Research on ultracold few-atomic molecules using ionization detection (C01班公募研究)

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Outline

Background

- Researches on Efimov state using ultracold atom

Our plan

- Direct observation of Efimov state using ionization

Experiment

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

Summary & outlook

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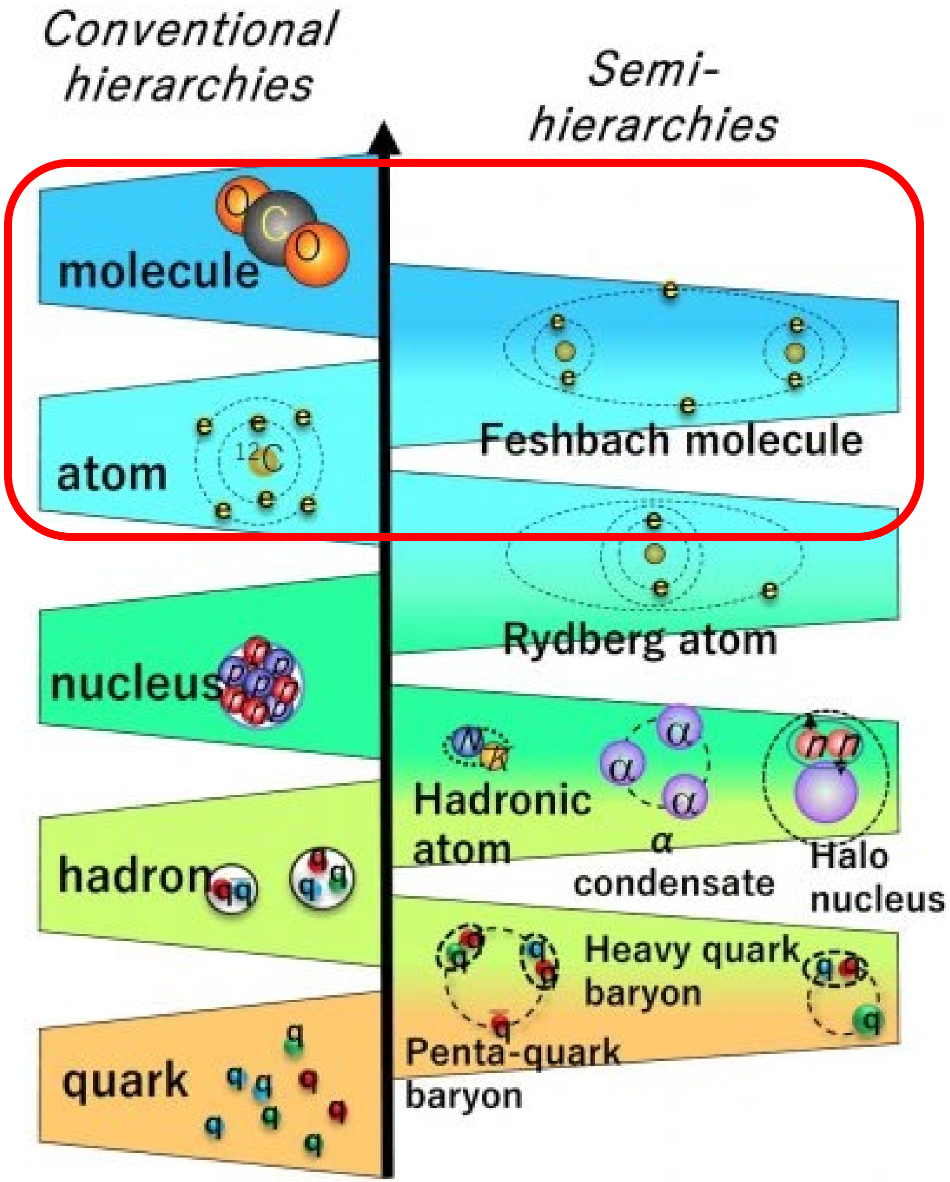
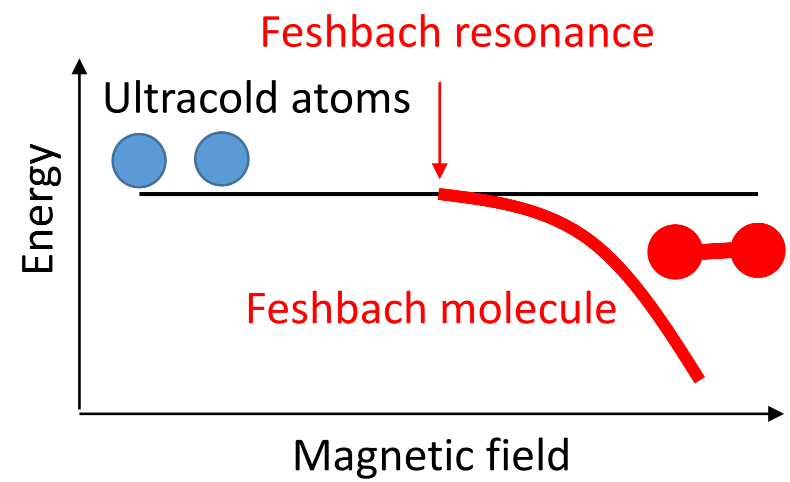
Summary & outlook

