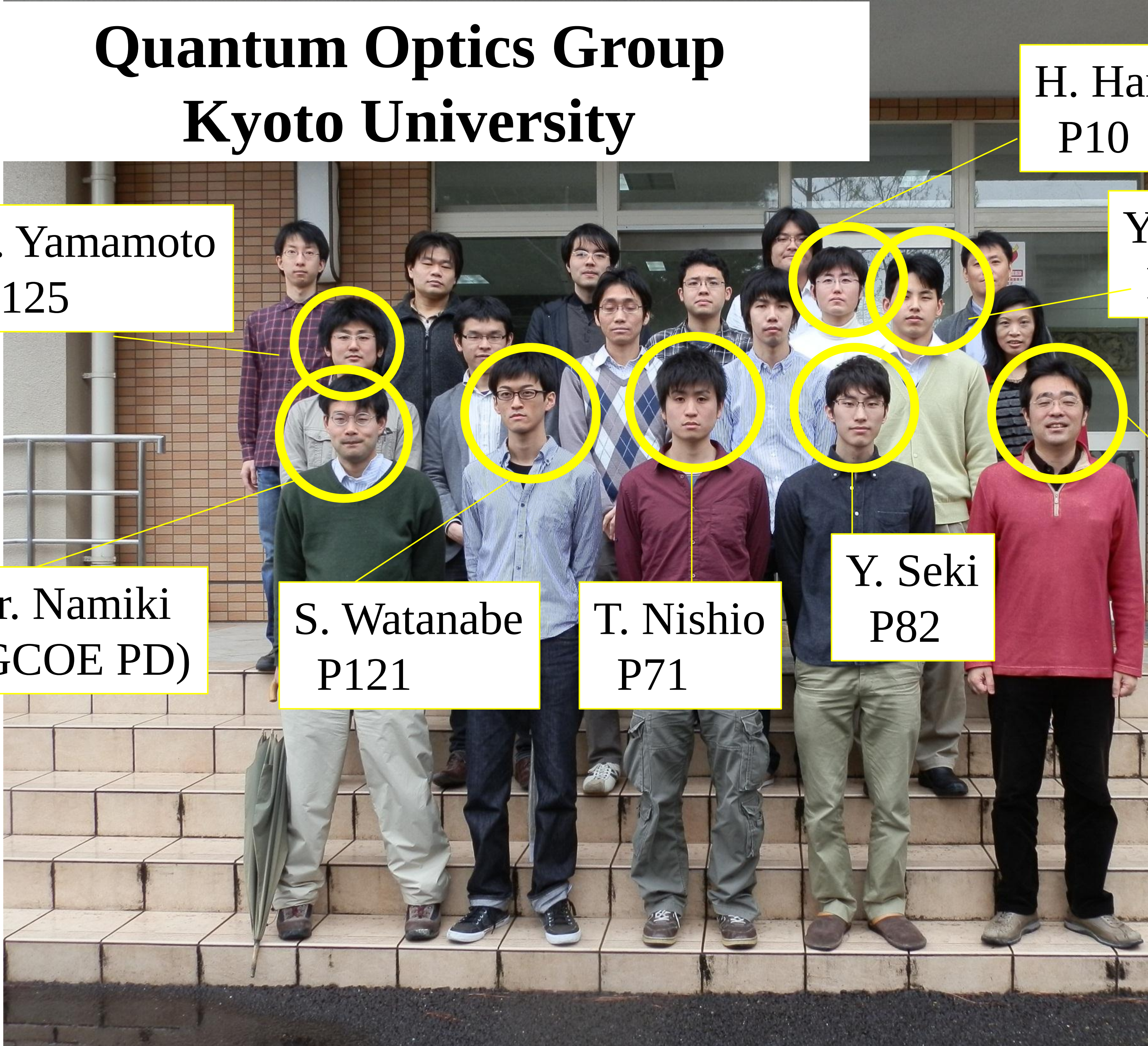
GCOE Symposium
Development of emergent new fields

February 14 2013

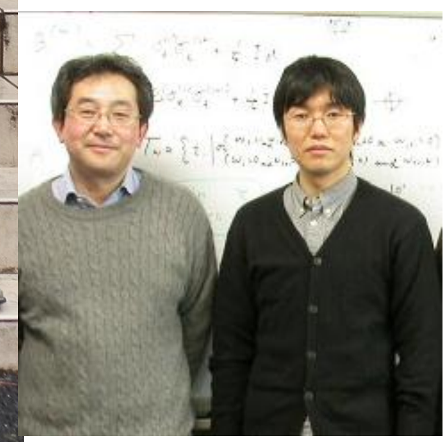
Ultracold atoms in an optical lattice -an ideal simulator of strongly-correlated quantum many-body system-

Kyoto University Y. Takahashi

Quantum Optics Group
Kyoto University



NTT:
K. Inaba
M. Yamashita



Research Objectives of Our Group in GCOE program

Application of atoms to investigating

1) quantum information (science)

and

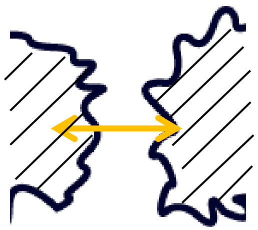
2) (aspects of) fundamental physics

(integrating optical and atomic experiments with elementary particle theories)

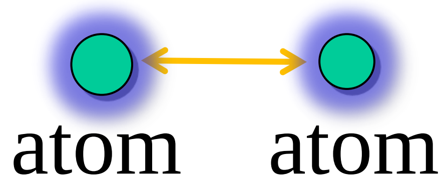
We have initiated a new research project :

“Test of Gravity at Nano-meter Scale by using Bose-Einstein Condensate”

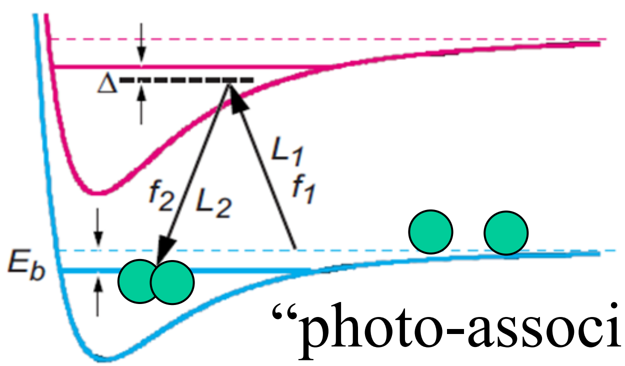
from the discussion with prof. Ando (special AP of GCOE)



Inhomogeneity
Reproducibility
Controllability

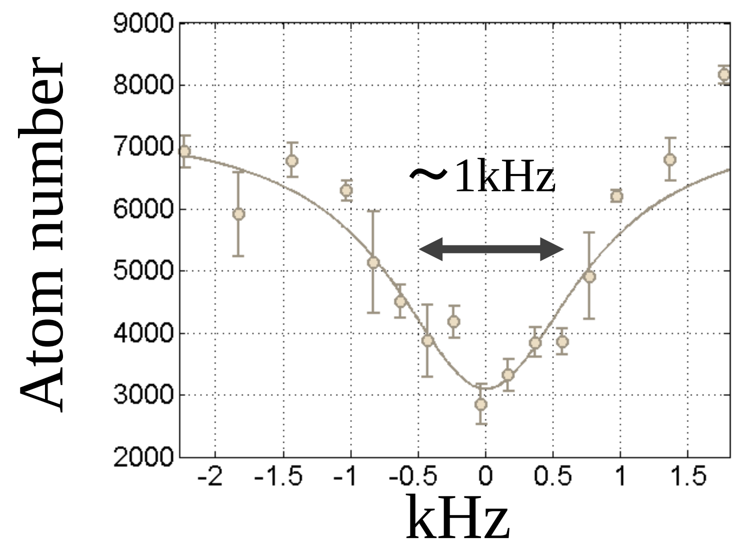


Precise measurement of binding energies of “molecule” to detect possible effect of gravity



“photo-association”

Current status:



“Revealed Insufficiency of simple mass-independent Potential”

Research Objectives of Our Group in GCOE program

Application of atoms to investigating

1) quantum information (science)

and

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(integrating optical and atomic experiments with elementary particle theories)

Quantum Simulation of Hubbard Model

Outline

Quantum Simulation of Strongly-Correlated System

dual Mott insulator of Boson and Fermion
SU(6) Mott insulator
high-resolution spectroscopy of SF-Mott insulator transition

Resonant Control of Interaction:

anisotropy-induced Feshbach resonance between $^1S_0$ and $^3P_2$ states

Prospects:

Lieb lattice
Quantum Gas Microscope
YbLi
Spin-Orbit Interaction

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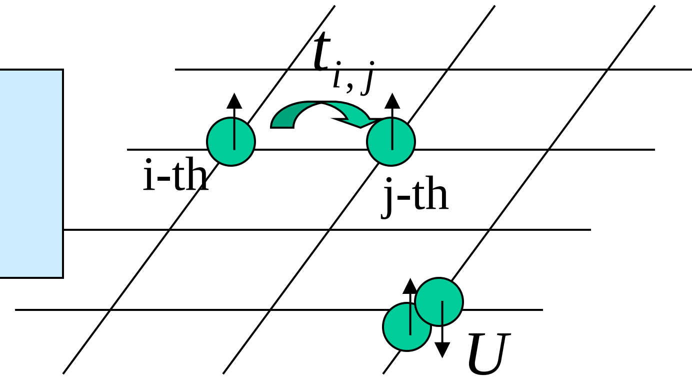
Quantum Simulation

