# The 11th US-Japan Seminar

## Ultimate Quantum Systems of Light and Matter
## - Control and Applications -

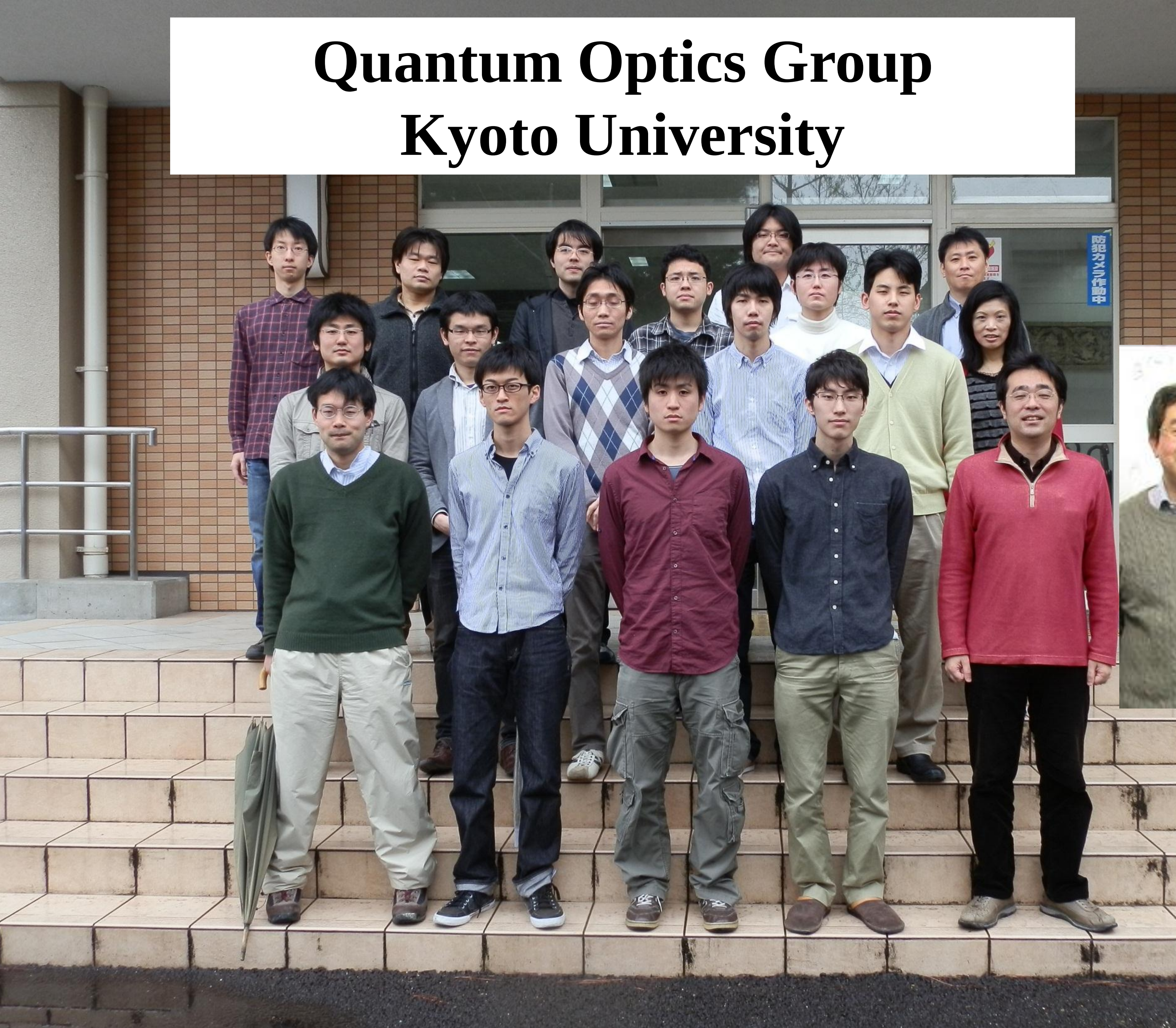
10 April 2013 Nara

# Quantum simulation using ultracold ytterbium atoms in an optical lattice

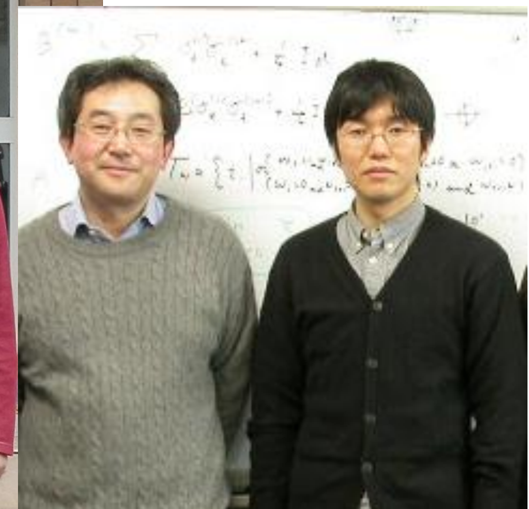
Kyoto University, JST

Y. Takahashi

# Quantum Optics Group
# Kyoto University




**NTT**:
K. Inaba
M. Yamashita



# Outline

## Quantum Simulation of Strongly-Correlated States

*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

Yb-Li atomic mixture

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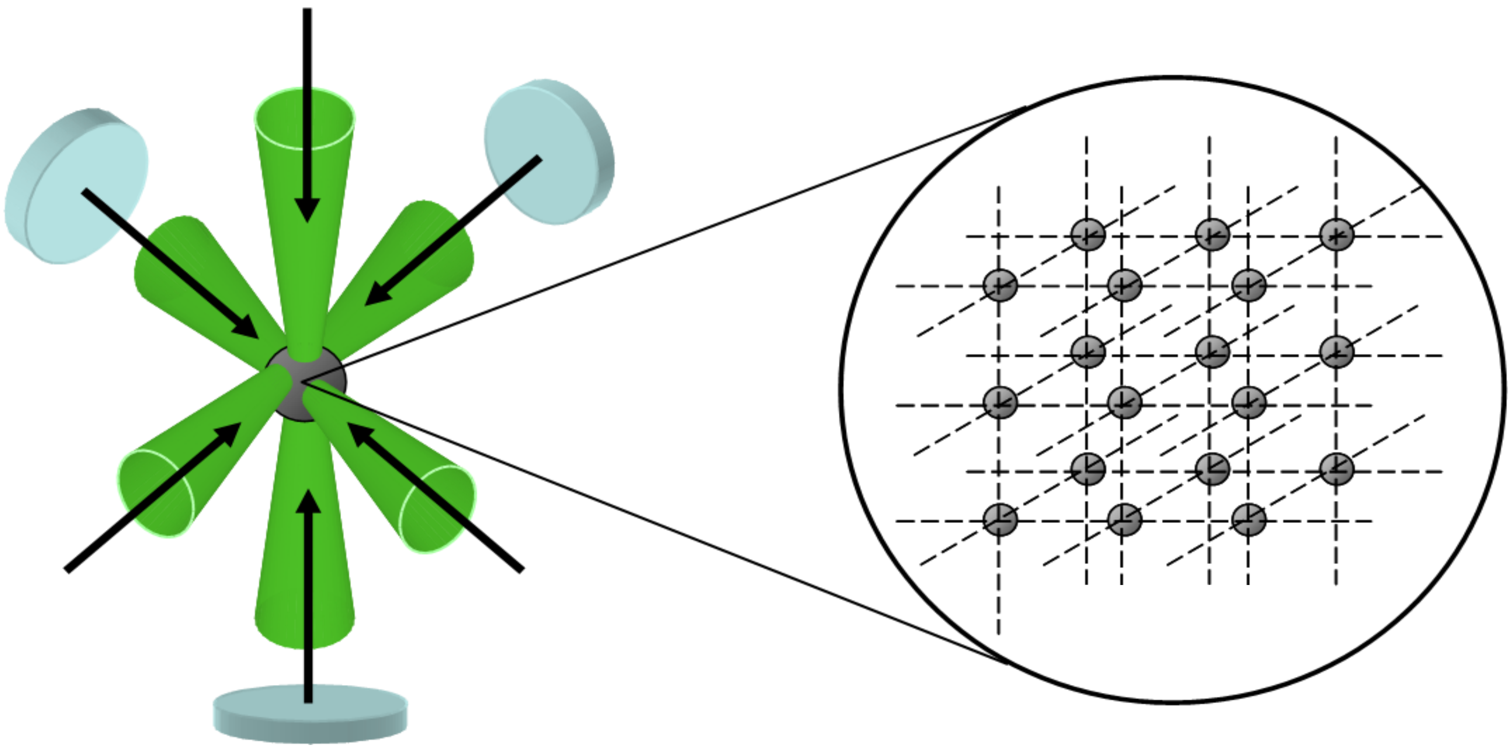
# Quantum Simulation
# Using ultracold atoms in an Optical Lattice