Background : Hierarchical structure of matter

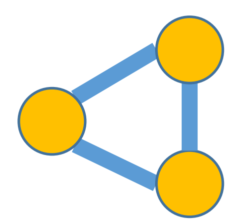


Ultracold Atoms and Molecules

Feshbach molecule
: Most loosely bound di-atomic molecule

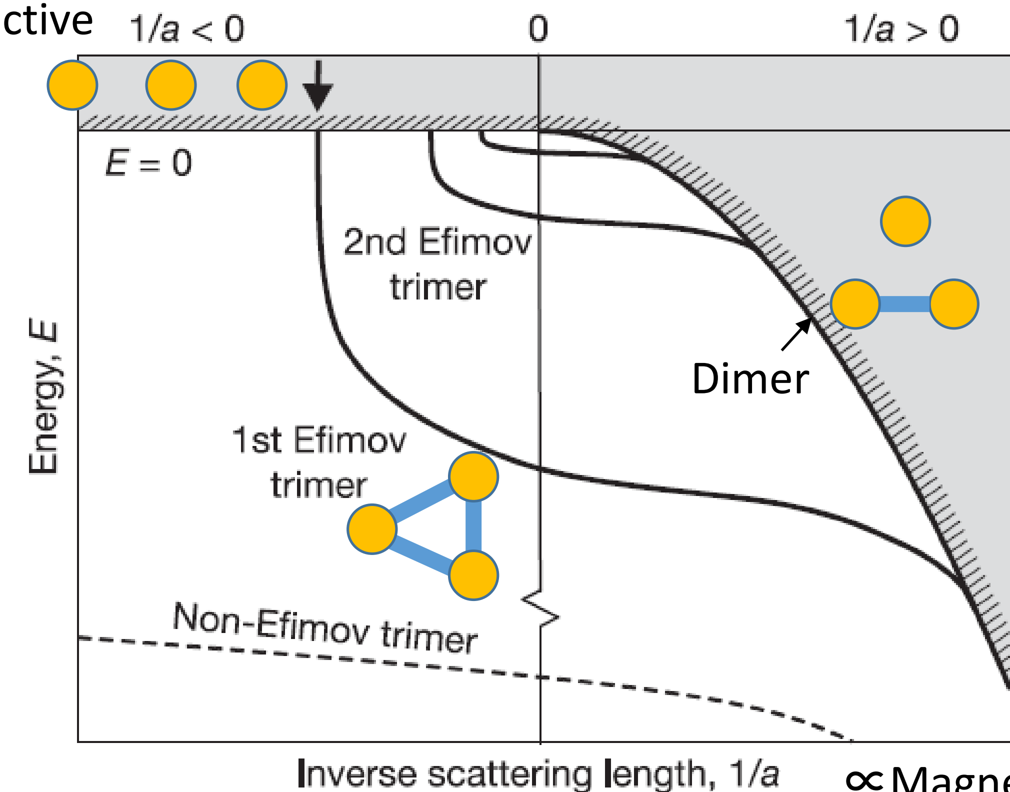


Efimov state
: Most loosely bound Tri-atomic molecule

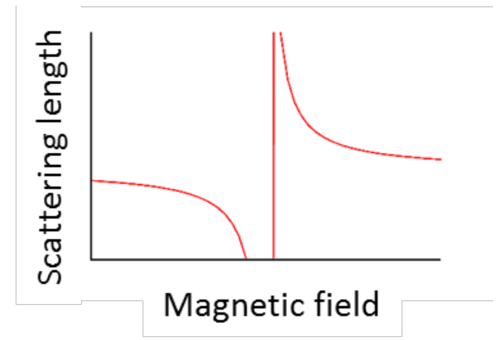


Efimov states

Attractive



Repulsive



∝Magnetic field

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

Arbitral particles with short range interactions

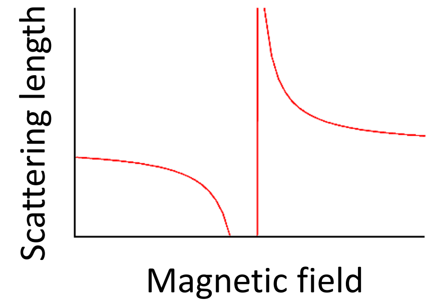
Efimov states are “Universal”.

- Ultracold atom
- Helium
- Nuclear
- ⋮

⇨ 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

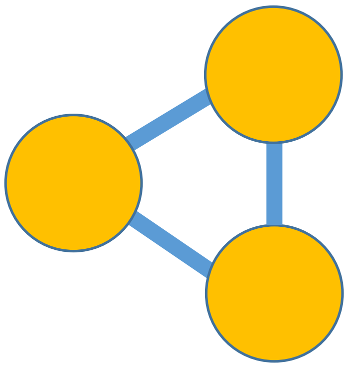
^{39}K - ^{39}K - ^{39}K

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

Fermions

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

in three spin states



Mixture of two species

Boson - Boson

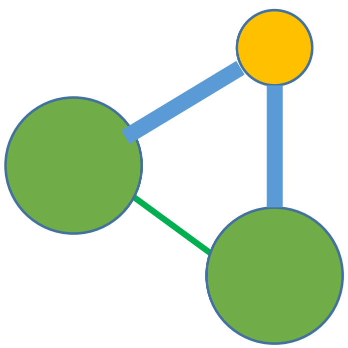
^{87}Rb - ^{87}Rb - ^{41}K

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

Boson - Fermion

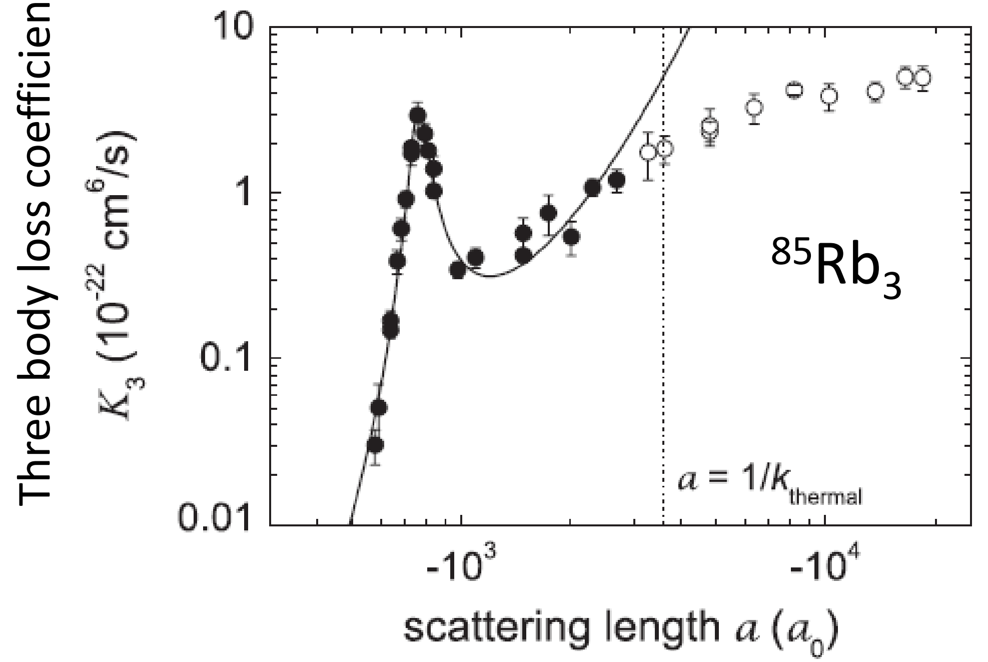
^{87}Rb - ^{87}Rb - ^{40}K

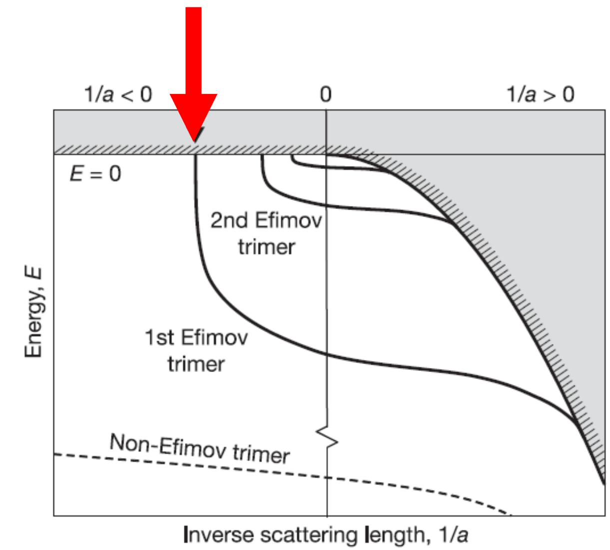
^{133}Cs - ^{133}Cs - ^{6}Li



Typical data of Efimov resonance

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



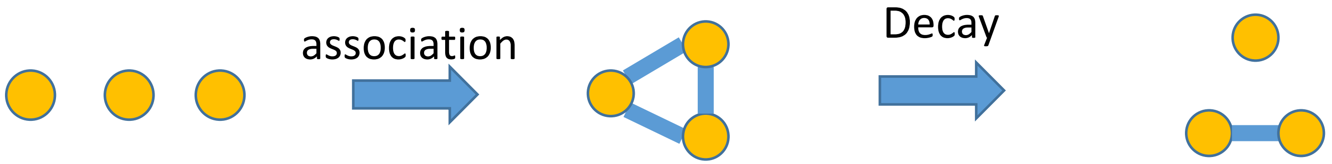


Efimov Trimer

Deeply bound dimer (not FB molecule)

association

Decay



Atomic loss is enhanced

Lifetime ~100us

Direct observation is difficult.

Almost all experiments are observations of atomic loss.

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Summary & outlook

Our plan: ionization detection of Efimov state

Direct observation of Efimov trimer using ionization detection

- Fast ionization pulse: 5ns << lifetime of trimer(~100us)
- High sensitivity : >50% (MCP)
- Mass spectroscopy by TOF

Atom, dimer, and trimer can be clearly distinguished.

