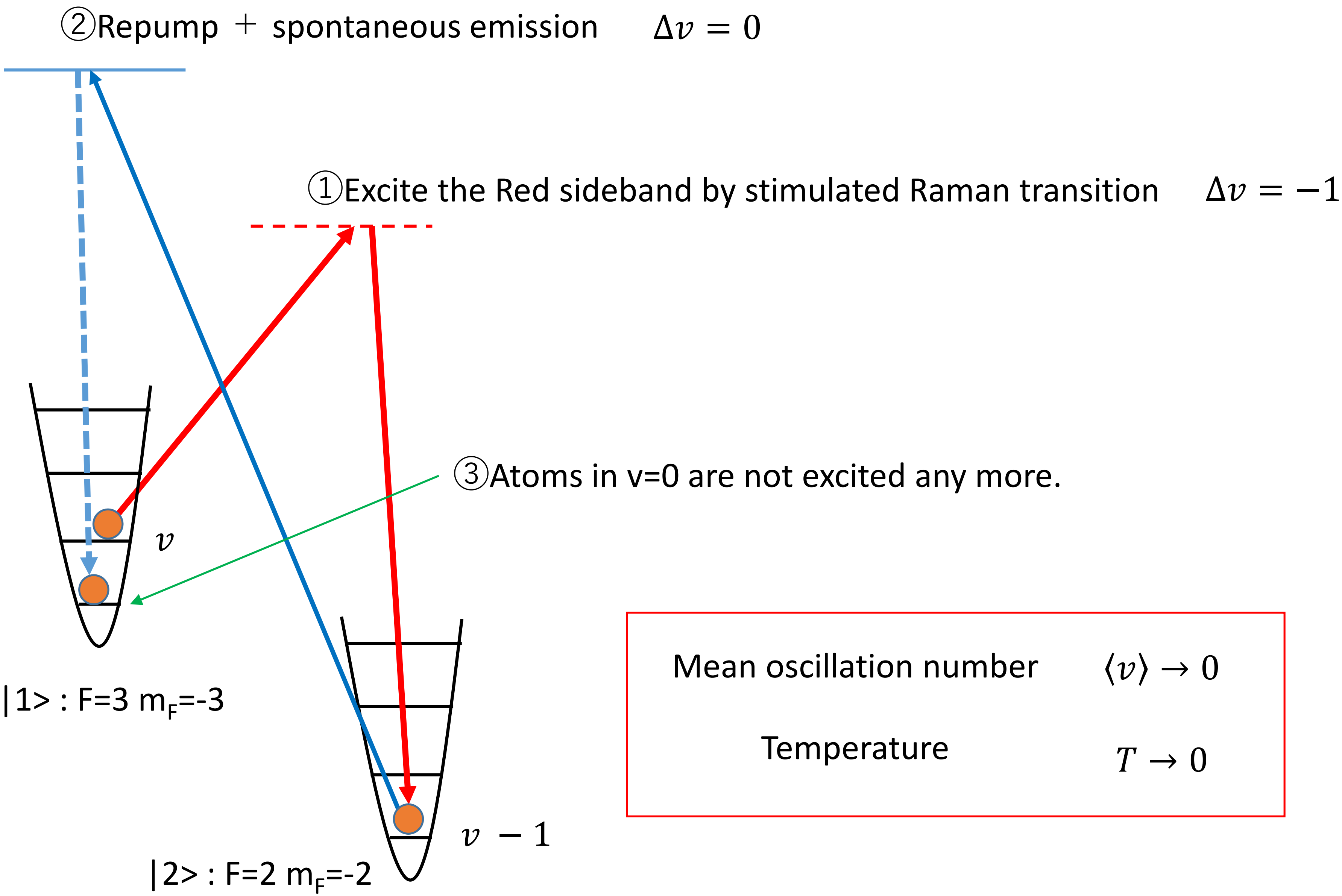


Loading into 3D cavity-enhanced lattice

Number of atoms ：N=2.4 × 10^7
Temperature : ~50 uK
Atomic density ： $2x10^{11}$/㎝^{3}