"Interesting"

Many-body Quantum System

Hubbard Model:

$$H = -t \sum_{<i,j>} c_i^+ c_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

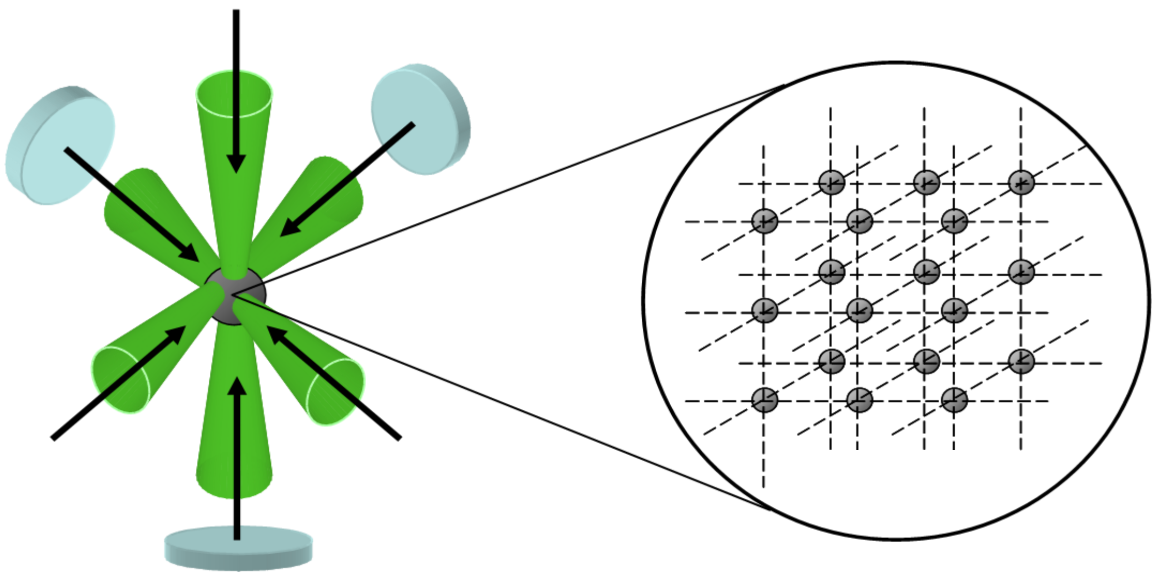


→ **Magnetism, Superconductivity**

Quantum Simulation
Using ultracold atoms in an Optical Lattice

$$H = -J \sum_{<i,j>} a_i^{+} a_j + \frac{U}{2} \sum_i n_i (n_i - 1) + \sum_i \varepsilon_i n_i$$

⟶ *clean system, high controllability, various geometry, etc*

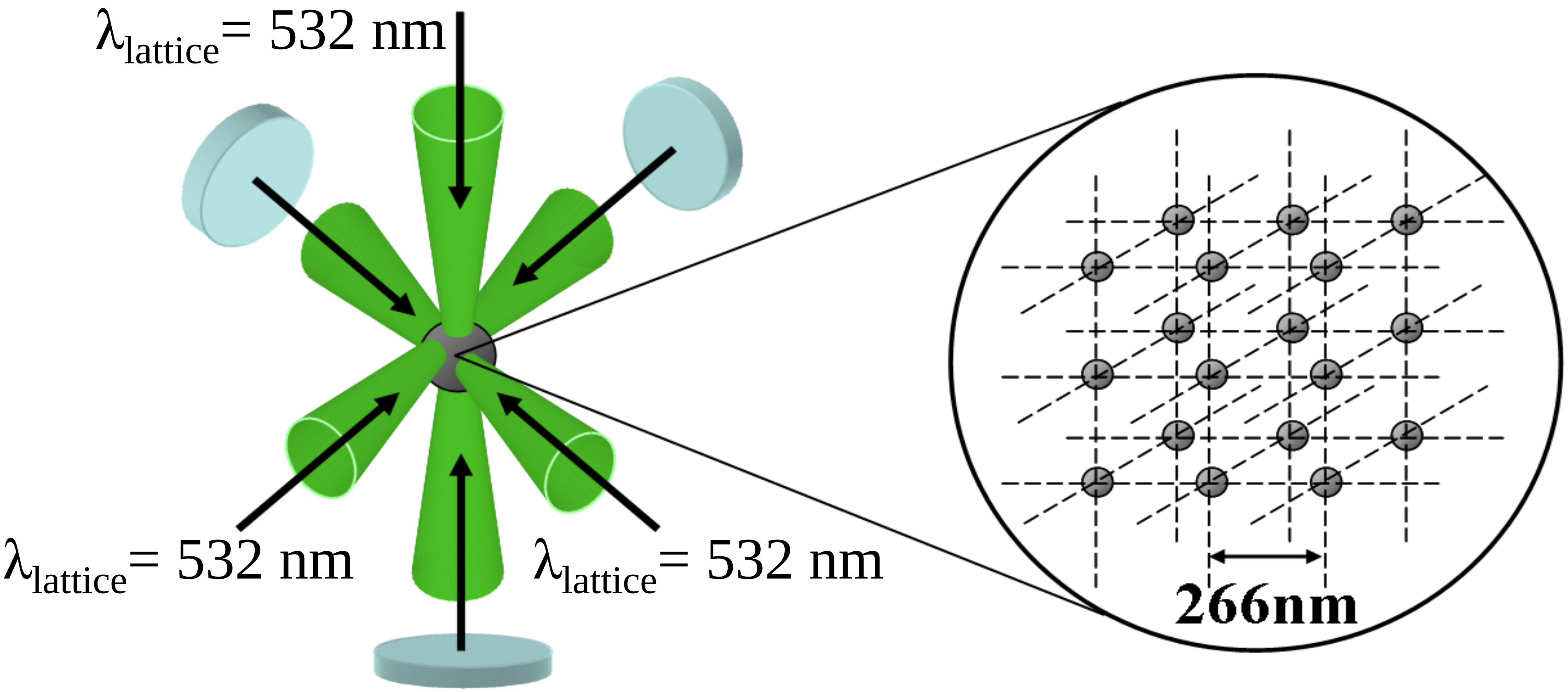


"Optical lattice"
= periodic potential for atoms generated by standing wave of laser light

In fact, there are many QS experiments using Alkali-atoms

Quantum Simulation
Using Ytterbium atoms in an Optical Lattice

$$H = -J\sum_{<i,j>} a_i^{+} a_j + \frac{U}{2}\sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i$$



Unique Features of Ytterbium Atoms

Rich Variety of Isotopes

^{168}Yb (0.13%)	^{170}Yb (3.05%)	^{171}Yb (14.3%)	^{172}Yb (21.9%)	^{173}Yb (16.2%)	^{174}Yb (31.8%)	^{176}Yb (12.7%)
Boson	**Boson**	**Fermion**	**Boson**	**Fermion**	**Boson**	**Boson**

- Attractive Interaction:

  a_{BF} = - 4.3 nm

  a_{BB} = +3.4 nm

  a_{FF} = +10.6 nm

- Repulsive Interaction:

  a_{BF} = +7.3 nm

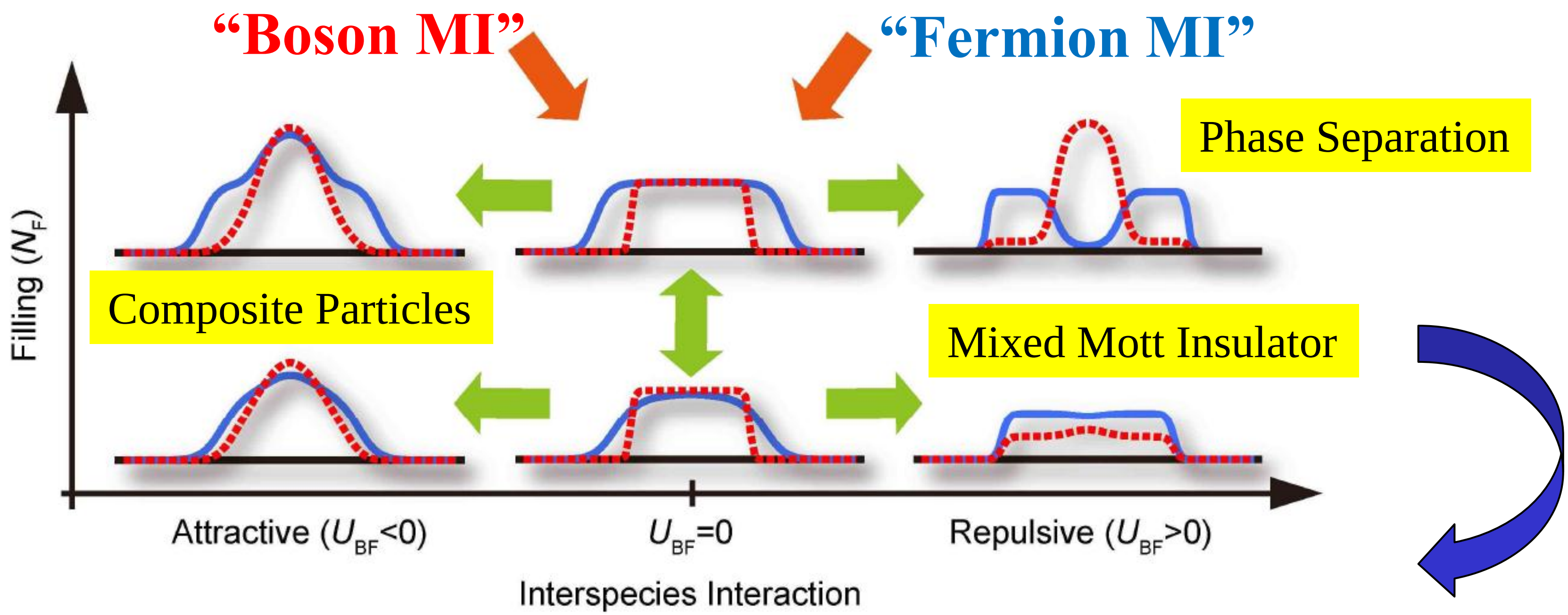
  a_{BB} = +5.6 nm

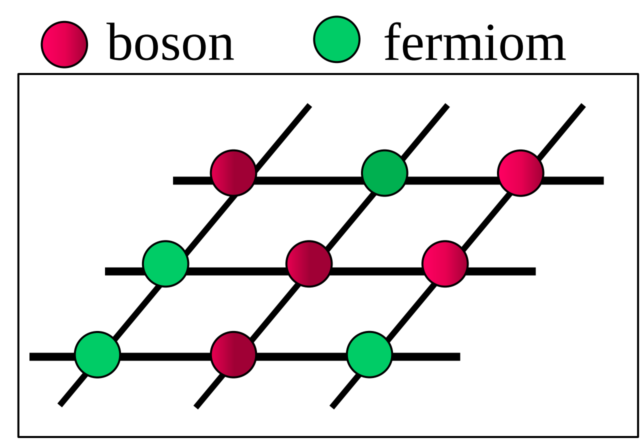
  a_{FF} = +10.6 nm

By loading the BF mixtures into 3D optical lattice, we successfully create

"Strongly Interacting Dual Mott Insulators"

[S. Sugawa, K. Inaba, *et al.*, *Nature Physics*. **7,** 642–648 (2011)]





__trigger theoretical studies__

- arXiv:1205.4026v1 Ehud Altman, Eugene Demler, Achim Rosch
  "Mott criticality and pseudogap in Bose-Fermi mixtures"
- arXiv:1204.3988 Ippei Danshita and L. Mathey
  "Counterflow superfluid of polaron pairs in Bose-Fermi mixtures in optical lattices"

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Boson	**Boson**	**Fermion**	**Boson**	**Fermion**	**Boson**	**Boson**

^{173}Yb (I=5/2) +5/2 +3/2 +1/2 -1/2 -3/2 -5/2

"origin of spin degrees of freedom is "*nuclear spin*"

$$H_{\text{int}} = \frac{4\pi\hbar^2 a_s}{M}\delta(\vec{r}_1 - \vec{r}_2)$$ **SU(6) system**

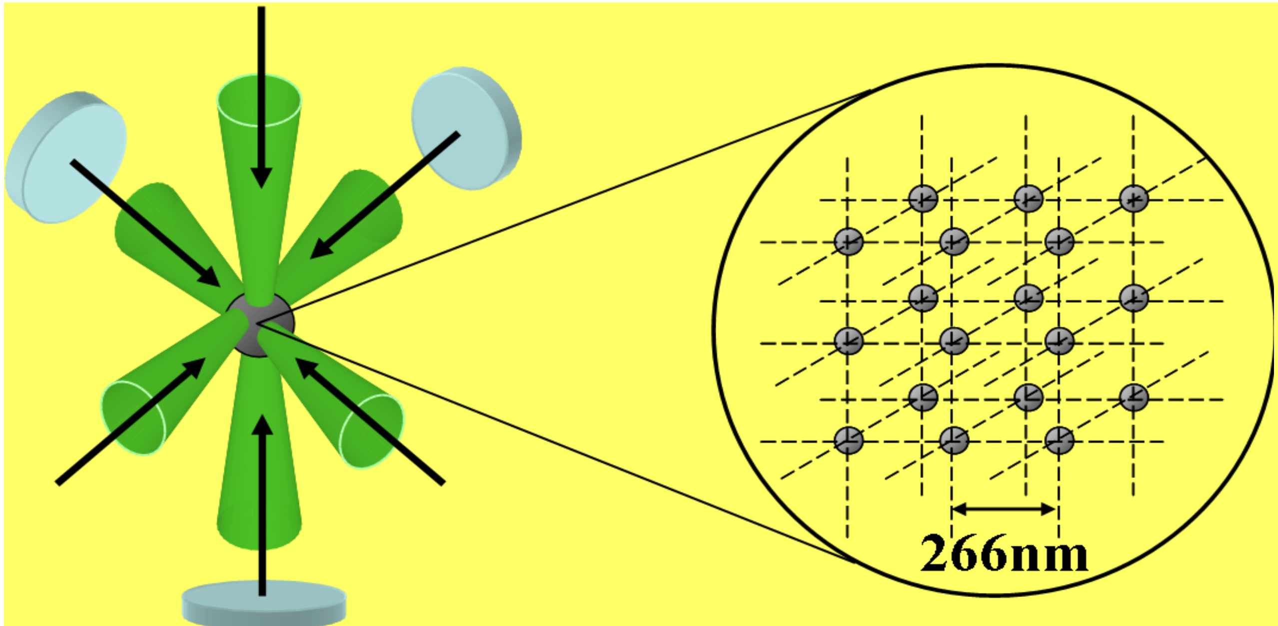
"Experimental realization is very difficult in solid state system"

SU(6) Fermion

The first quantum gas with SU(N>2) symmetry

^{173}Yb:SU(6)

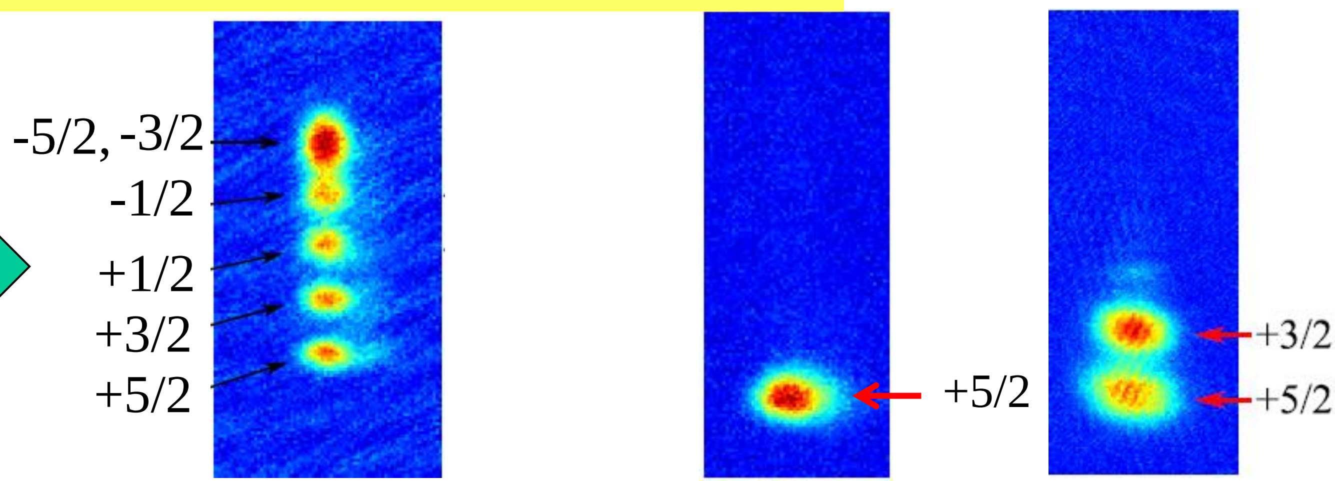
[T. Fukuhara *et al.*, PRL. **98**, 030401 (2007)]



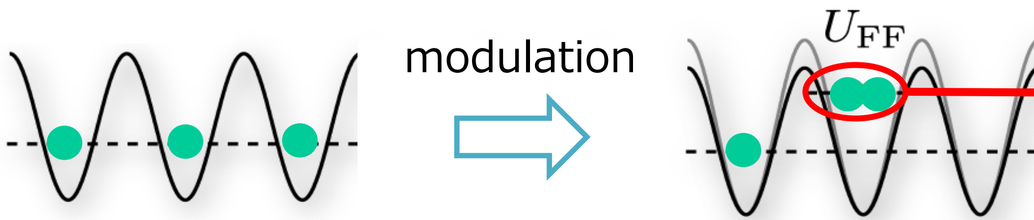
SU(6) Hubbard model

Optical Stern-Gerlach Spin-Separator for nuclear spin

[S. Taie *et al* ., PRL**105**, 190401(2010)]