⇨ Direct observation of Efimov trimer

⇩

Further study about decay process

Production of polyatomic cluster

Stable polyatomic molecule

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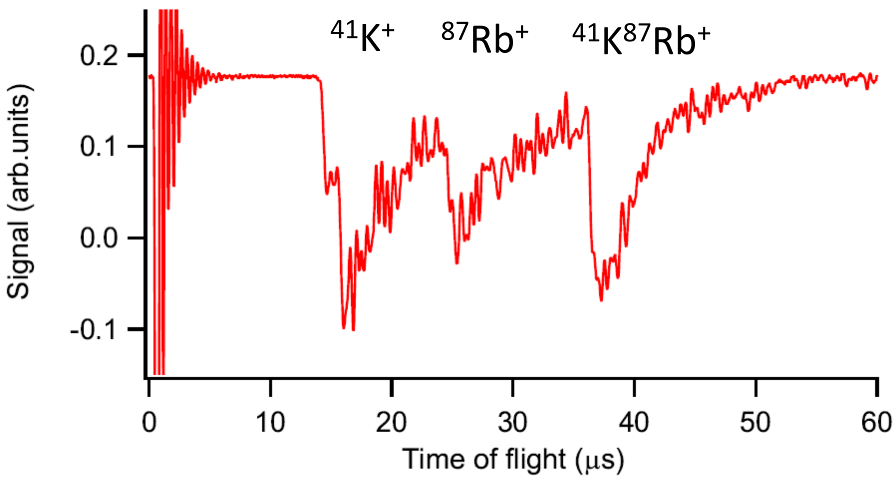
Typical ion signal (K, Rb, KRb)

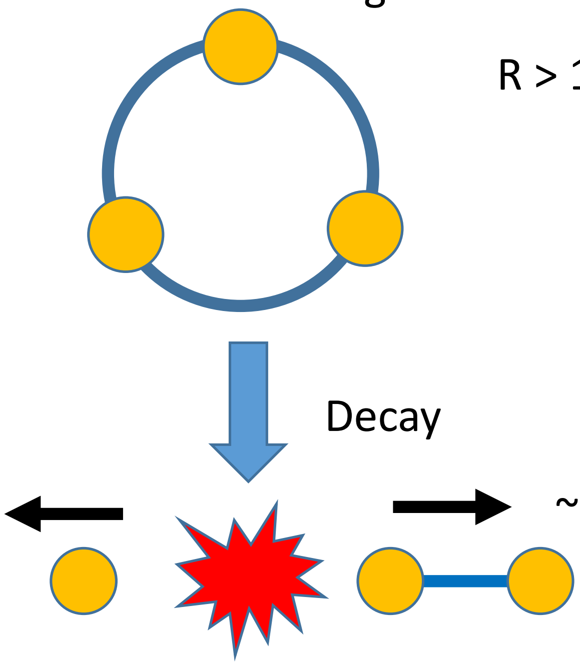


Decay process of Efimov trimer

Efimov state

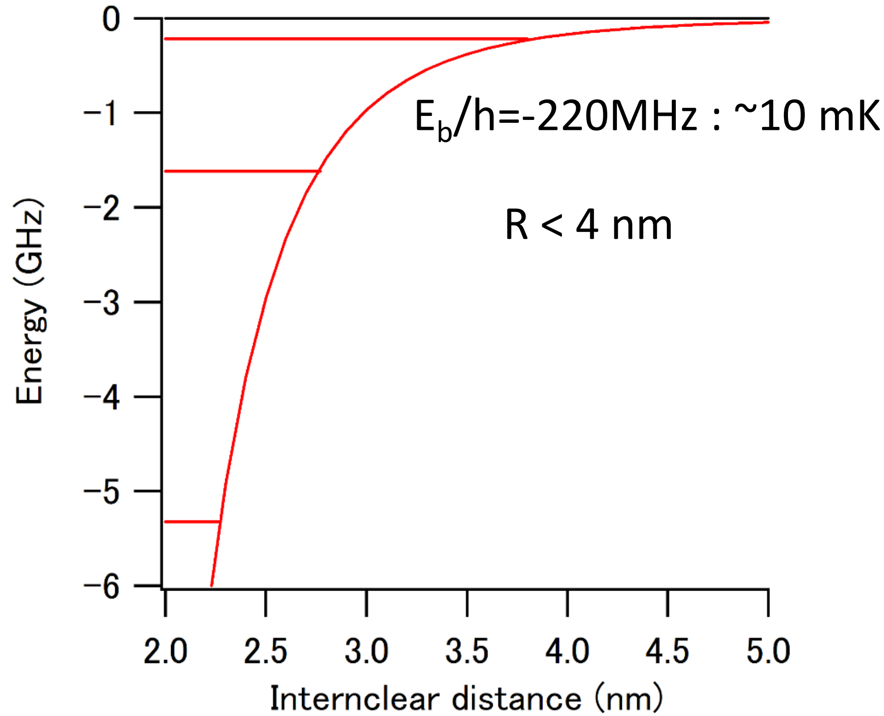
Large internuclear distance

R > 10 nm



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

Detection of the product molecule

Atoms 4×10^4, $10^{13}cm^{-3}$

↓ 1ms

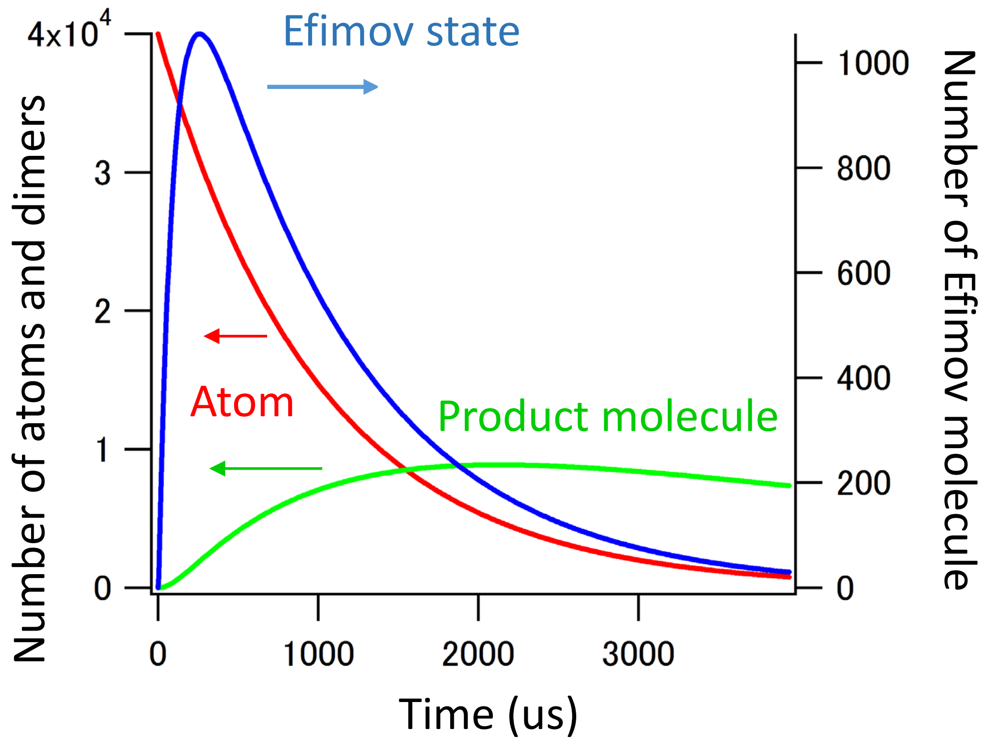
Efimov state

↓ 100us

Product molecule

↓ 5ms

out of detection region



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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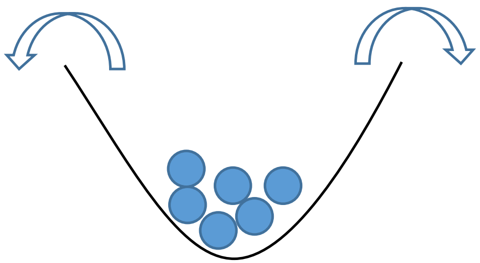
Summary & outlook