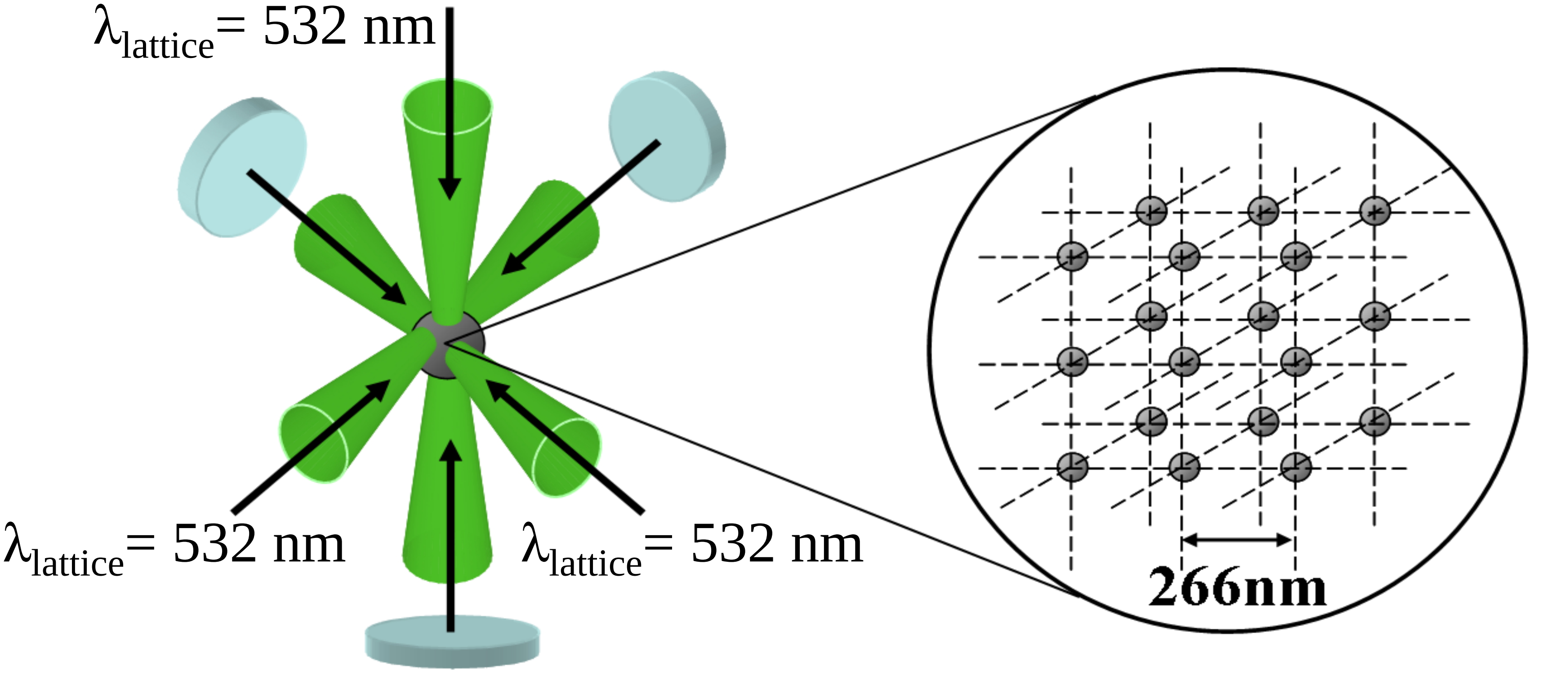
$$H = -J\sum_{<i,j>} a_i^{+} a_j + \frac{U}{2}\sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i$$

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



# 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** |

$^{170}$Yb – $^{173}$Yb:

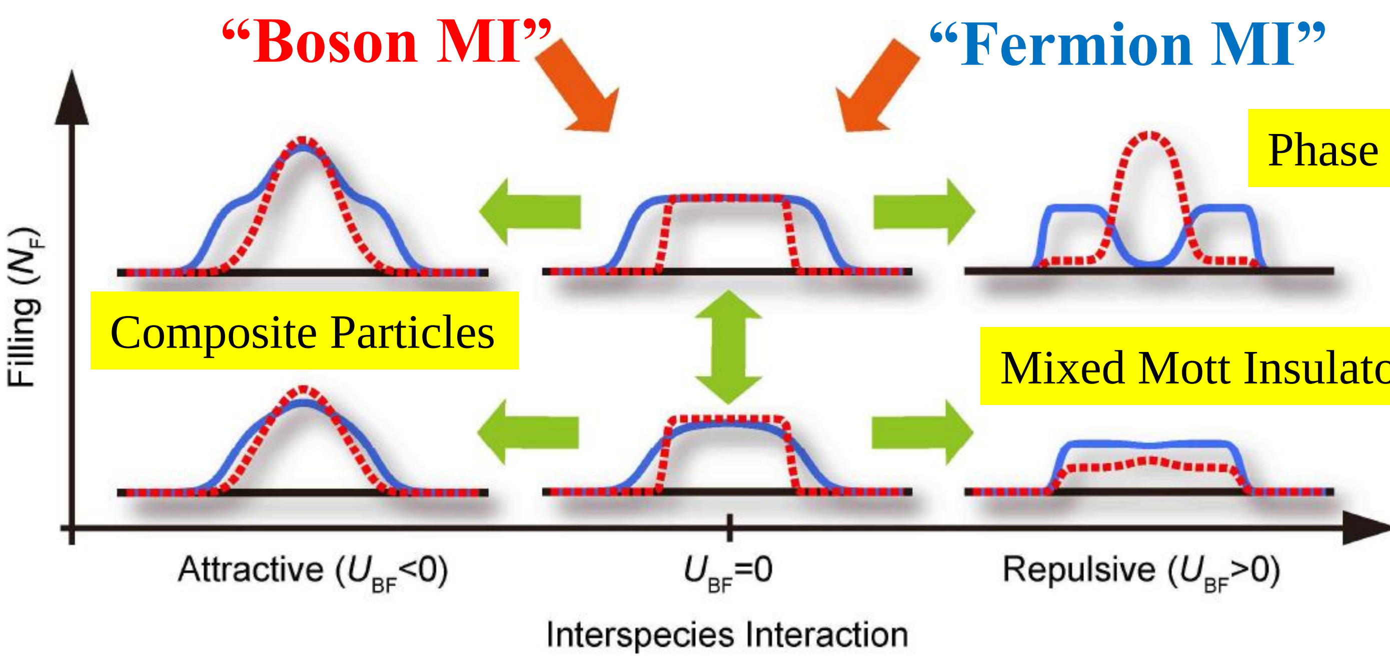
- Attractive Interaction:
  $a_{BF}$ = - 4.3 nm
  $a_{BB}$ = +3.4 nm
  $a_{FF}$ = +10.6 nm

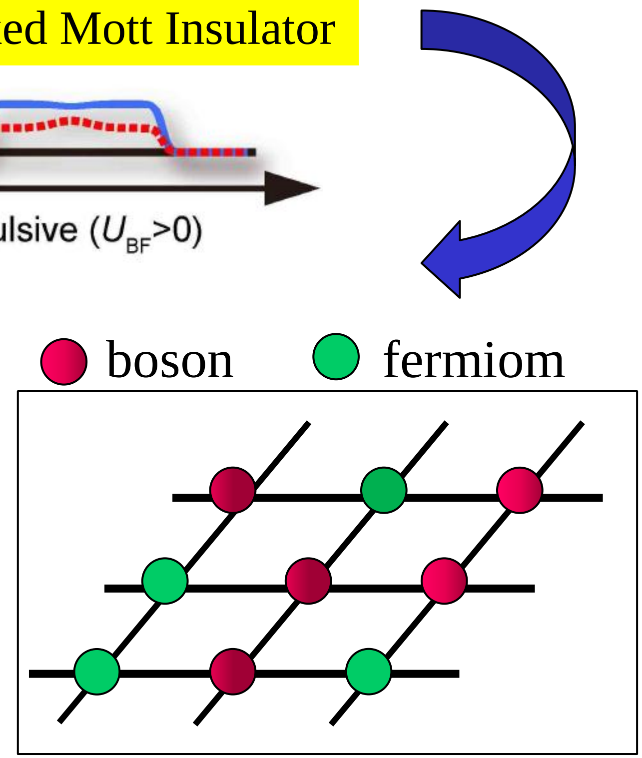
$^{174}$Yb – $^{173}$Yb:

- Repulsive Interaction:
  $a_{BF}$ = +7.3 nm
  $a_{BB}$ = +5.6 nm
  $a_{FF}$ = +10.6 nm

# "Strongly Interacting Dual Mott Insulators"

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




*<u>trigger theoretical studies</u>*

- 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"*

# Unique Features of Ytterbium Atoms

Theoretically, *Physics of large-spin Fermi gas* was extensively discussed

C. Wu *et al.*, PRL**91**, 186402(2003); C. Wu, MPL.B**20**, 1707(2006); C. Wu, PRL**95**, 266404(2005), etc

E. Szirmai and J. Solyom, PRB**71**, 205108(2005), K. Buchta, et al., PRB**75**, 155108(2007)

M. A. Cazalilla, *et al.*, N. J. Phys**11**, 103033(2009), M. Hermele *et al.*,PRL **103**, 135301(2009)
A. V. Gorshkov, *et al.*, Nat. Phys. **6**, 289(2010)
, etc

valence bond solid, spin liquid, etc

$^{173}$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*"

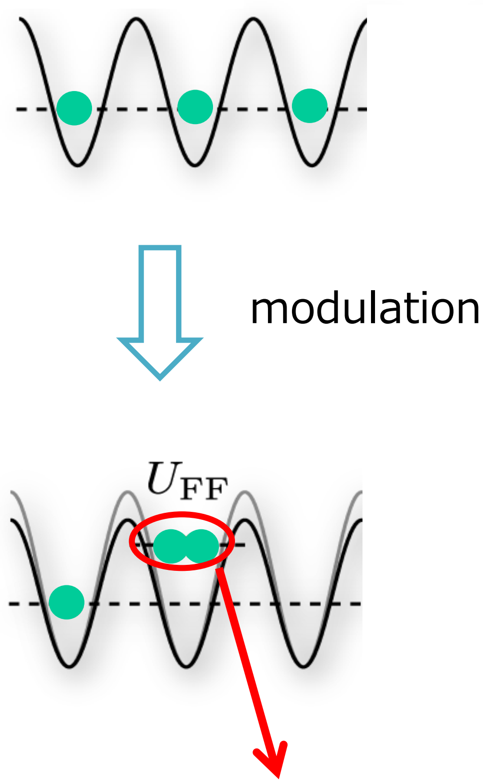
$$H_{\text{int}} = \frac{4\pi\hbar^2 a_s}{M}\delta(\vec{r}_1 - \vec{r}_2)$$ **SU(6) system**

*"Experimental realization is very difficult in solid state system"*

# “Formation of SU(6) Mott insulator”

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

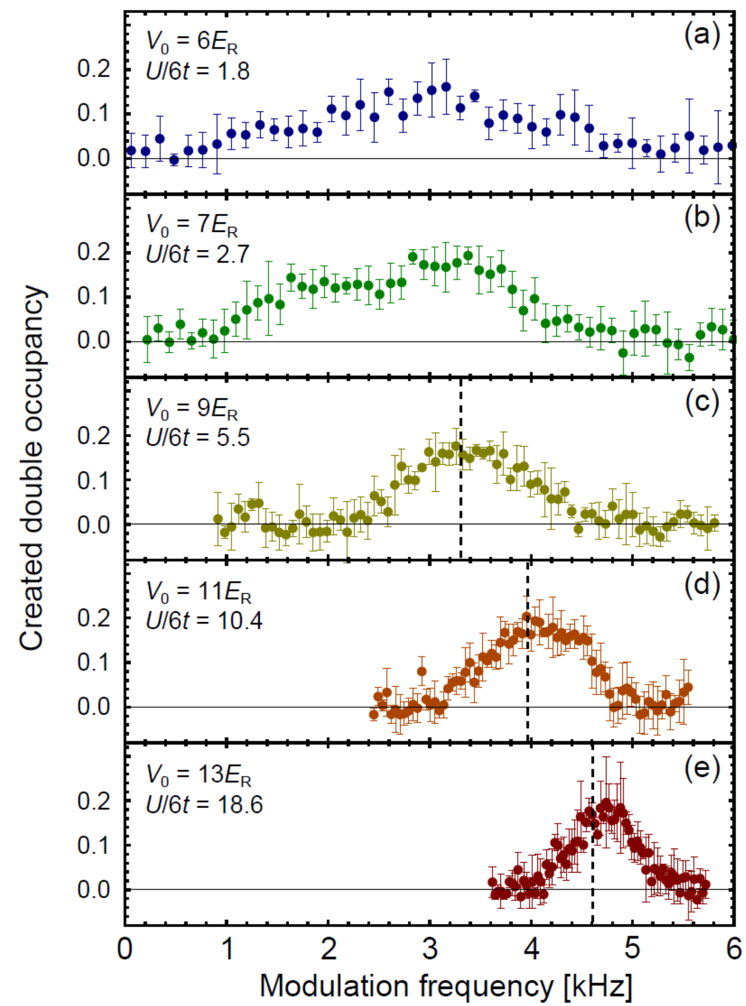
## Lattice modulation




Photoassociation

## Doublon Production Spectra

## **Excitation (Mott) Gap**



# “Formation of SU(6) Mott insulator”

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

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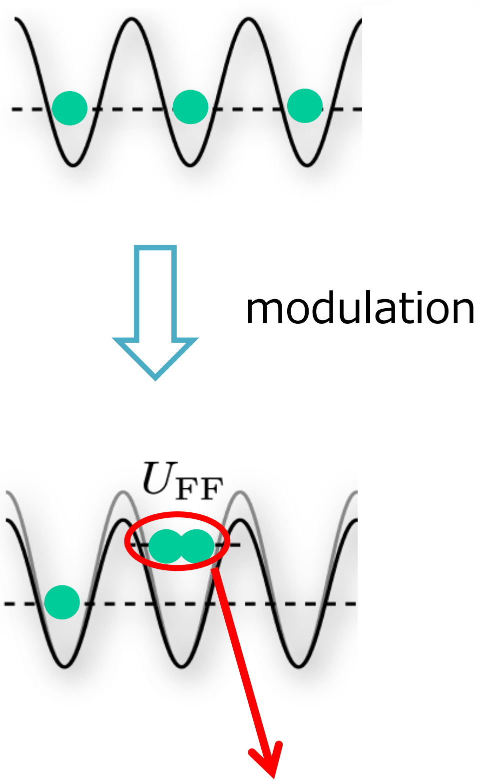
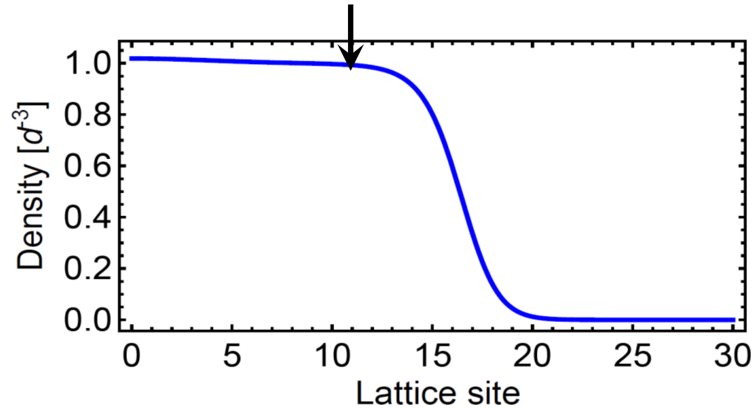



Photoassociation

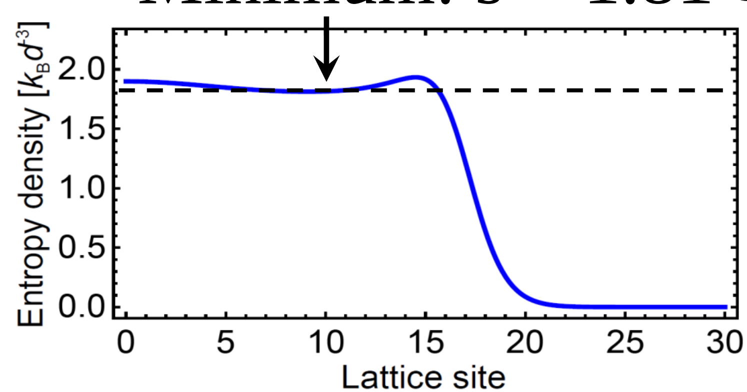
## Doublon Production Rate

**$T_{lattice}$=5.1t= 16 nK at U/t=62.4**

Mott Plateau (n=1)