Lattice Modulation Technique

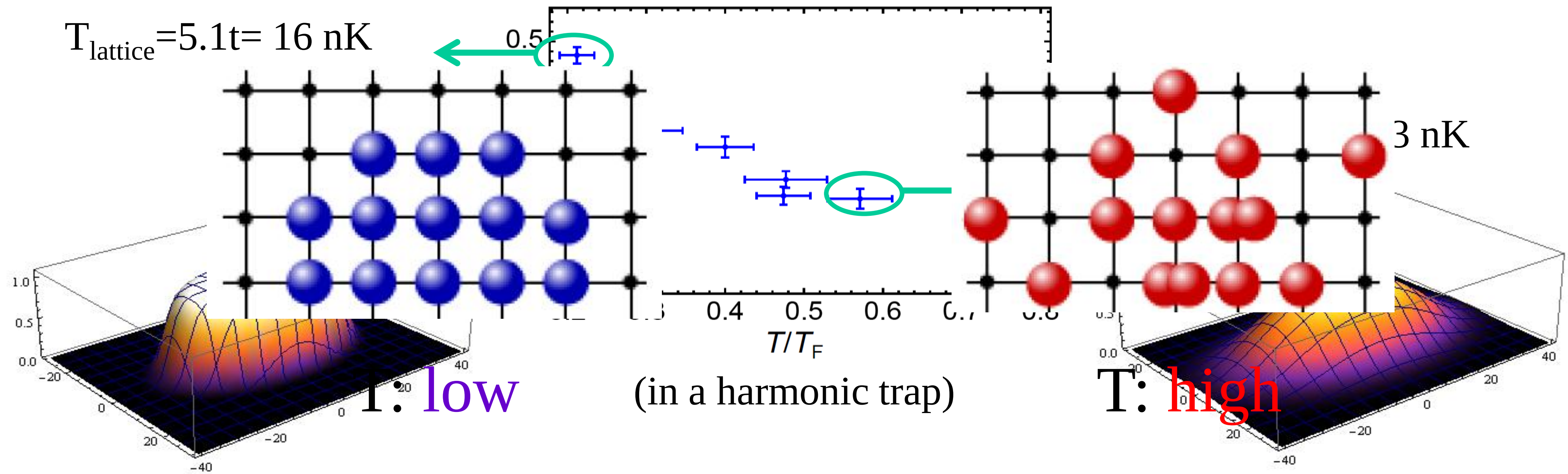


"doublon production rate Γ is a sensitive probe of $T_{lattice}$"

[D. Greif *et al* ., PRL**106**, 145302 (2011)]

N=1.9× 104, $11E_R$, 18%pp mod. U/t=62.4

$T_{lattice}$=5.1t= 16 nK



T: low

(in a harmonic trap)

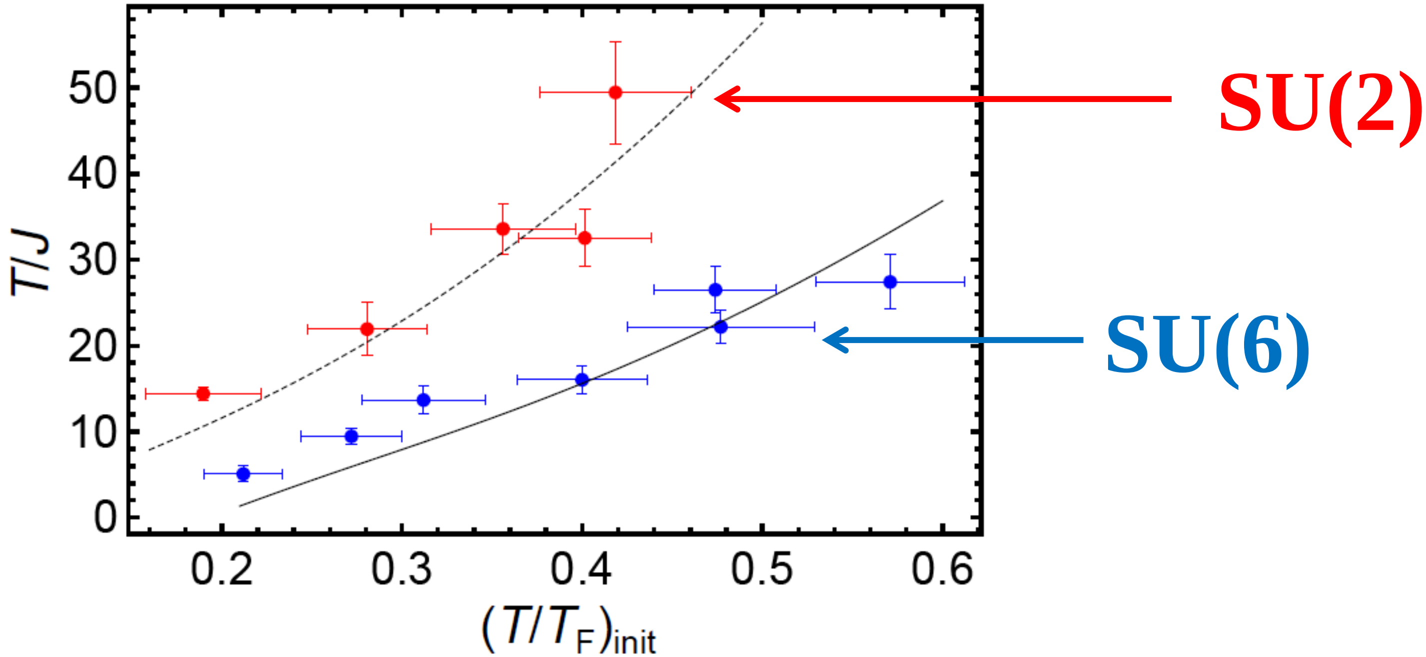
T: high

We could successfully create SU(6) Mott Insulator

*"**Lower** temperature is achieved with **larger** spin system"*

[S. Taie *et al*, *Nature Physics* **8**, 825(2012)]

SU(6) versus SU(2)



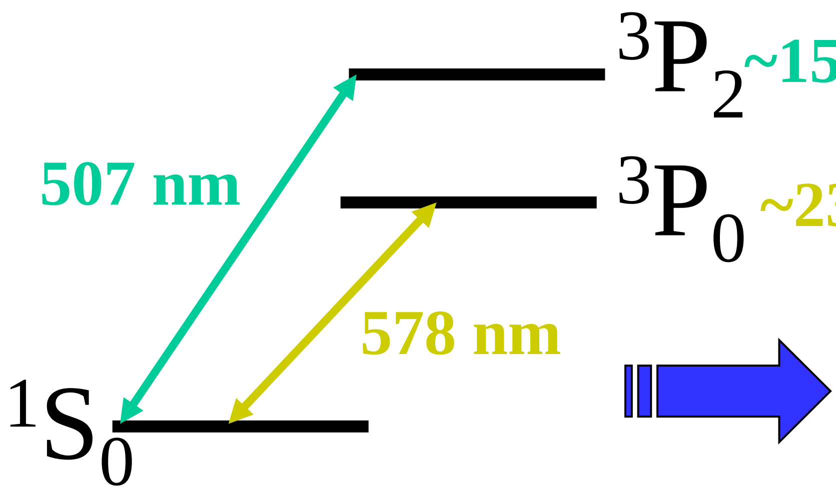
→ "Enhanced Pomeranchuk Cooling of an Atomic Gas"

"isolated spin carries large entropy of log(N)"

Theory (T > t): [M. A. Cazalilla, et al, N. J. Phys.**11**, 103033(2009)]
[K. R. A. Hazzard, et al, arXiv:1011.0032(2010)]

Unique Features of Ytterbium Atoms

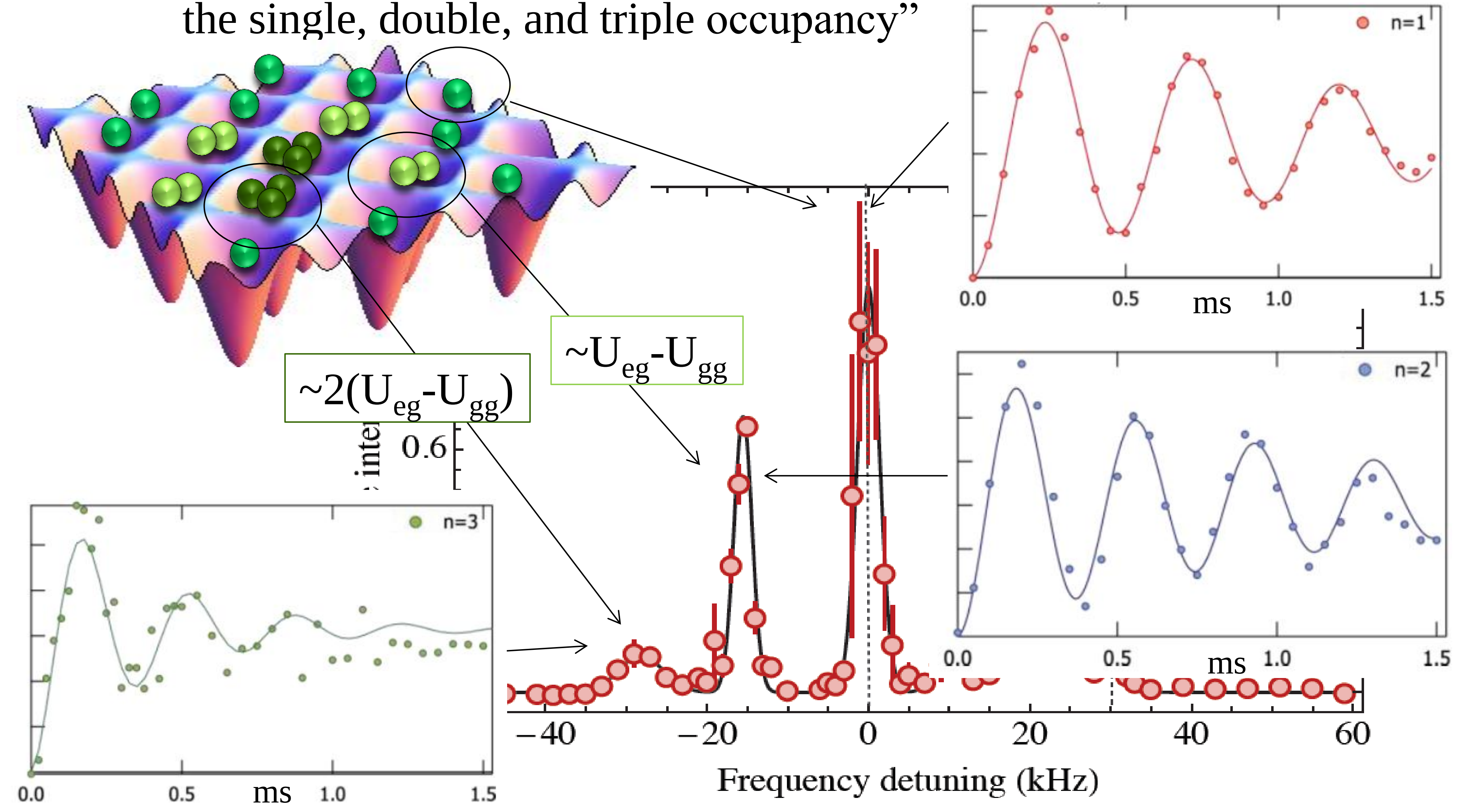
Long-lived metastable state
/Ultra-narrow Optical Transitions