Our plan for Efimov experiment

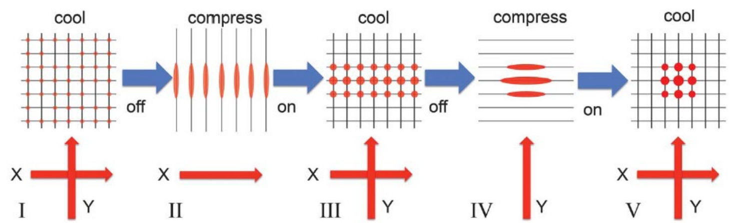
Evaporative cooling

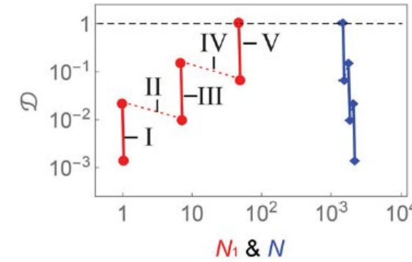
Slow ：~10 s
Large loss ：~99%



Laser cooling + Compression in lattice

Fast : ~300 ms
Small loss ~30％



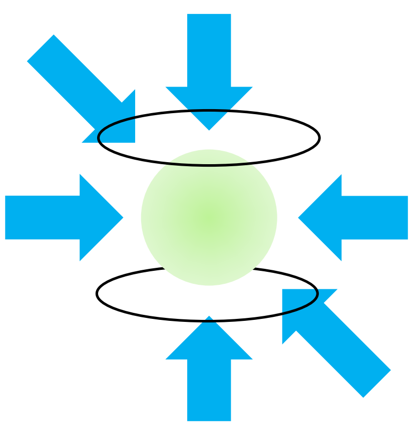


$N{\sim}10^3$

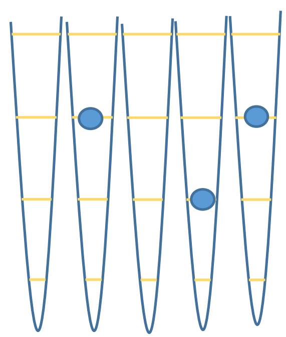
[J. Hu et al., Science 358 1078-1080 (2017)]

Our Plan

MOT

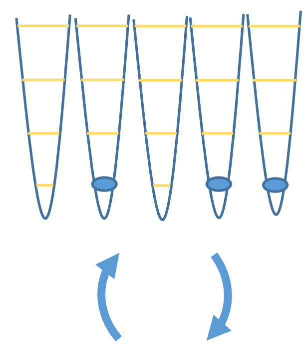


Large and deep lattice



Large number of atoms

Laser cooling in lattice



Compression by controlling lattice depth

$T{\sim}T_{BEC}$

BEC

Feshbach resonance

Efimov

Detection

Optical lattice enhanced by high-finesse cavity

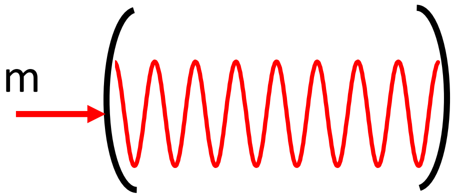
High finesse optical cavity in vacuum chamber