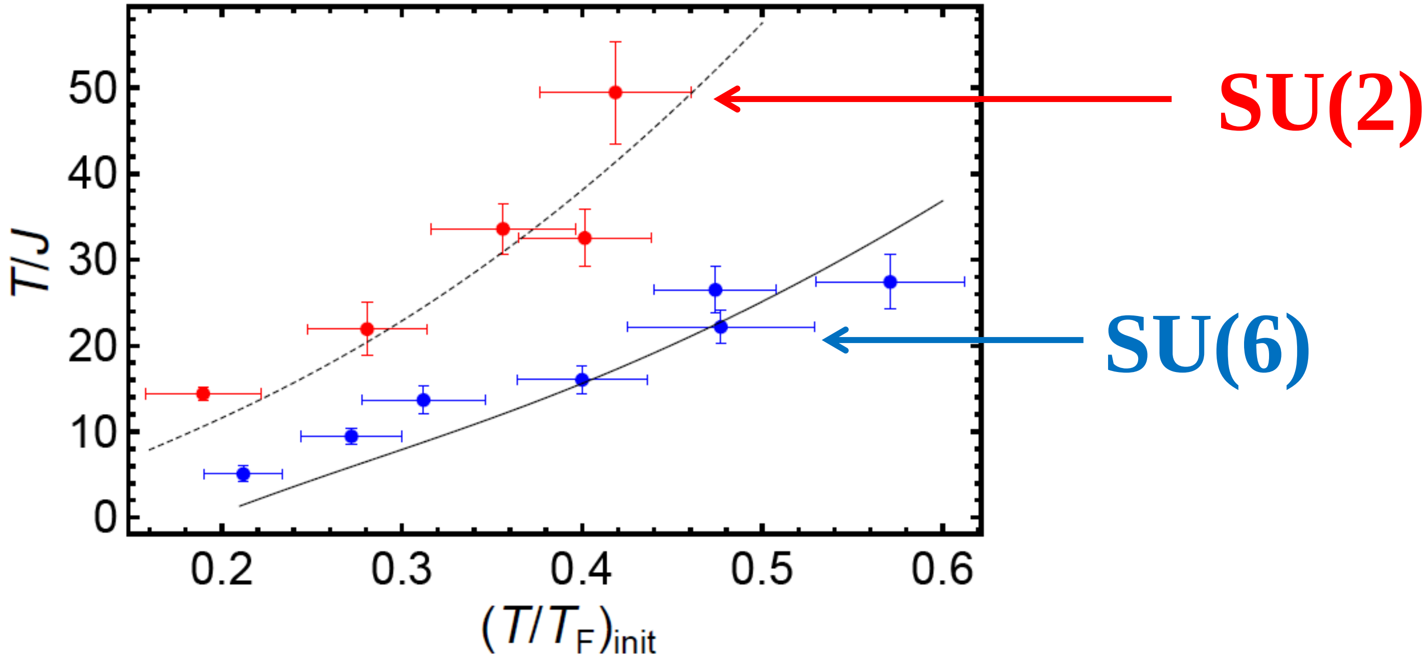

Minimum: s = 1.81 cf. ln(6)
= 1.79



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

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

## SU(6) versus SU(2)



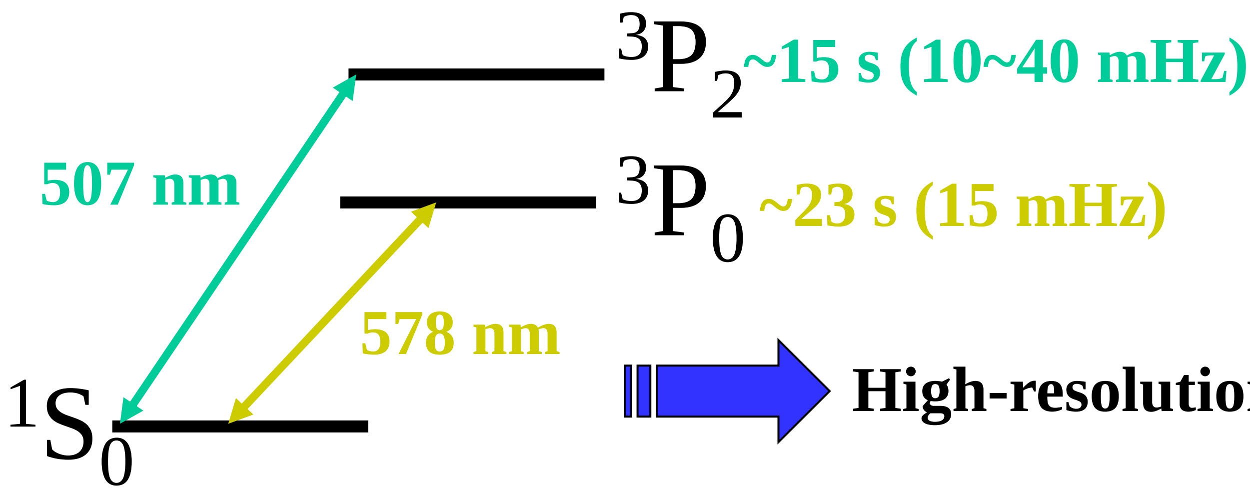

→ "Enhanced Pomeranchuk Cooling of an Atomic Gas"

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

Theory SU(2) case: [F. Werner, et al, PRL.**95**, 056401(2005)]
SU(N) case: [M. A. Cazalilla, et al, N. J. Phys.**11**, 103033(2009)]
[K. R. A. Hazzard, et al, PRA**85**, 041604(2012)]

# Unique Features of Ytterbium Atoms

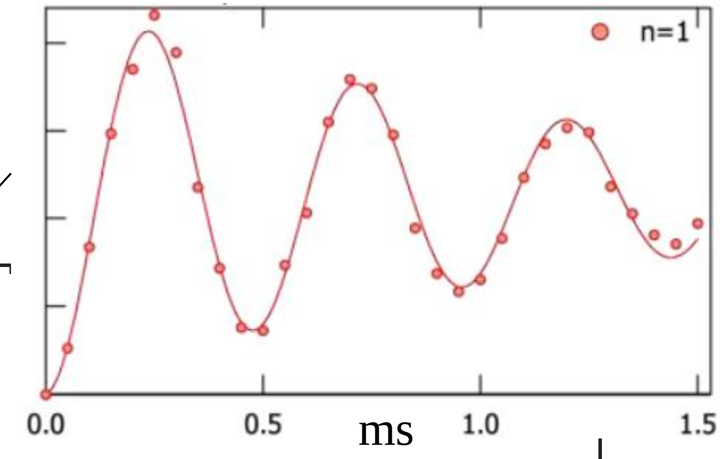
***<u>Long-lived metastable state</u>***
***<u>/Ultra-narrow Optical Transitions</u>***