High-resolution laser spectroscopy

Spectroscopy of Atoms in a Mott Insulating State

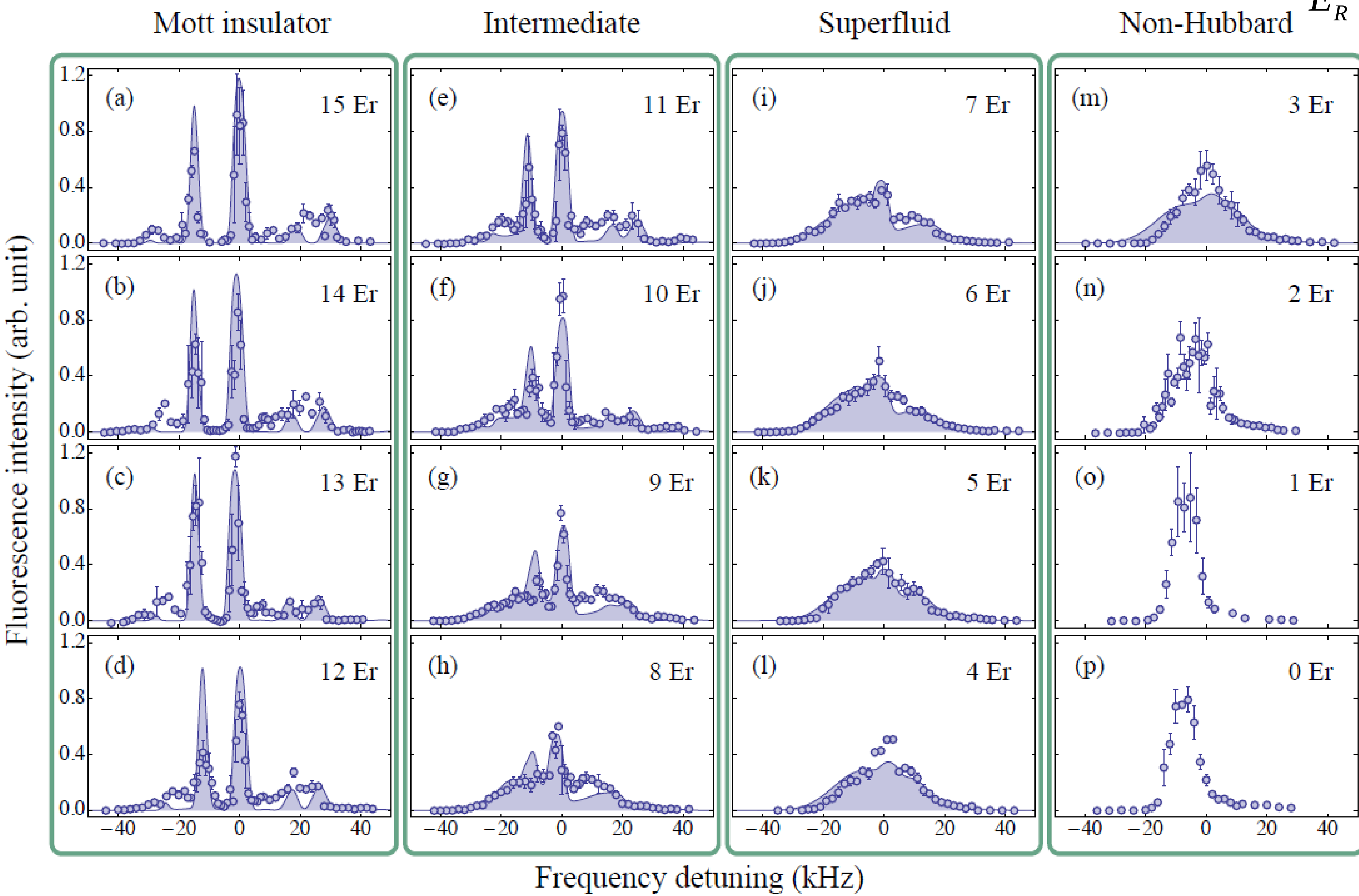
"We can spectroscopically resolve and independently control the single, double, and triple occupancy"



Spectroscopy of Superfluid-Mott Insulator Transition

Theory (NTT) and Experiment (Kyoto)

$$E_R = \frac{\hbar^2 k_L^{\ 2}}{2m}$$



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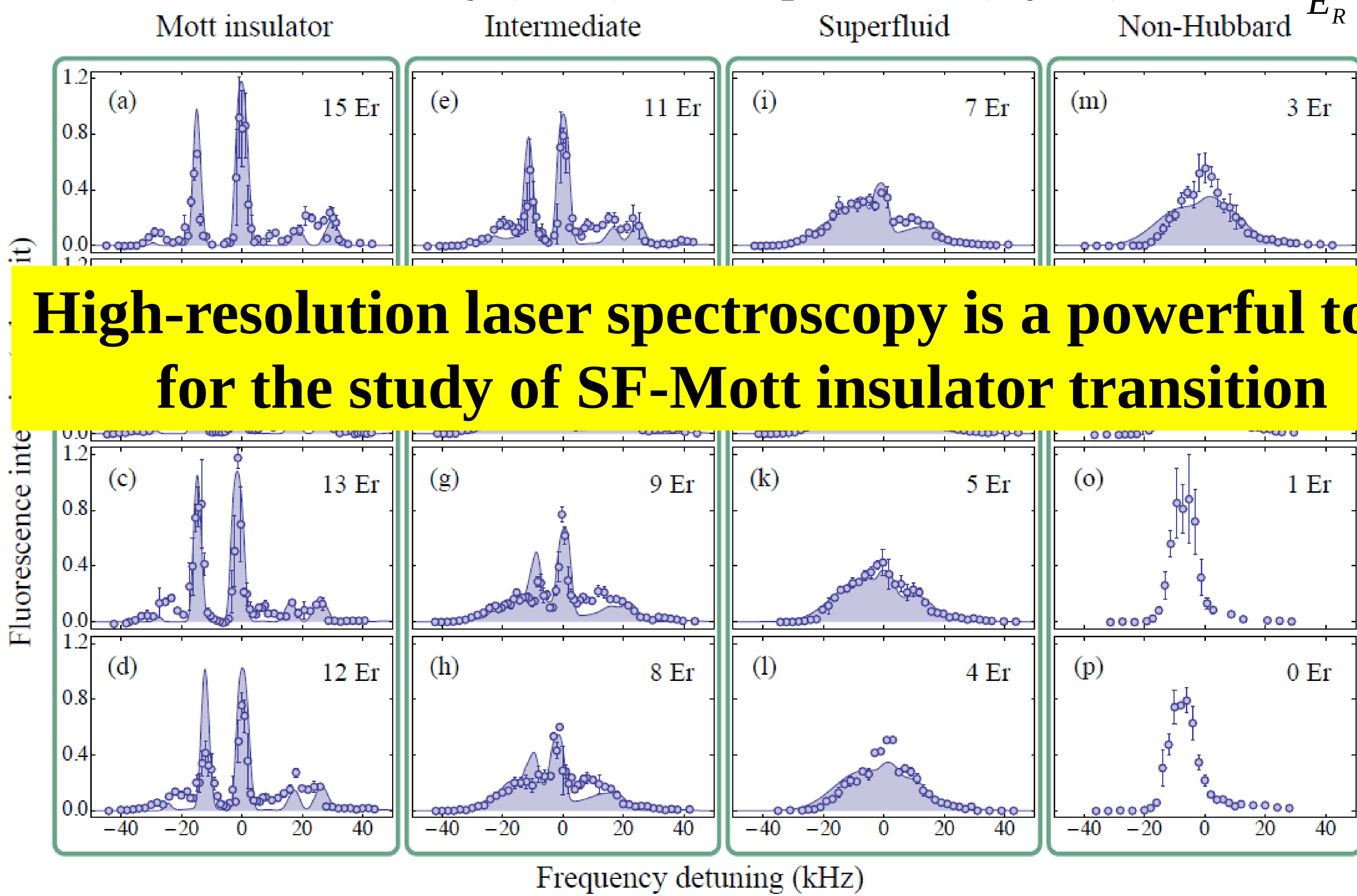

High-resolution laser spectroscopy is a powerful tool for the study of SF-Mott insulator transition