Finesse：~7x10^4

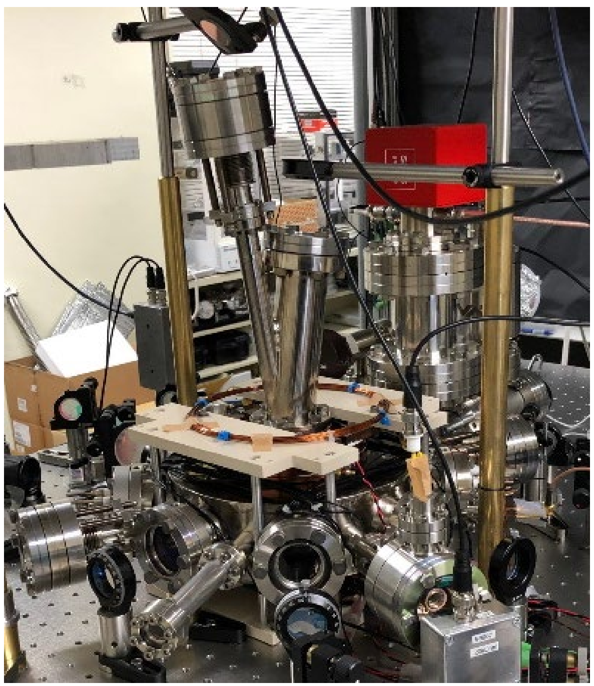
Enhancement：~2x10^4

In cavity
P ~200W

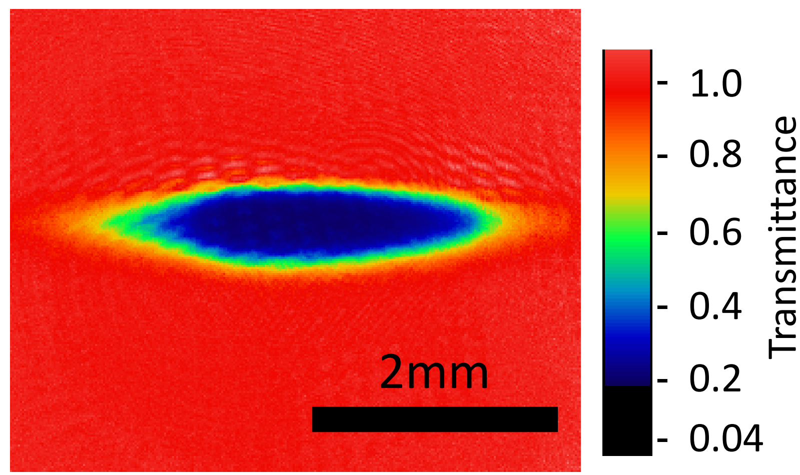
Wavelength λ=1038nm
Input P ~10mW



Diameter~1mm, Depth U~300uK



Absorption imaging



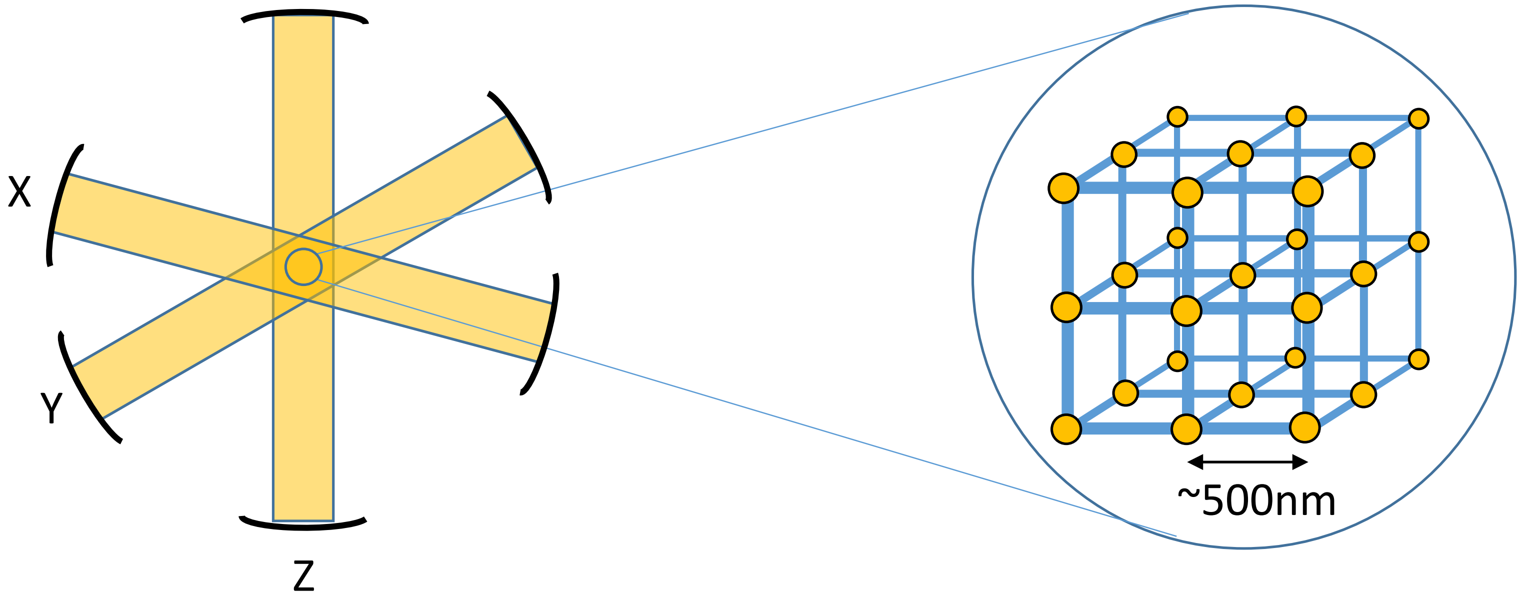
Rb

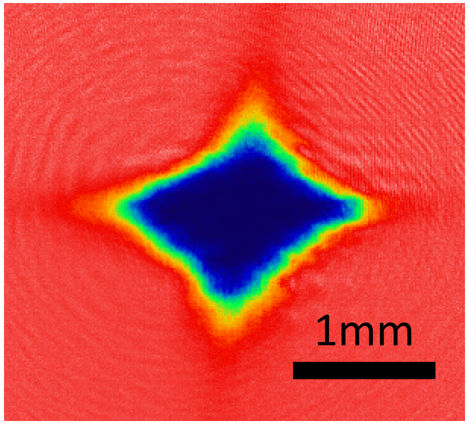
N = 2 x 10^7

T ~60 μK

Lifetime ~3s

Cavity-enhanced 3D optical lattice



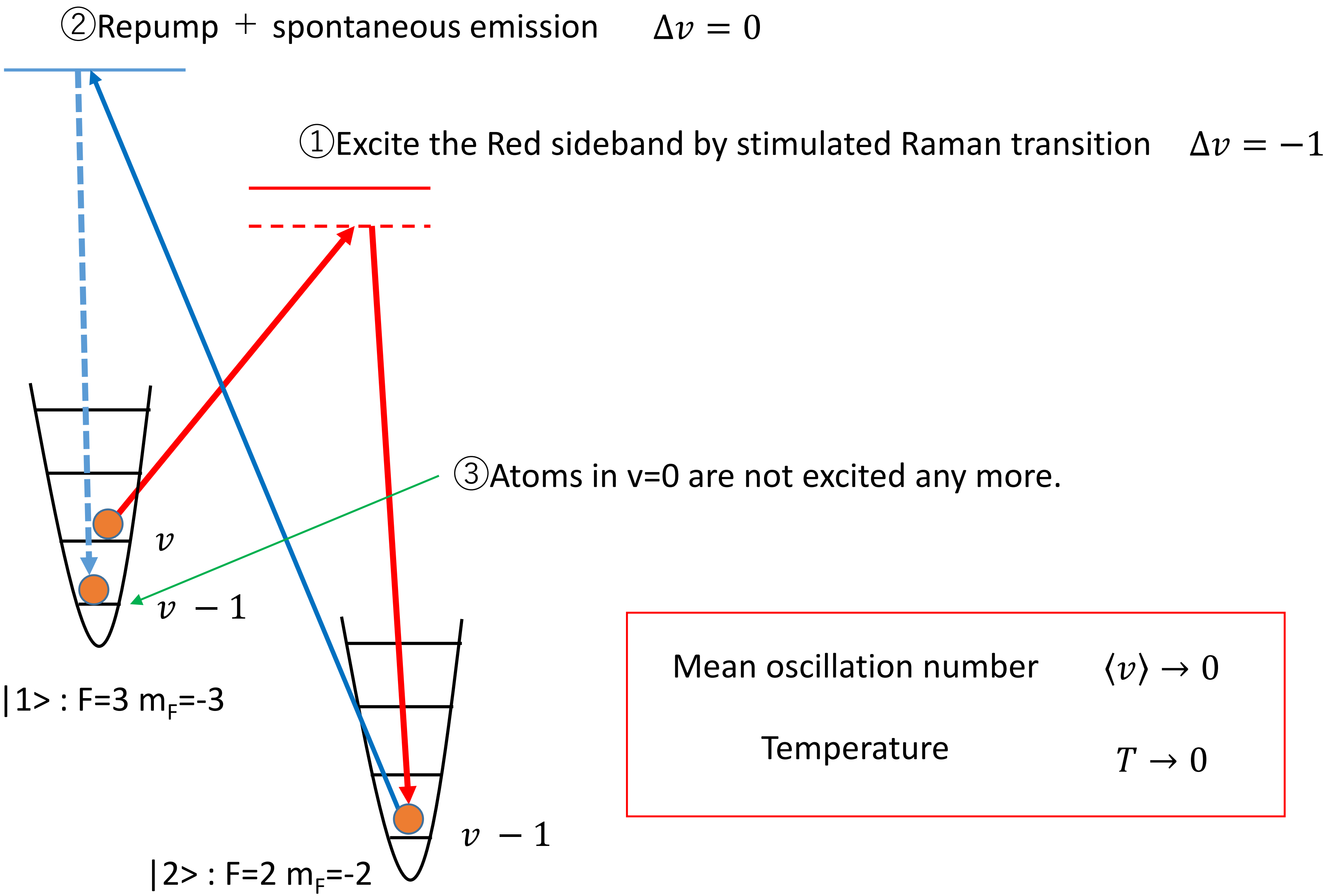


Loading into 3D cavity-enhanced lattice

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

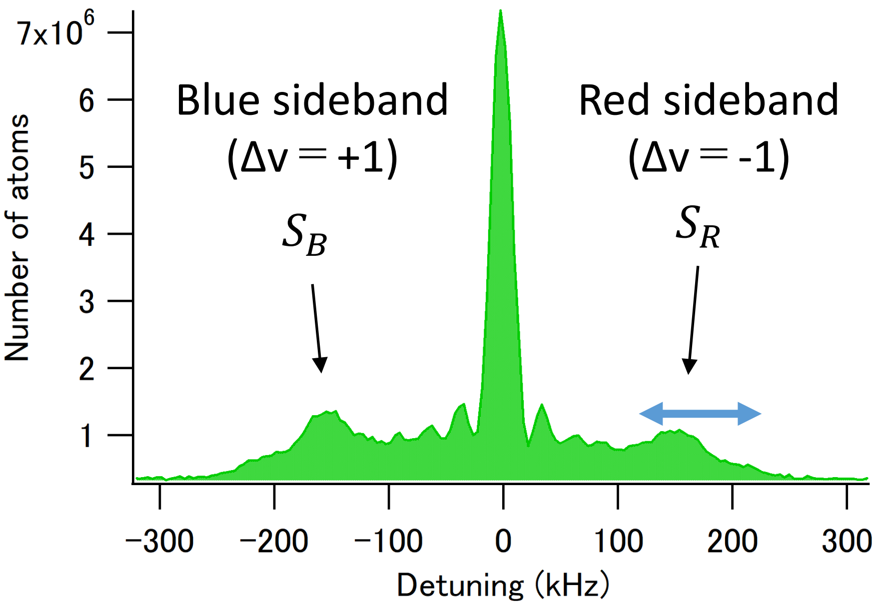
→ Laser cooling & compression

Raman sideband cooling