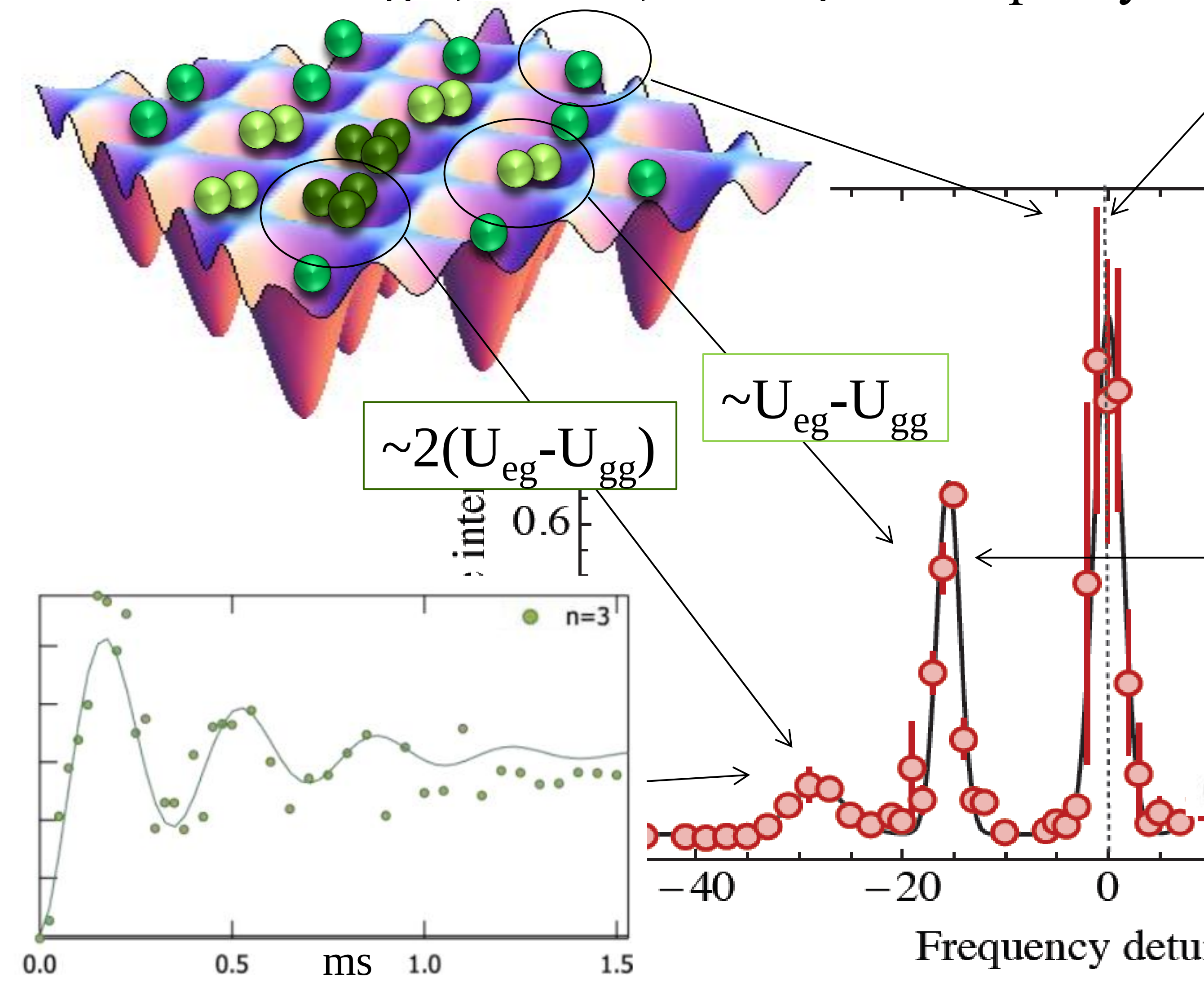


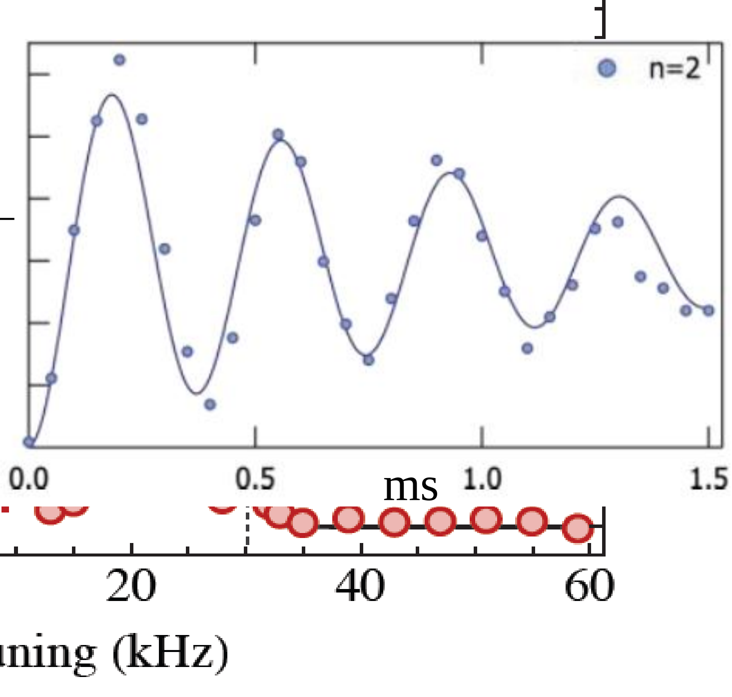

**High-resolution laser spectroscopy**

# Spectroscopy of Atoms in a Mott Insulating State

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



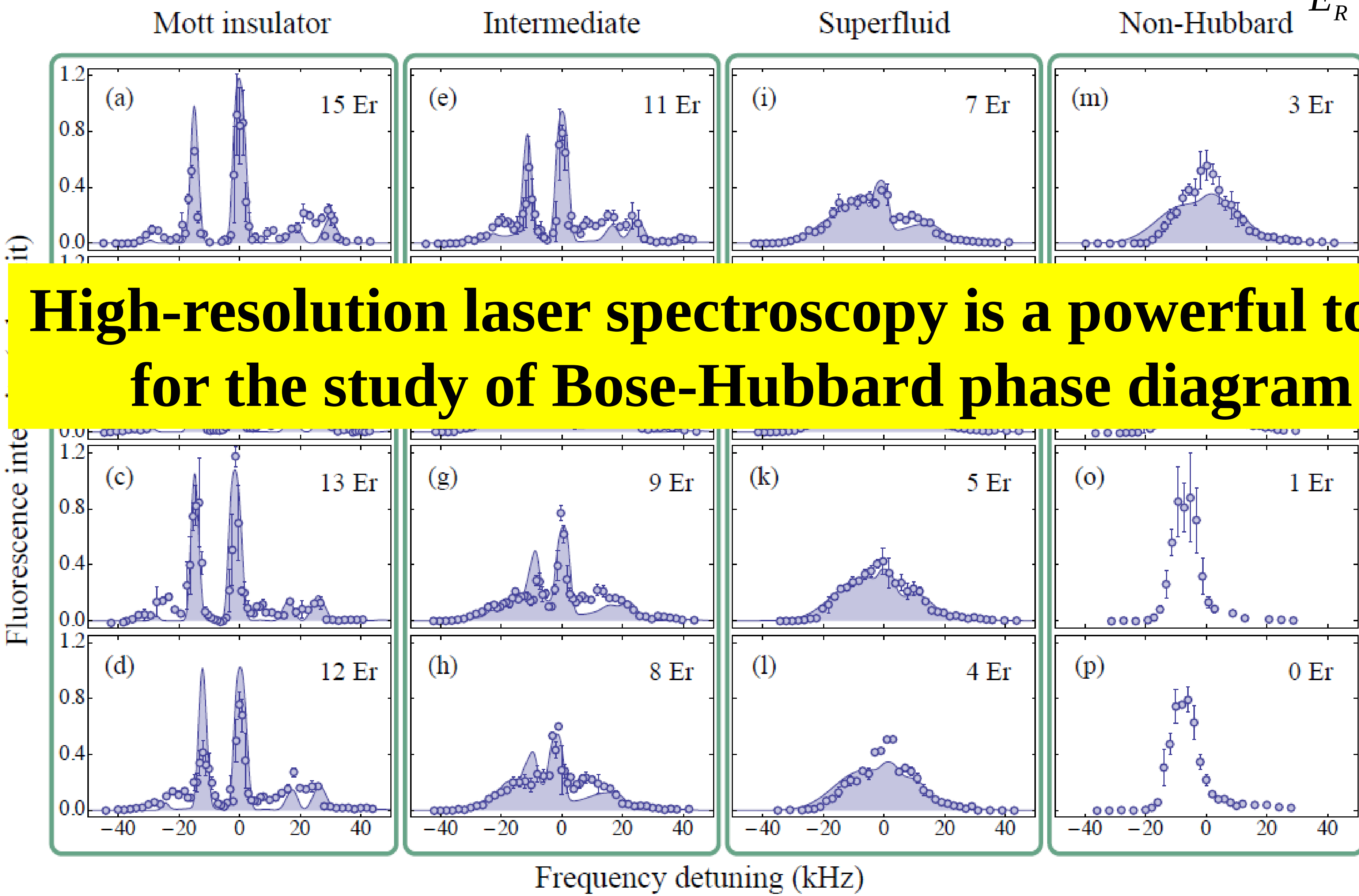



# Spectroscopy of Superfluid-Mott Insulator Transition

## Theory (NTT) and Experiment (Kyoto)

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




**High-resolution laser spectroscopy is a powerful tool for the study of Bose-Hubbard phase diagram**

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**Prospects:**

Lieb lattice

Yb-Li atomic mixture

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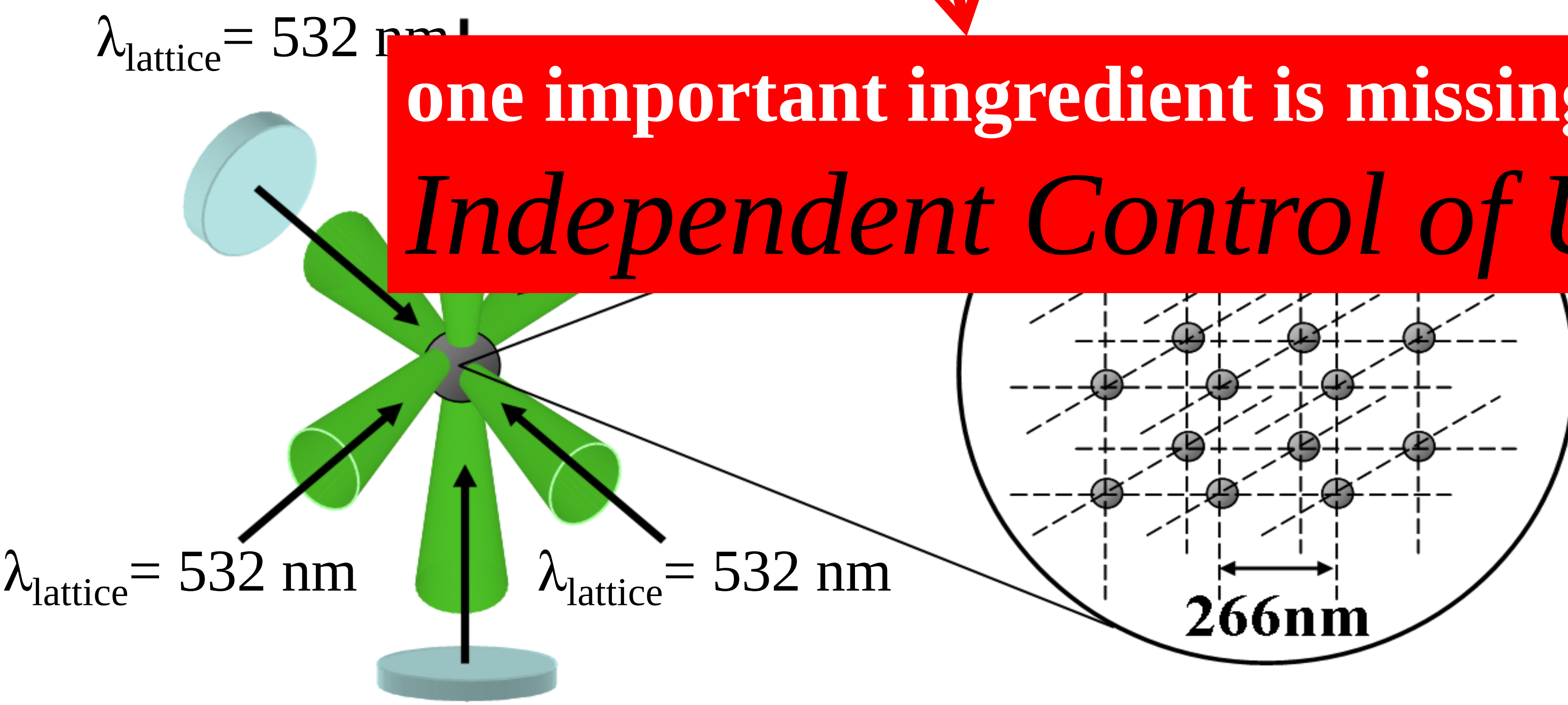
$$H = -J\sum_{<i,j>} a_i^{+} a_j + \frac{U}{2}\sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i$$