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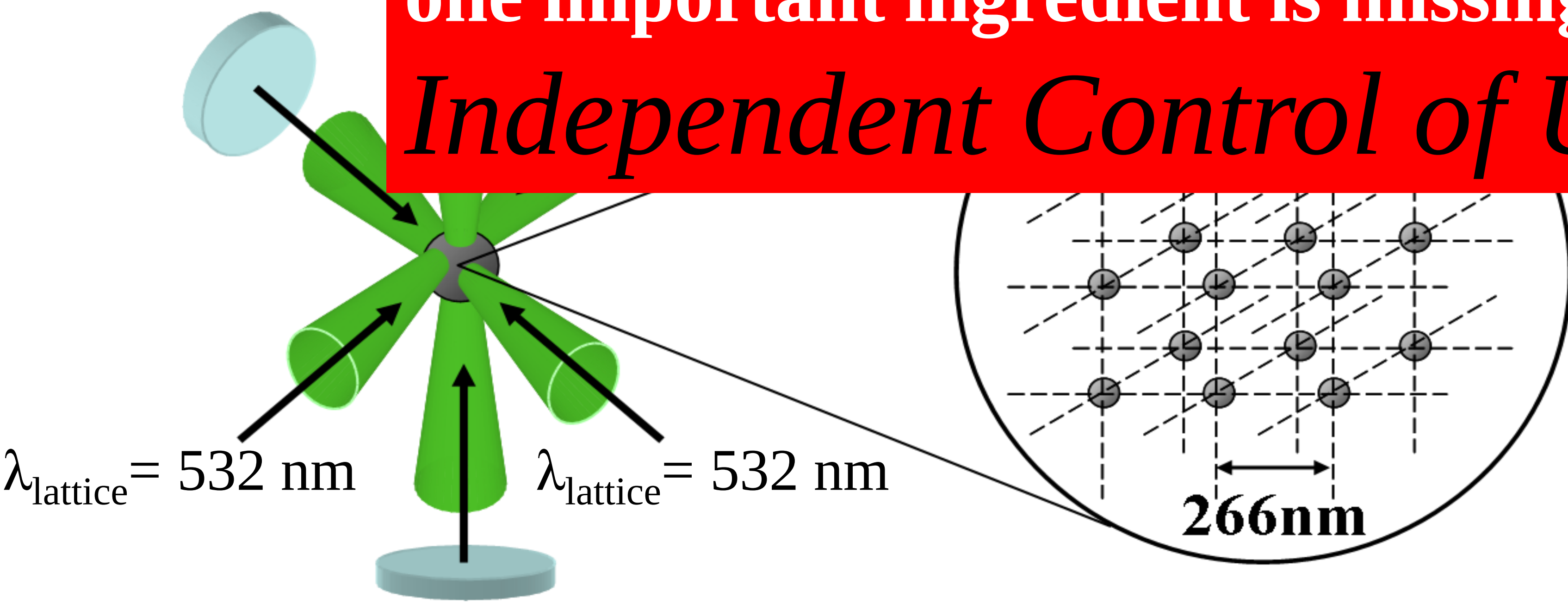
Using Ytterbium atoms in an Optical Lattice

$$H = -J\sum_{<i,j>} a_i^{+} a_j + \frac{U}{2}\sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i$$

one important ingredient is missing

Independent Control of U



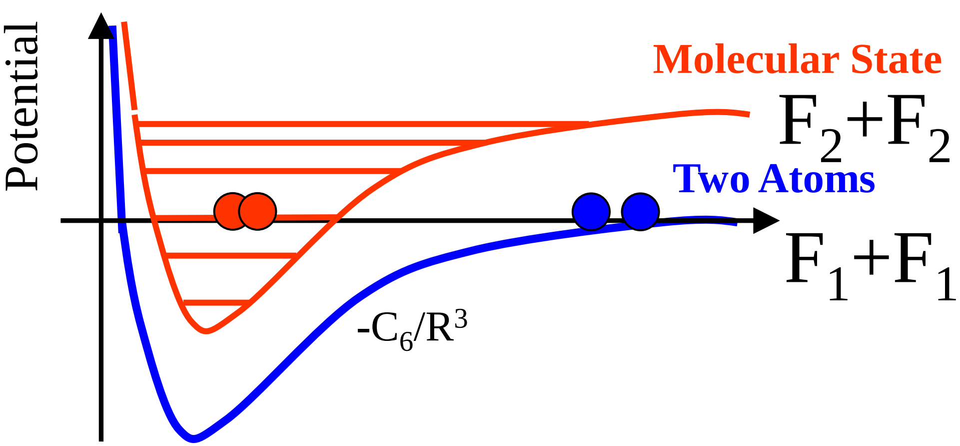
How to Control *U* *for alkali-atoms*

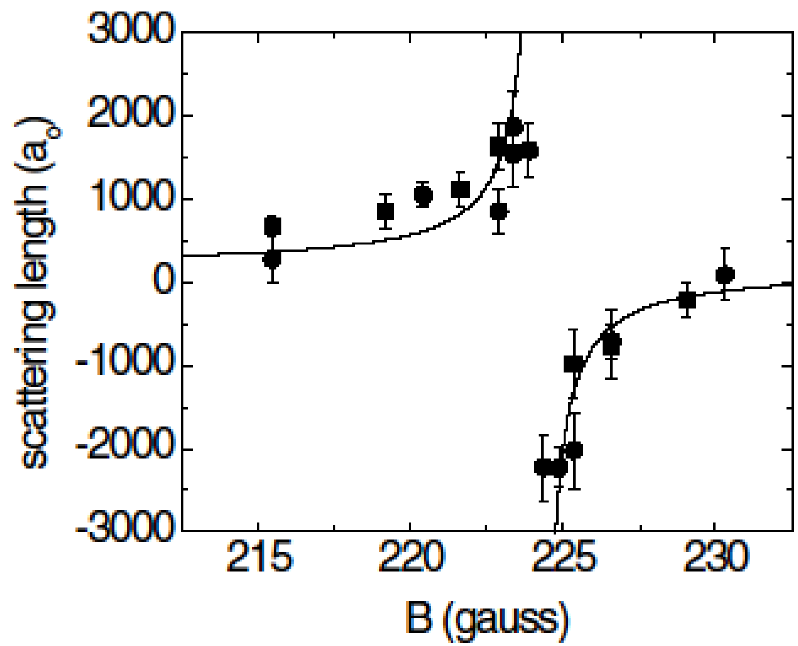
Magnetic Feshbach Resonance **($^2S_{1/2}$+$^2S_{1/2}$)**

Coupling between “**Open Channel**” and “**Closed Channel**” results in

→ **Resonant Control of Interaction(a_s)**

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





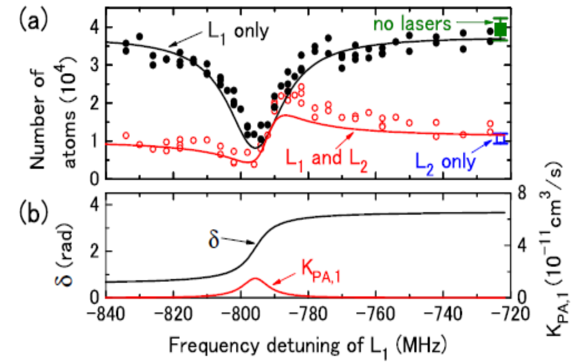
[C. Regal and D. Jin, PRL**90**, 230404(2003)]

How to Control *U* ***for Yb atoms***

Optical Feshbach Resonance for Yb atoms **($^1S_0$+$^1S_0$)**

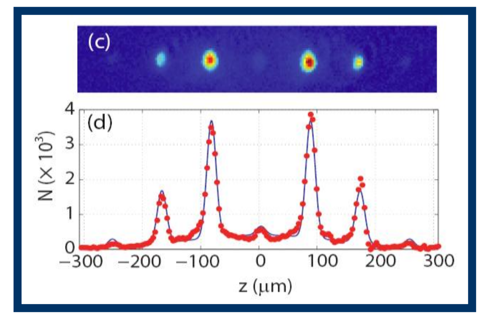
"Optical Feshbach Resonance Using the Intercombination Transition”

K. Enomoto, *et al.*, PRL,101, 203201(2008),



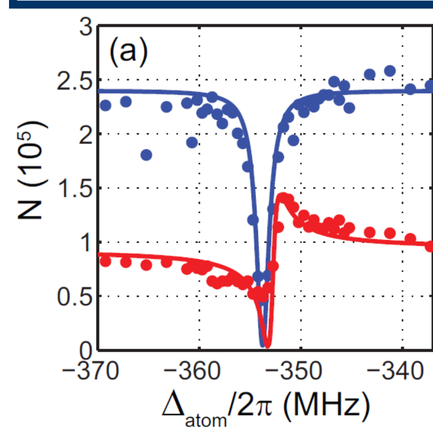
“Submicron Spatial Modulation of an Interatomic Interaction in a BEC”

R. Yamazaki, *et al.*, PRL,105, 050405(2010)



“Manipulating Higher Partial-Wave Interatomic Interaction with an Optical Feshbach Resonance”