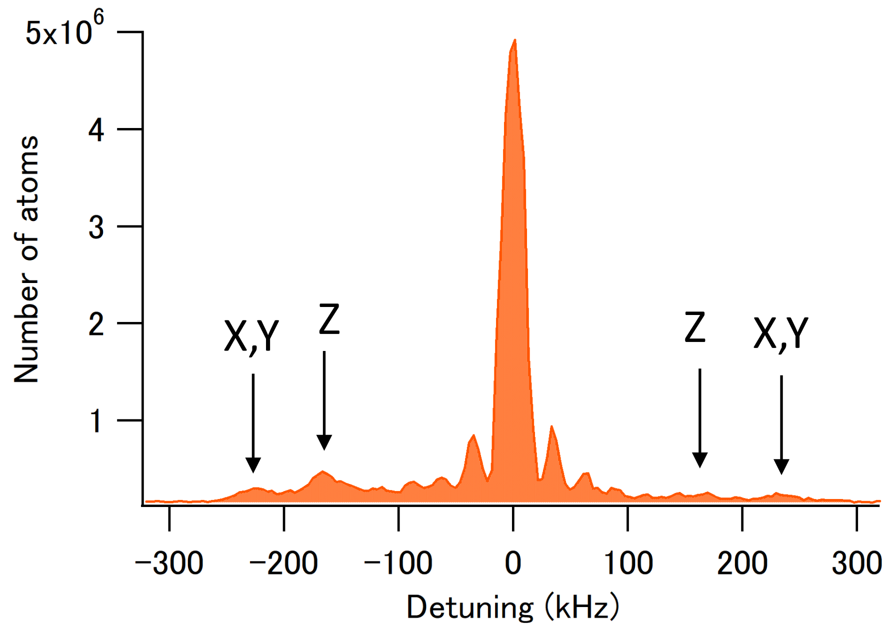


Raman sideband cooling

Before cooling



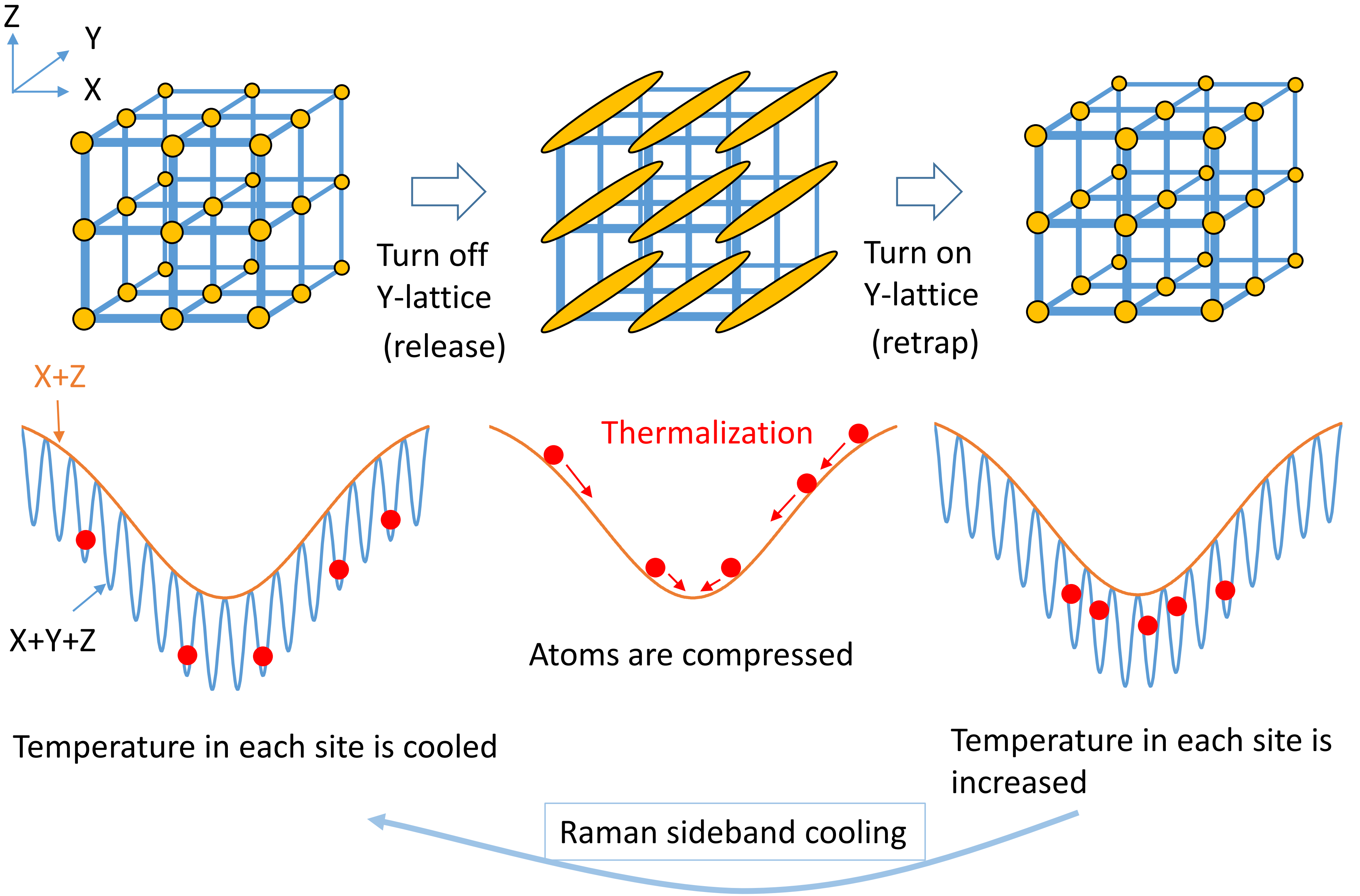
After cooling



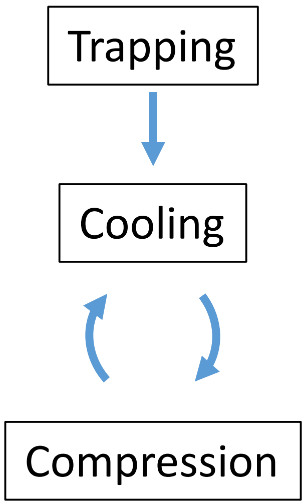
	Before cooling	After cooling (Z)	After cooling (X,Y)
Area ratio	$R \equiv \frac{S_R}{S_B} = 0.85$	$R_Z = 0.22$	$R_{X,Y} = 0.45$
Mean oscillation quantum number	$\langle v \rangle = \frac{R}{1-R} = 5.6$	$\langle v_Z \rangle = 0.23$	$\langle v_{X,Y} \rangle = 0.8$
Temperature	T=46 uK	T_Z = 5 uK	$T_{X,Y}$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

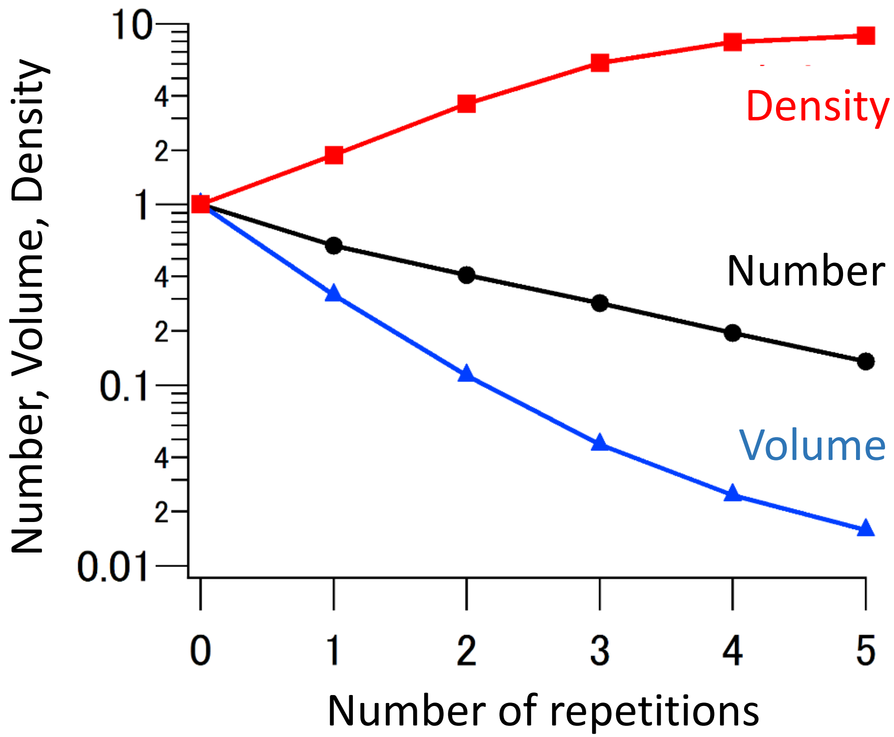
Succeeded in laser cooling in optical lattice