**one important ingredient is missing**

***Independent Control of U***



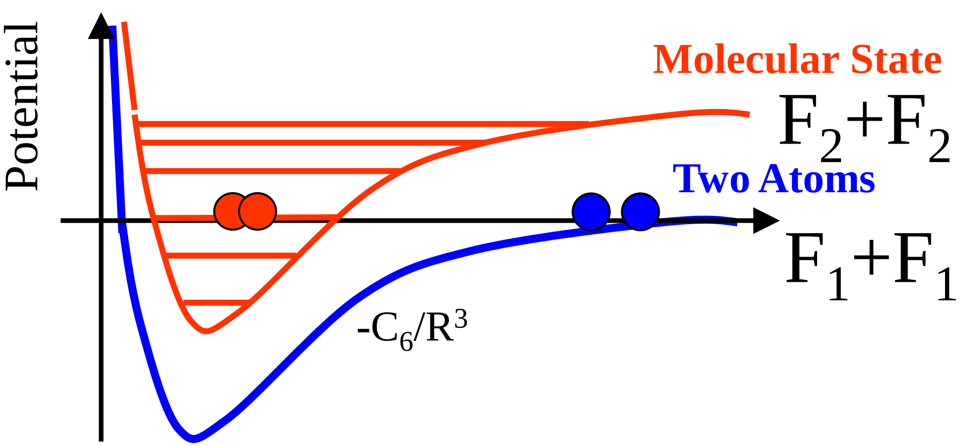
# How to Control *U* *for alkali-atoms*

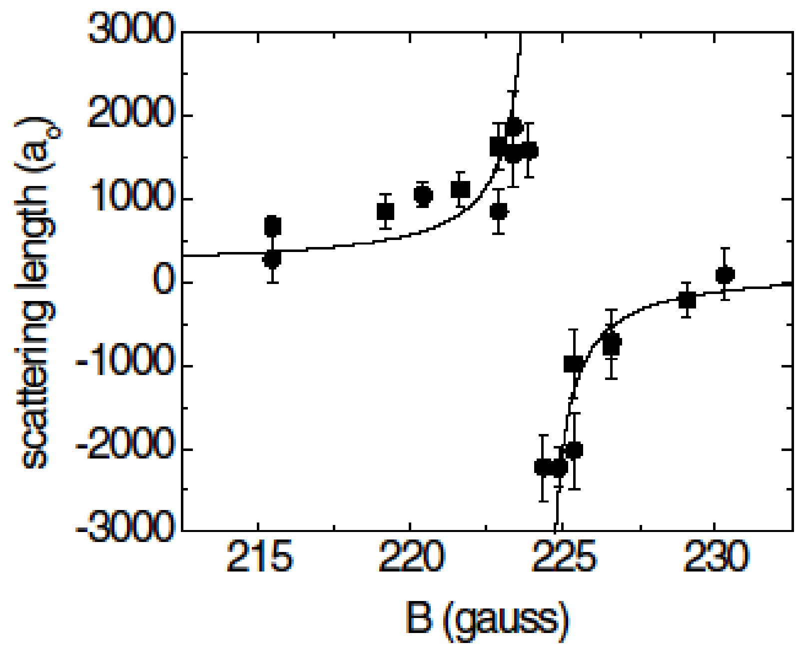
## **Magnetic** Feshbach Resonance **($^2S_{1/2}+^2S_{1/2}$)**

Coupling between "**Open Channel**" and "**Closed Channel**"

→ Control of Interaction($a_s$)

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



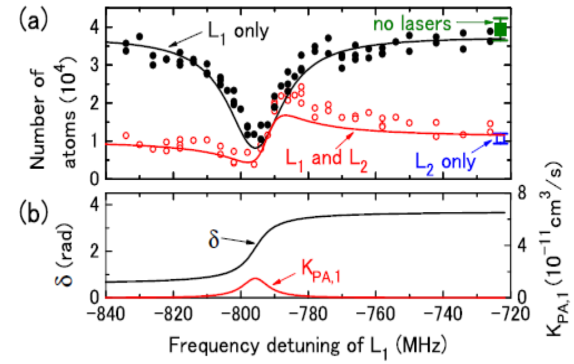




[C. Regal and D. Jin, PRL**90**, 230404(2003)]

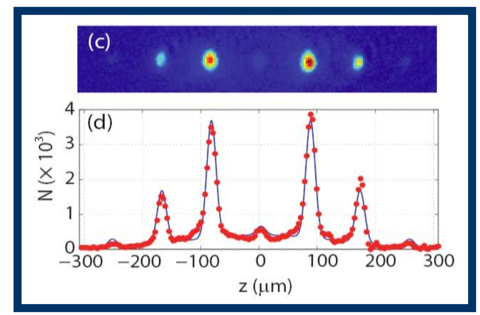
# How to Control *U* ***for Yb atoms***

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

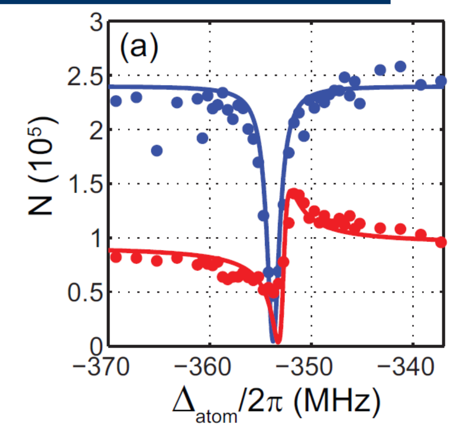
**"Optical Feshbach Resonance Using the Intercombination Transition"**
K. Enomoto, *et al.*, PRL,101, 203201(2008),