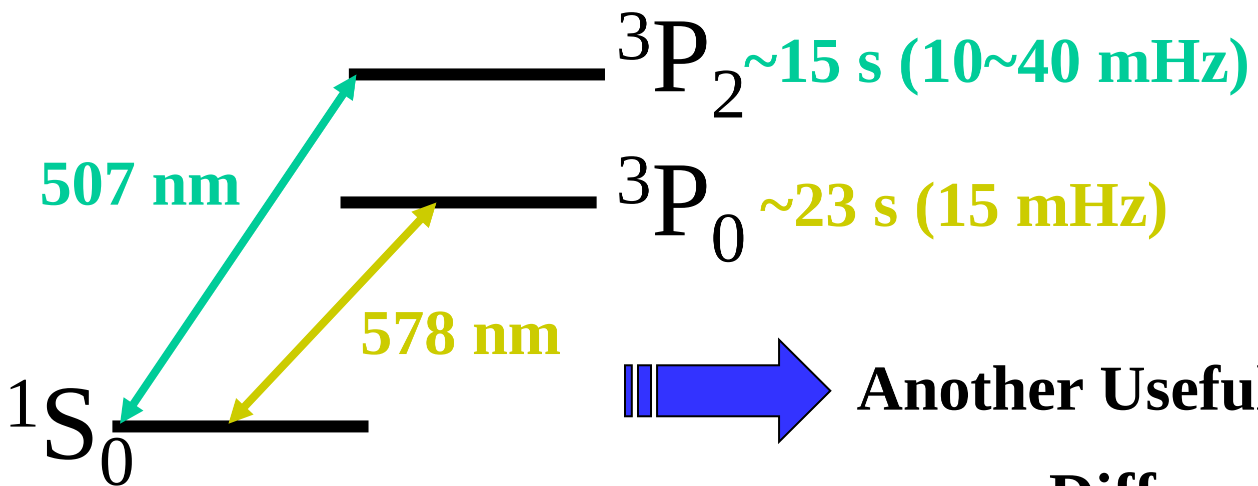
R. Yamazaki et al., arXiv:1210.2567



There is a significant loss due to Photoassociation

Unique Features of Ytterbium Atoms

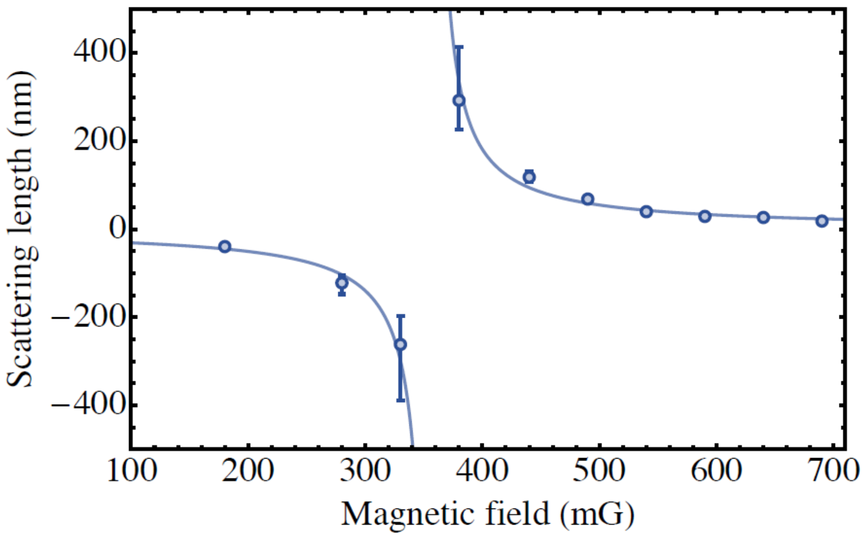
Long-lived metastable state



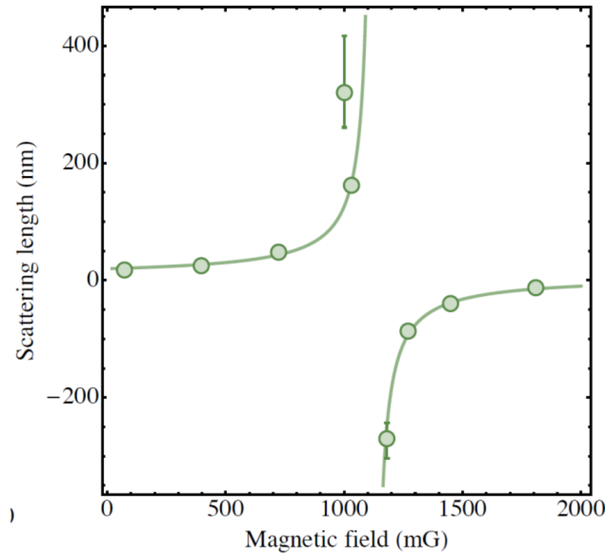
Another Useful Orbital States with Different Characters

Magnetic Feshbach Resonance between $^1S_0$ and $^3P_2$

"$^1S_0 \longleftrightarrow {}^3P_2(m=+2)$": ^{174}Yb



"$^1S_0 \longleftrightarrow {}^3P_2(m=-2)$": ^{170}Yb



[S. Kato *et al.*, arXiv:1204.3988]

⇨ We can study various interesting physics with resonant interaction

Outline

Quantum Simulation of Strongly-Correlated System

dual Mott insulator of Boson and Fermion

SU(6) Mott insulator

high-resolution spectroscopy of SF-Mott insulator transition

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anisotropy-induced Feshbach resonance between $^1S_0$ and $^3P_2$ states

Prospects:

Lieb lattice

Quantum Gas Microscope

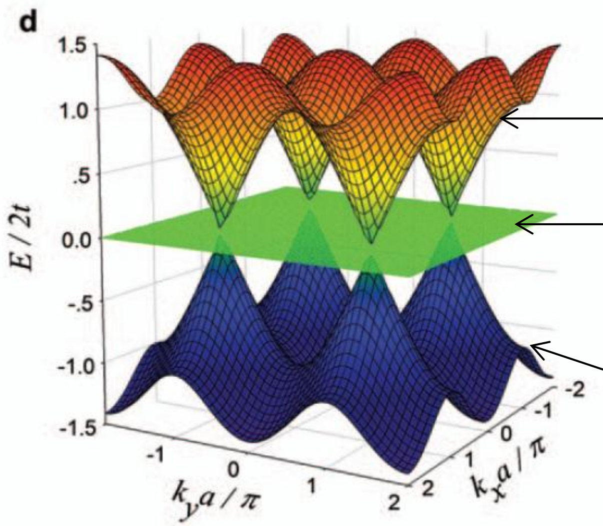
YbLi

Spin-Orbit Interaction

“Non-Standard Lattice-Lieb Lattice-”

E. H. Lieb, PRL 62, 1201 (1989)

$\Delta = 0$

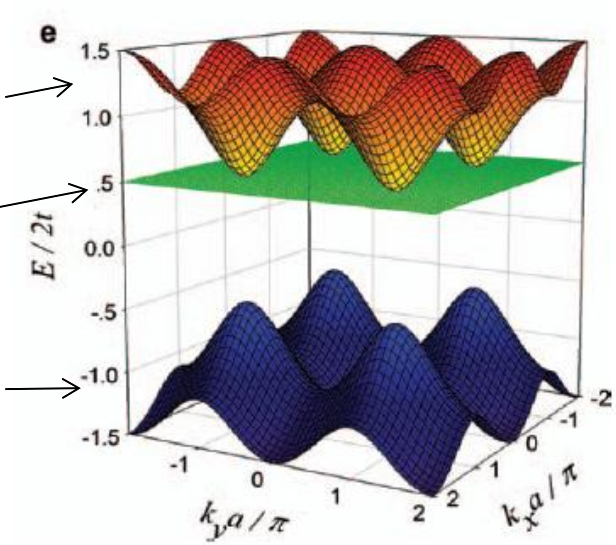


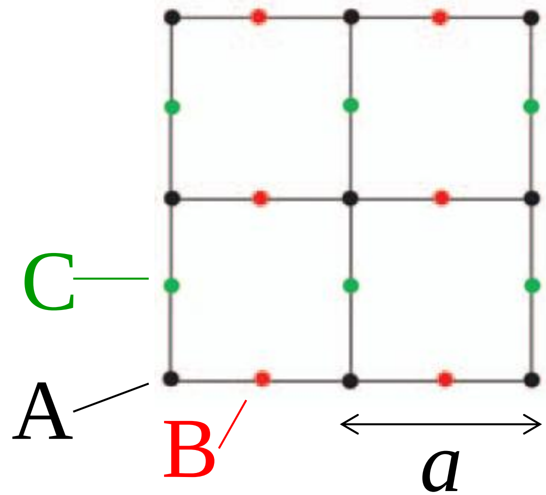
$E_+(\Delta, k)$

$E_0 = \Delta$

$E_-(\Delta, k)$

$\Delta \neq 0$

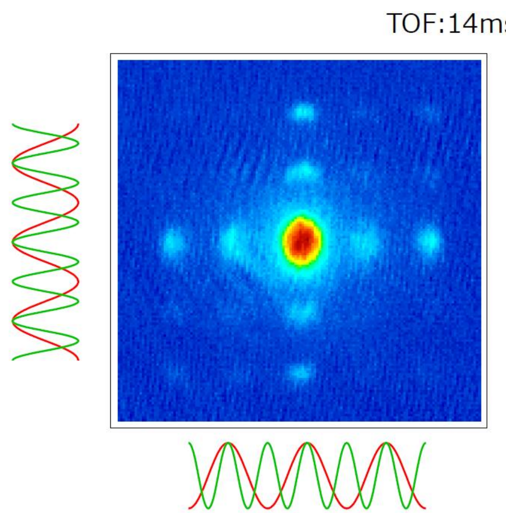




$$E_\pm = \pm\sqrt{\Delta^2 + 4t^2\{\cos^2(k_x a/2) + \cos^2(k_y a/2)\}}$$

“proposal for optical lattice implementation”