Compression



Raman sideband cooling + Compression

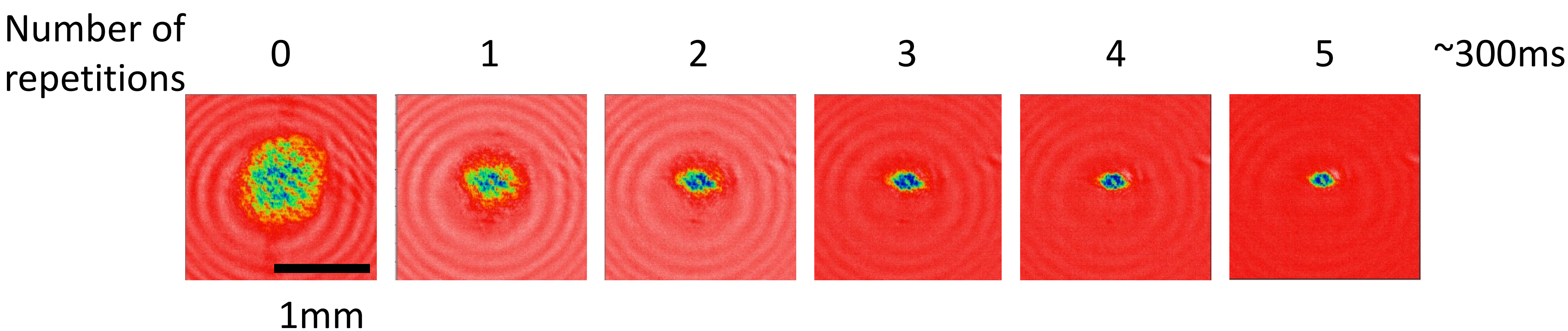




Density is increased

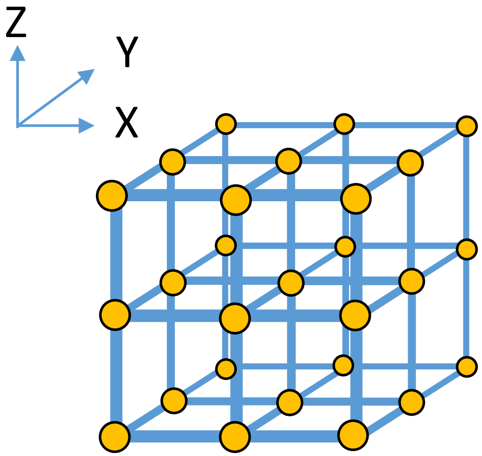
Atomic loss is still large

Volume and temperature($\propto V^{2/3}$) are decreased

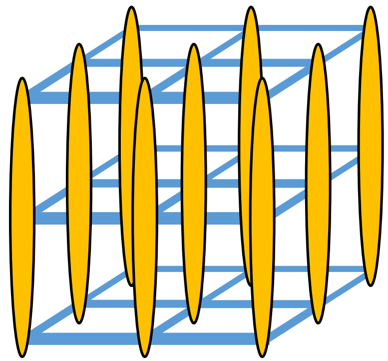


Succeeded in cooling and compression in optical lattice

1D system



Turn off
Z-lattice



Trapping frequency

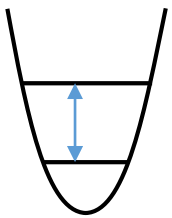
$\nu_{x,y} = 240$ kHz

$\nu_z = 144$ Hz

Strong anisotropy (1 : 1700)

In low temperature,

$$T \ll \frac{\hbar\omega_{x,y}}{k_B} = T^{*} \sim 12\ \mu K$$

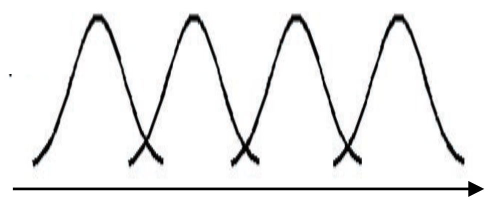


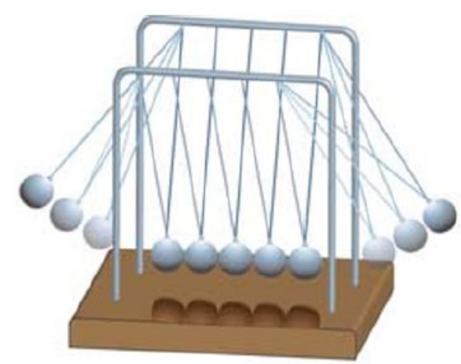
Motions in x and y directions are frozen.
Motion in z direction is allowed.

Specific properties to 1D system

- No thermalization
- Fermionization of bosonic gas
- Suppression of 3-body collisions
- ⋮

Small overlapping
of wavefunctions

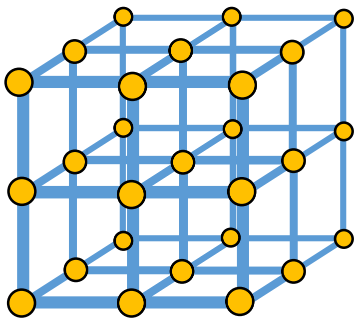


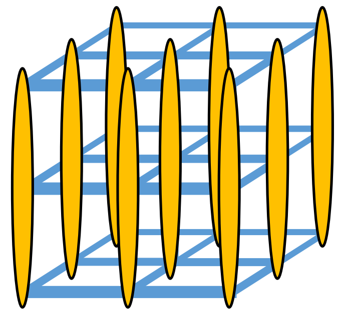


Newton's cradle

[Nature 440 900 (2006)]