**"Submicron Spatial Modulation of an Interatomic Interaction in a BEC"**
R. Yamazaki, *et al.*, PRL,105, 050405(2010)



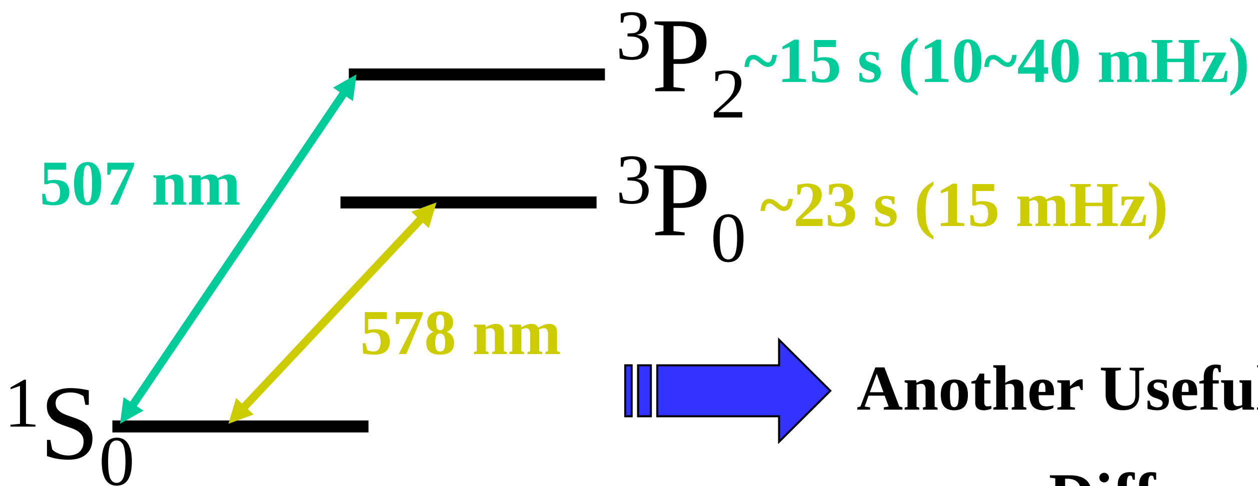

**"Observation of a *p*-wave Optical Feshbach Resonance"**
R. Yamazaki et al., PRA**87**,010704(R)(2013)




There is a significant loss due to Photoassociation

# Unique Features of Ytterbium Atoms

***Long-lived metastable state***

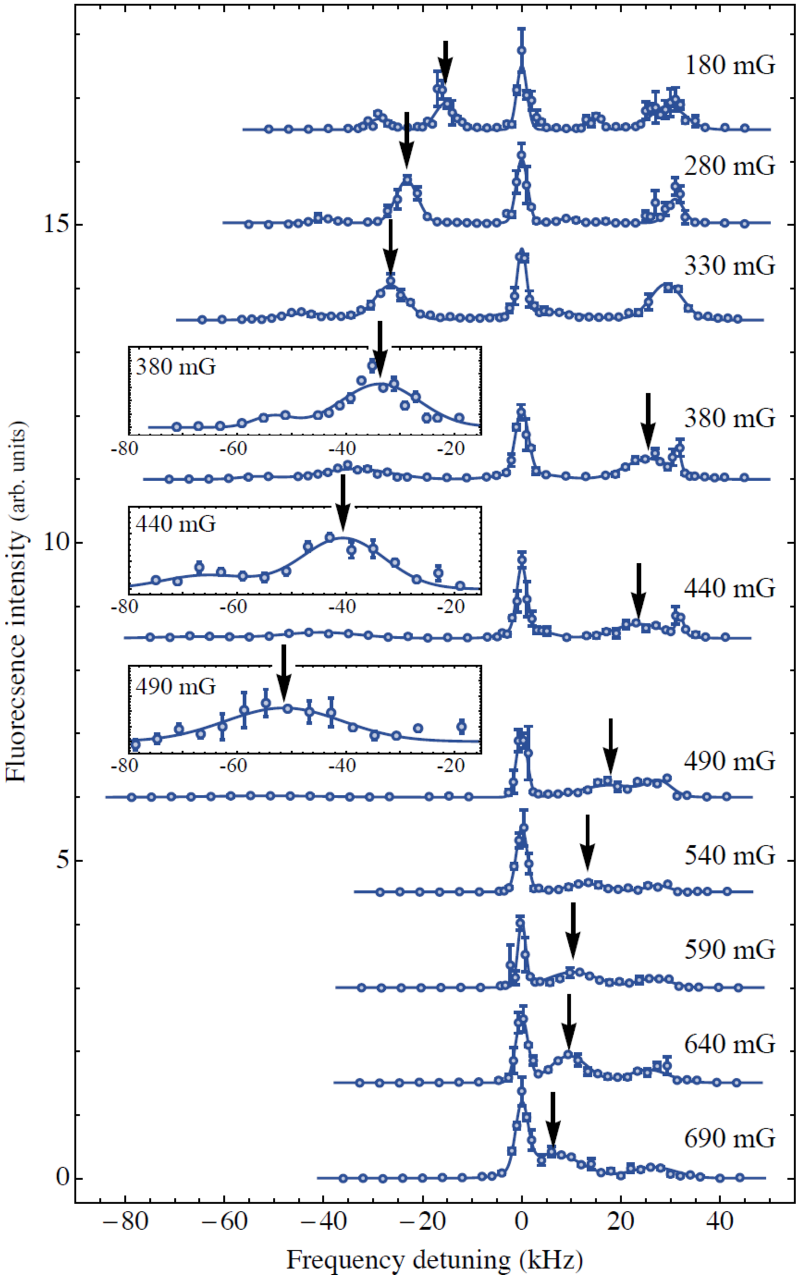


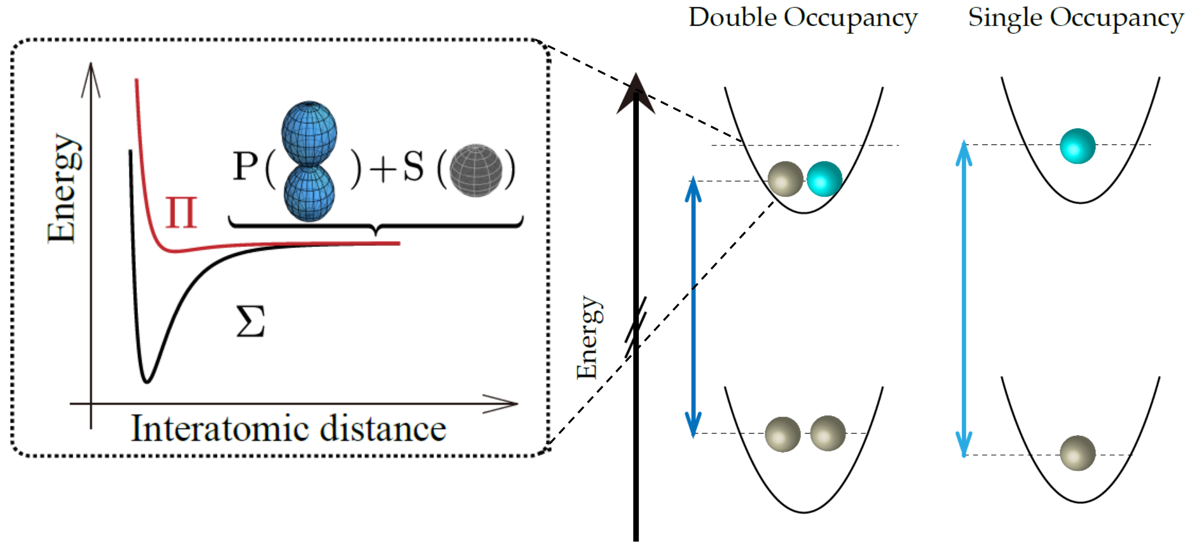