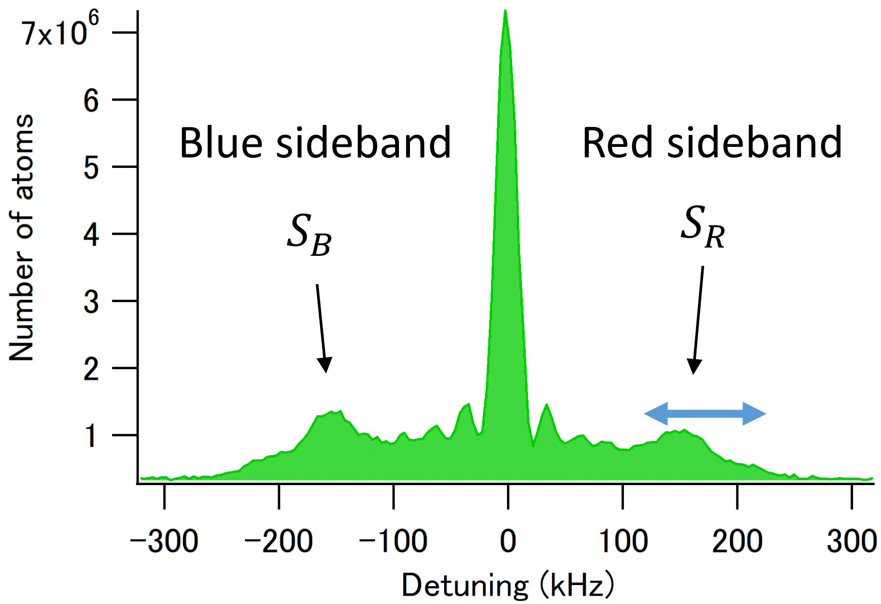
Laser cooling & compression

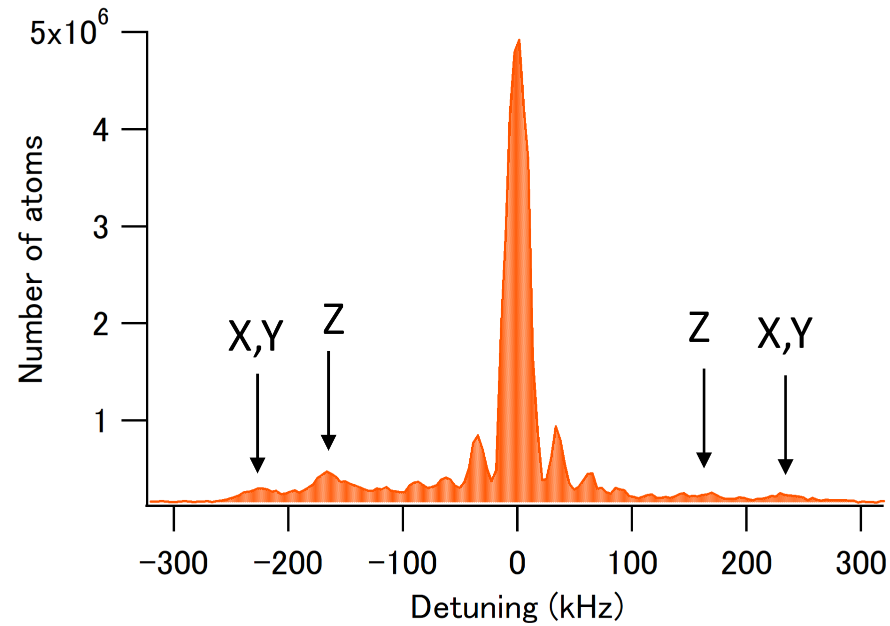
Raman sideband cooling



Raman sideband cooling (preliminary)

Before cooling → After cooling





	Before cooling		After cooling	
Area ratio	$R \equiv \frac{S_R}{S_B} = 0.85$		$R_Z = 0.22$	$R_{X,Y} = 0.45$
Mean oscillation quantum number	$\langle v \rangle = \frac{R}{1-R} = 5.6$		$\langle v_Z \rangle = 0.23$	$\langle v_{X,Y} \rangle = 0.8$
Temperature	T=46 uK	→	T_Z = 5 uK	$T_{X,Y}$ = 9.5 uK

Succeeded in laser cooling in optical lattice

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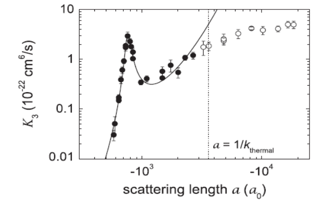
Summary & outlook

Summary and outlook

Summary

Researches on Efimov states using ultracold atoms.



Because of the difficulty of the direct detection of Efimov states, atomic loss experiments have been mainly performed.

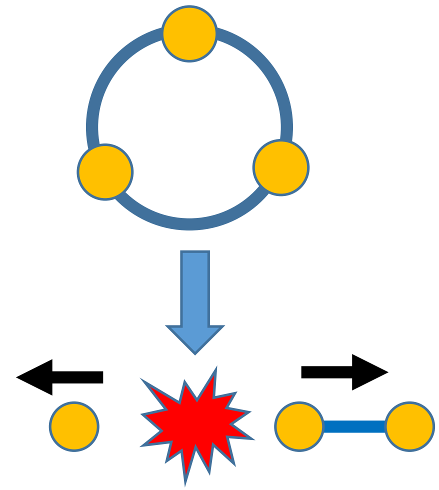
⇕

Our plan

Direct detection of the Efimov state using ionization detection.

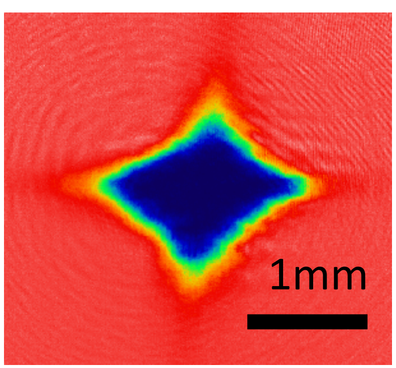
⇩

Study about the decay process by detecting product molecule.



Progress of experiment

- ✓ Atom trapping in 3D cavity-enhanced optical lattice
- ✓ Raman sideband cooling



$N=2.5 \times 10^7$

Outlook

Improve cooling of atoms

Detection of Efimov states by ionization