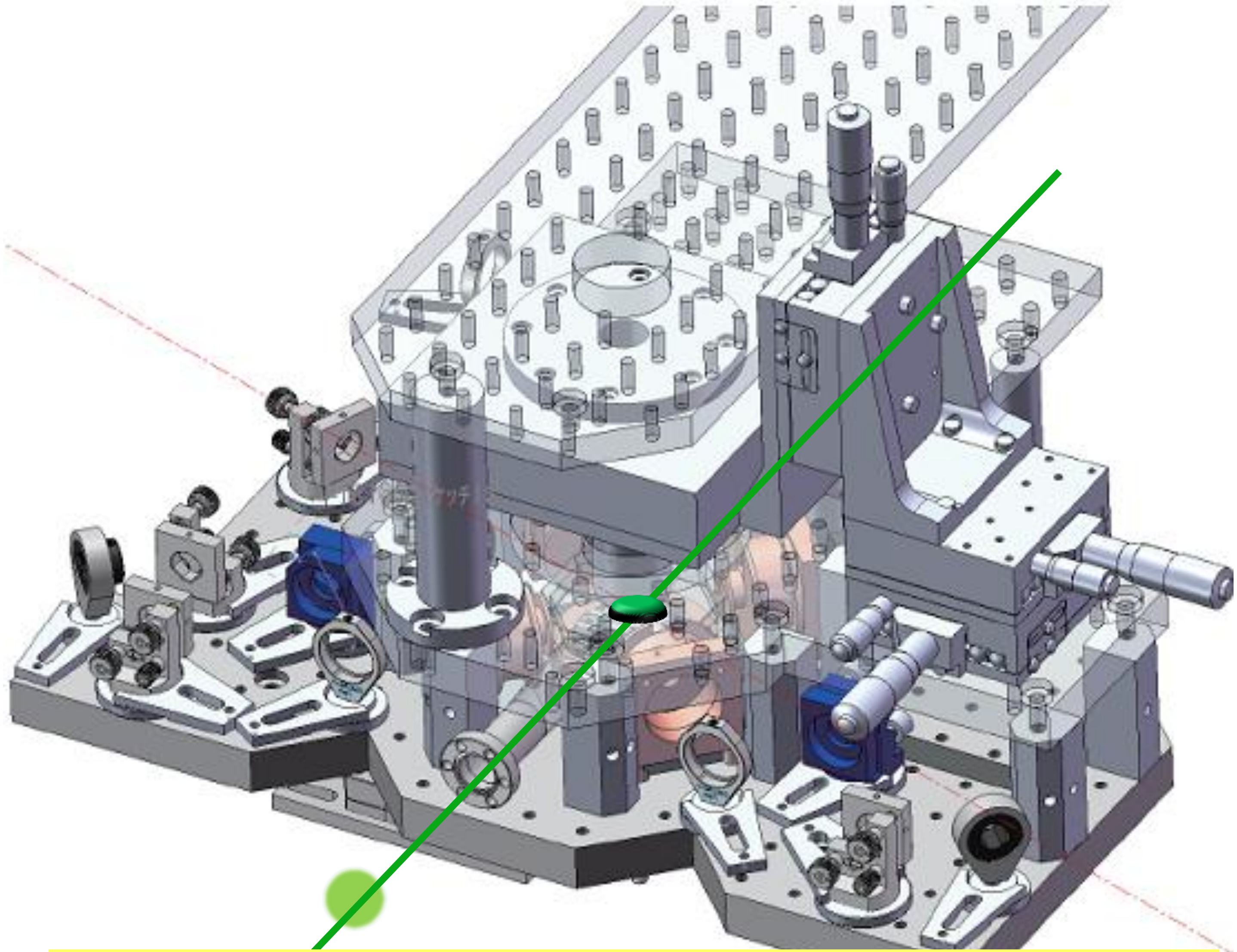
R. Shen et al., PRB**81**, 041410R,2010



λ_1= 532 nm

λ_2=1064 nm

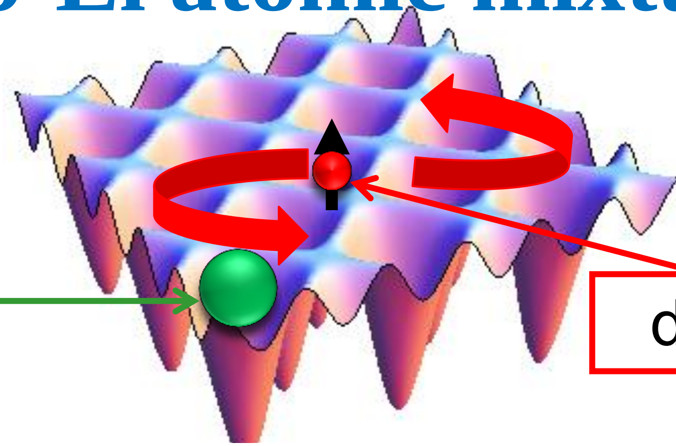
Developing Yb Quantum Gas Microscope



Boson, Fermion, Bose-Fermi Mixture

Simulation of Impurity System with Yb-Li atomic mixture

the hopping rate $t_{Yb} << t_{Li}$



localized impurity

Yb

Li

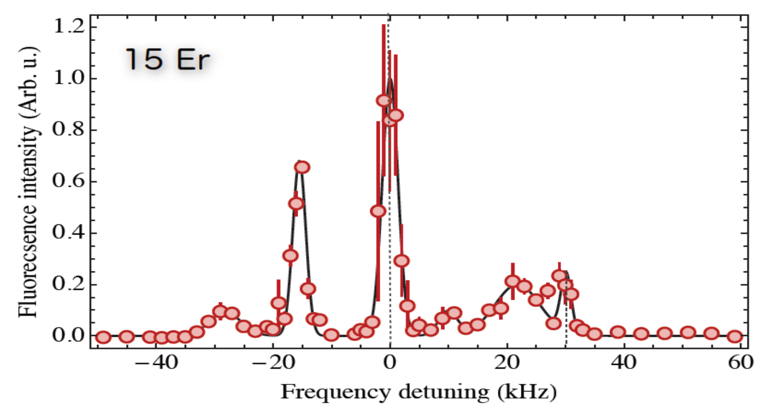
delocalized carrier

Anderson Hubbard Model

$$H = -J \sum_{<i,j>,m=\uparrow,\downarrow} c^{+}_{i,m} c_{j,m} + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow} + \sum_{i} W_i n_i$$

$$W_i = \begin{cases} W & \text{(with Yb)} \\ 0 & \text{(without Yb)} \end{cases}$$

High-resolution Spectroscopy:
Anderson Othogonality Catastorophe

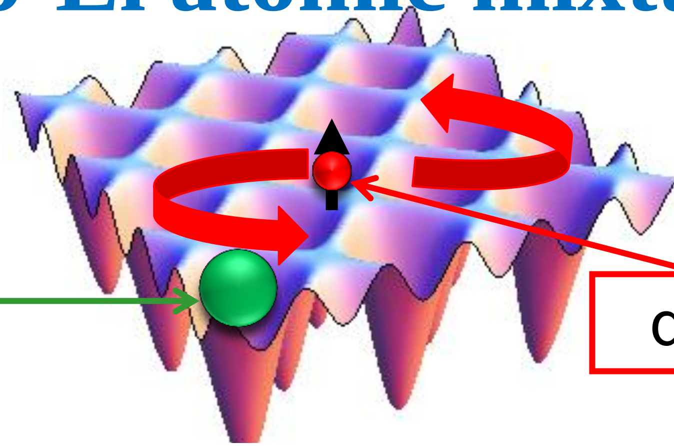


Simulation of Impurity System with Yb-Li atomic mixture

the hopping rate $t_{Yb} << t_{Li}$

localized impurity

Yb



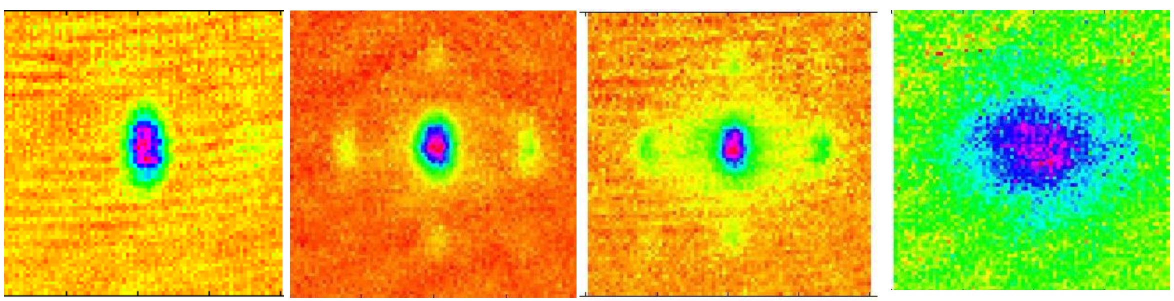
Li

delocalized carrier

Anderson Hubbard Model

$$H = -J \sum_{<i,j>,m=\uparrow,\downarrow} c^{+}_{i,m} c_{j,m} + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow} + \sum_{i} W_i n_i \qquad W_i = \begin{cases} W & \text{(with Yb)} \\ 0 & \text{(without Yb)} \end{cases}$$

"Superfluid-Mott insulator Transition of Yb"



$0\ E_R$ $10\ E_R$ $15\ E_R$ $20\ E_R$

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Prospects:

Lieb lattice: *implementation of 2D super-lattice*
Quantum Gas Microscope: *fluorescence imaging with dual molasses*
YbLi: optical lattice setup for impurity problem
spin-Orbit Interaction

Thank you very much for attention

16 August   Mount Daimonji at Kyoto