1D system

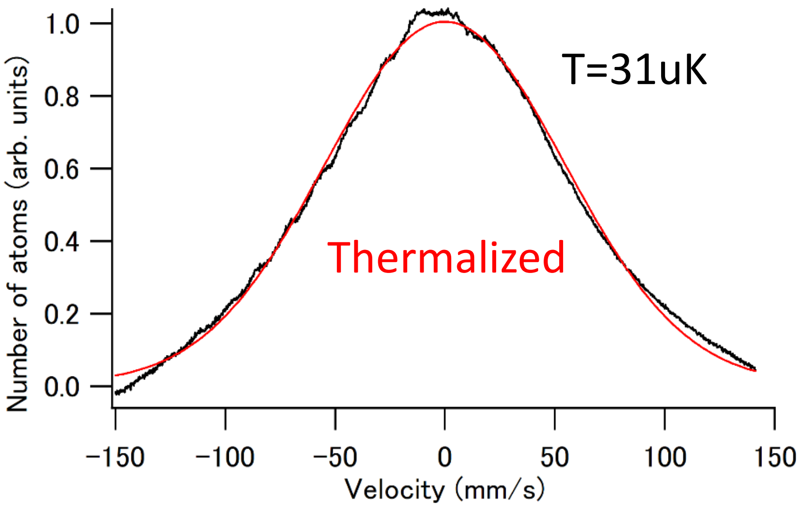




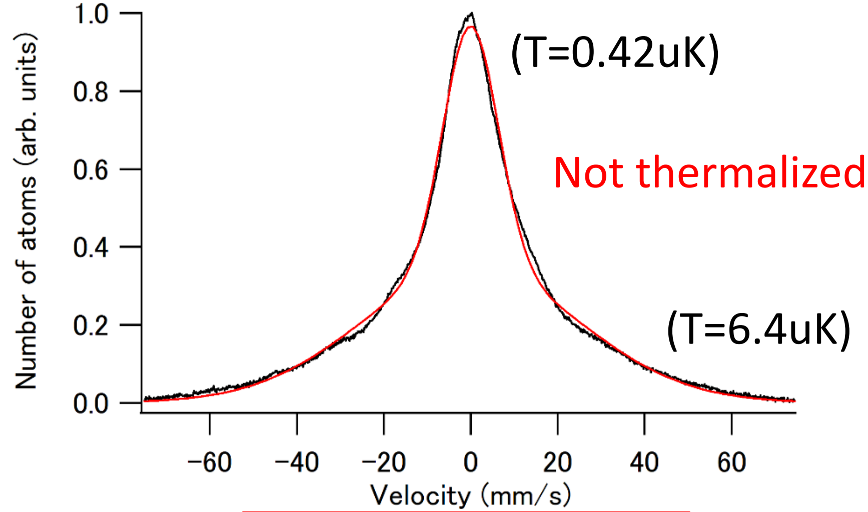
Hold in 20ms

Velocity measurement

Before cooling $T > 12\ \mu K$



After cooling $T < 12\ \mu K$

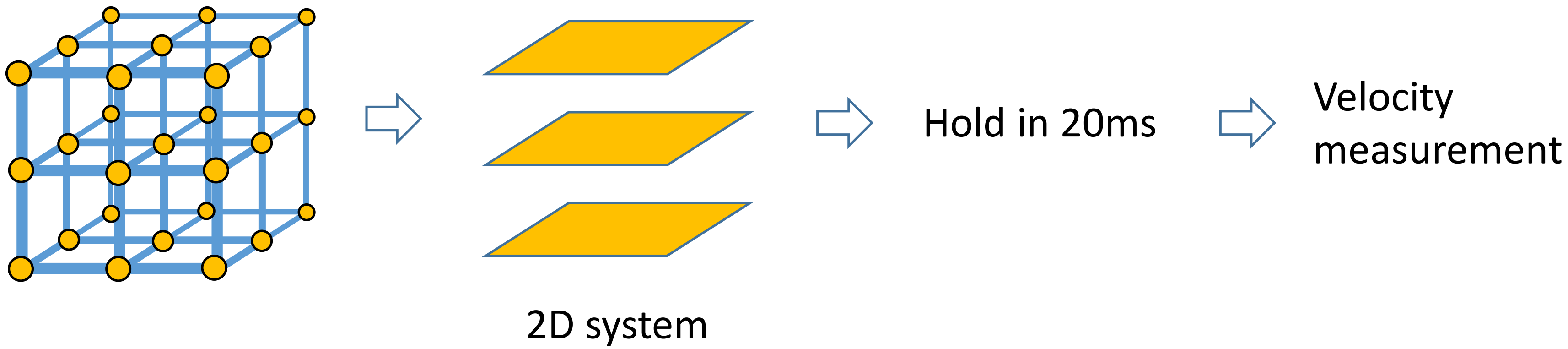


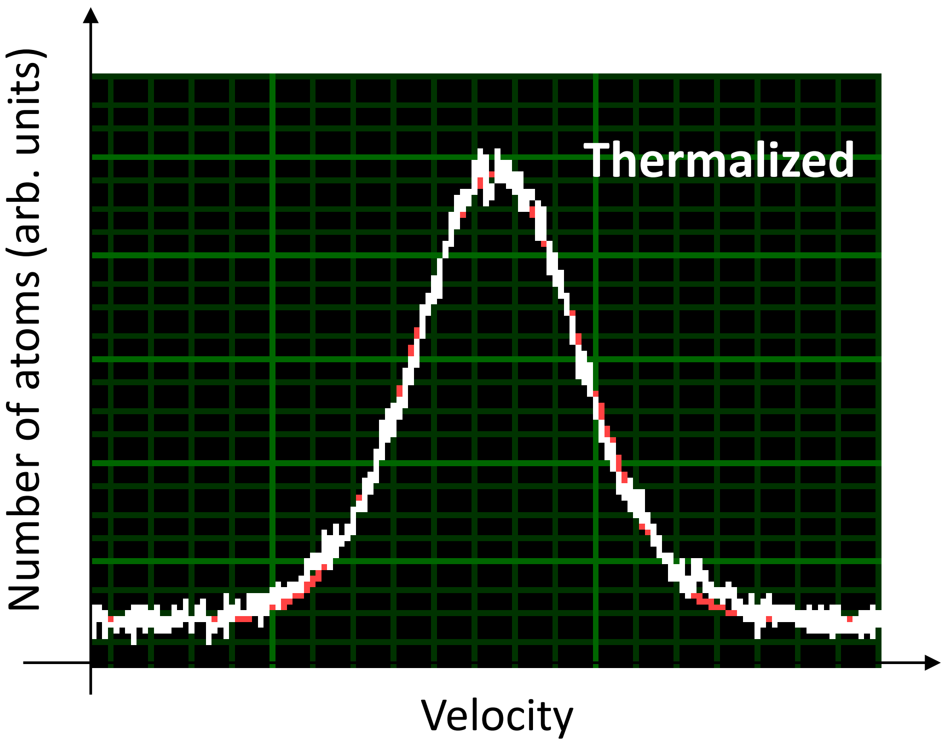
1D system is realized

In 1D system, 3-body collision is strongly suppressed

→ Can be used as a trigger of Efimov state production

2D system





Temperature in X,Y directions

$T_{X,Y}$~ 550 nK

Critical temperature of BEC transition

Tc ~ a few 100 nK

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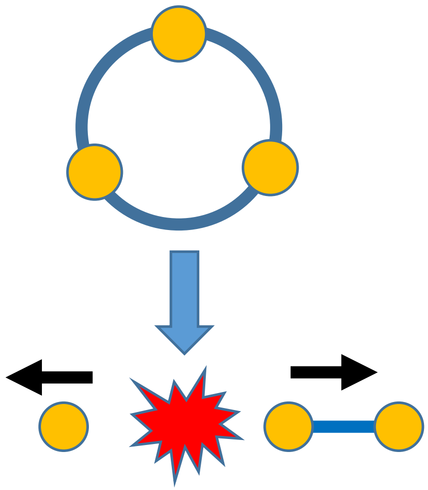
Summary and outlook

Summary Researches on Efimov states using ultracold atoms.



Our plan

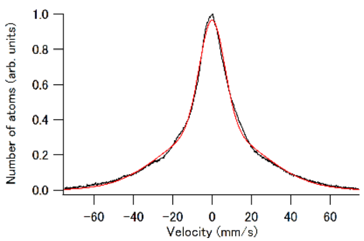
Direct detection of the Efimov state using ionization detection.

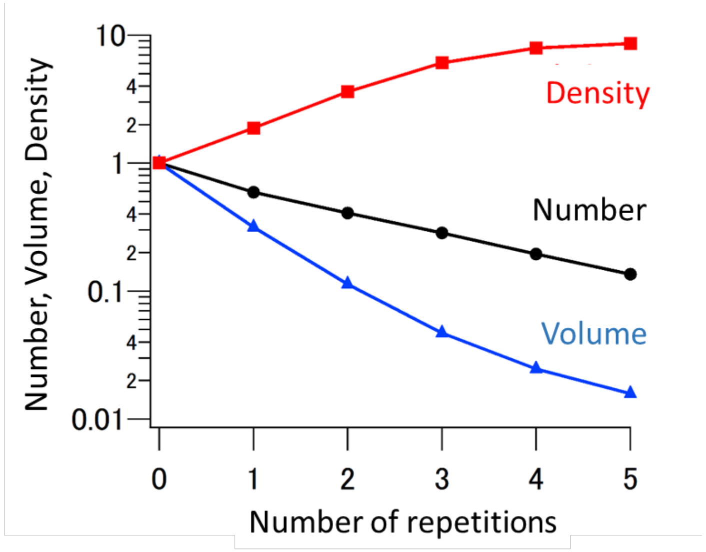
↓

Study about the decay process by detecting product molecule.

Experiment

- ✓ Atom trapping in 3D cavity-enhanced optical lattice
- ✓ Raman sideband cooling and compression
- ✓ 1D system





Outlook

Improve cooling

Detection of Efimov states by ionization