**Another Useful Orbital States with Different Characters**

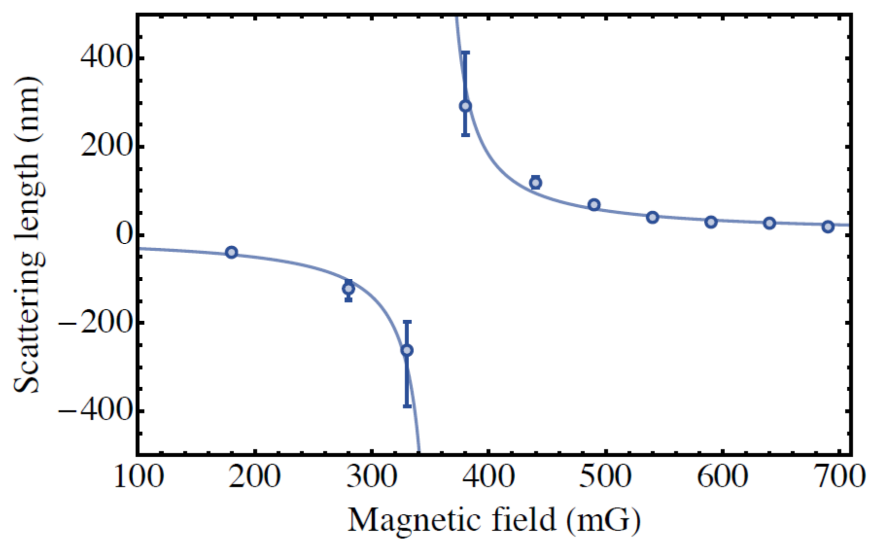
# Magnetic Feshbach Resonance ($^{174}$Yb)

[S. Kato *et al.*, arXiv:1204.3988] to appear in PRL

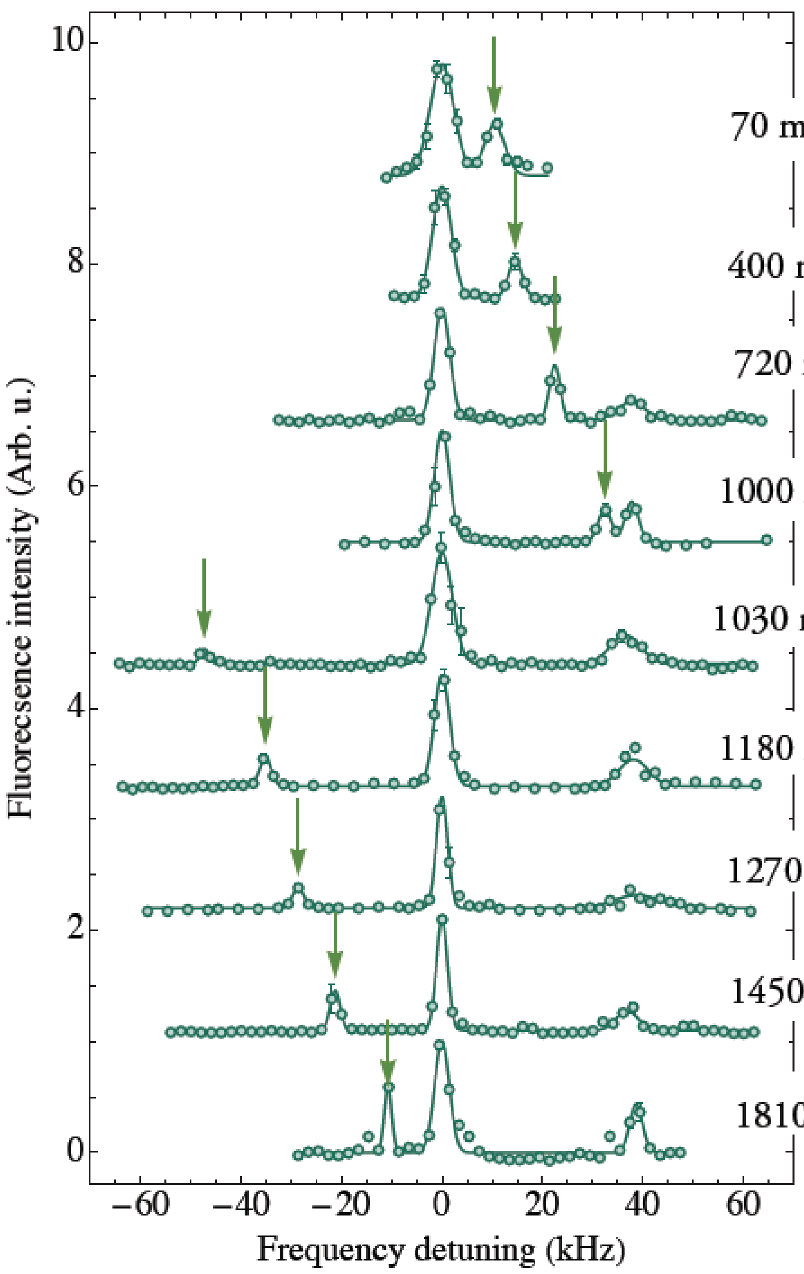
"$^1S_0 \longleftrightarrow {}^3P_2(m=+2)$": $^{174}$Yb



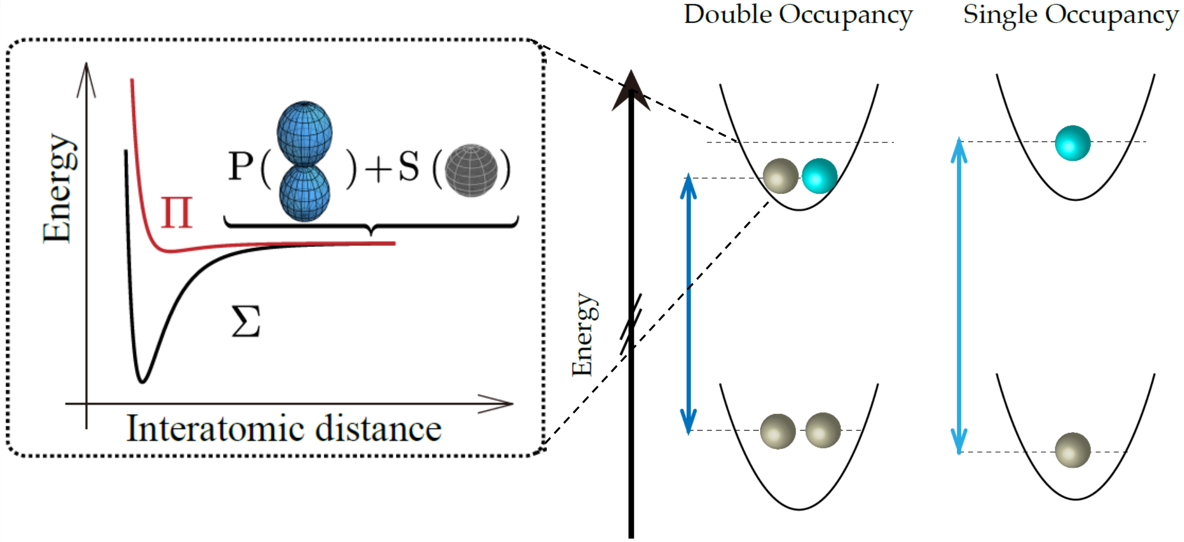



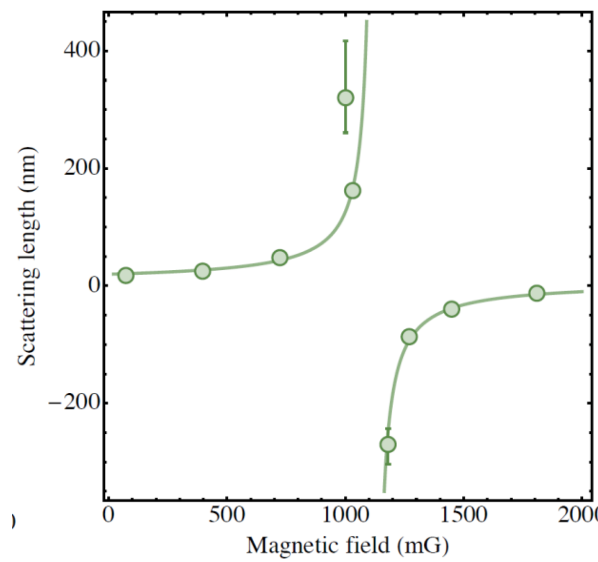
# Magnetic Feshbach Resonance ($^{170}$Yb)




[S. Kato *et al.*, arXiv:1204.3988] to appear in PRL

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



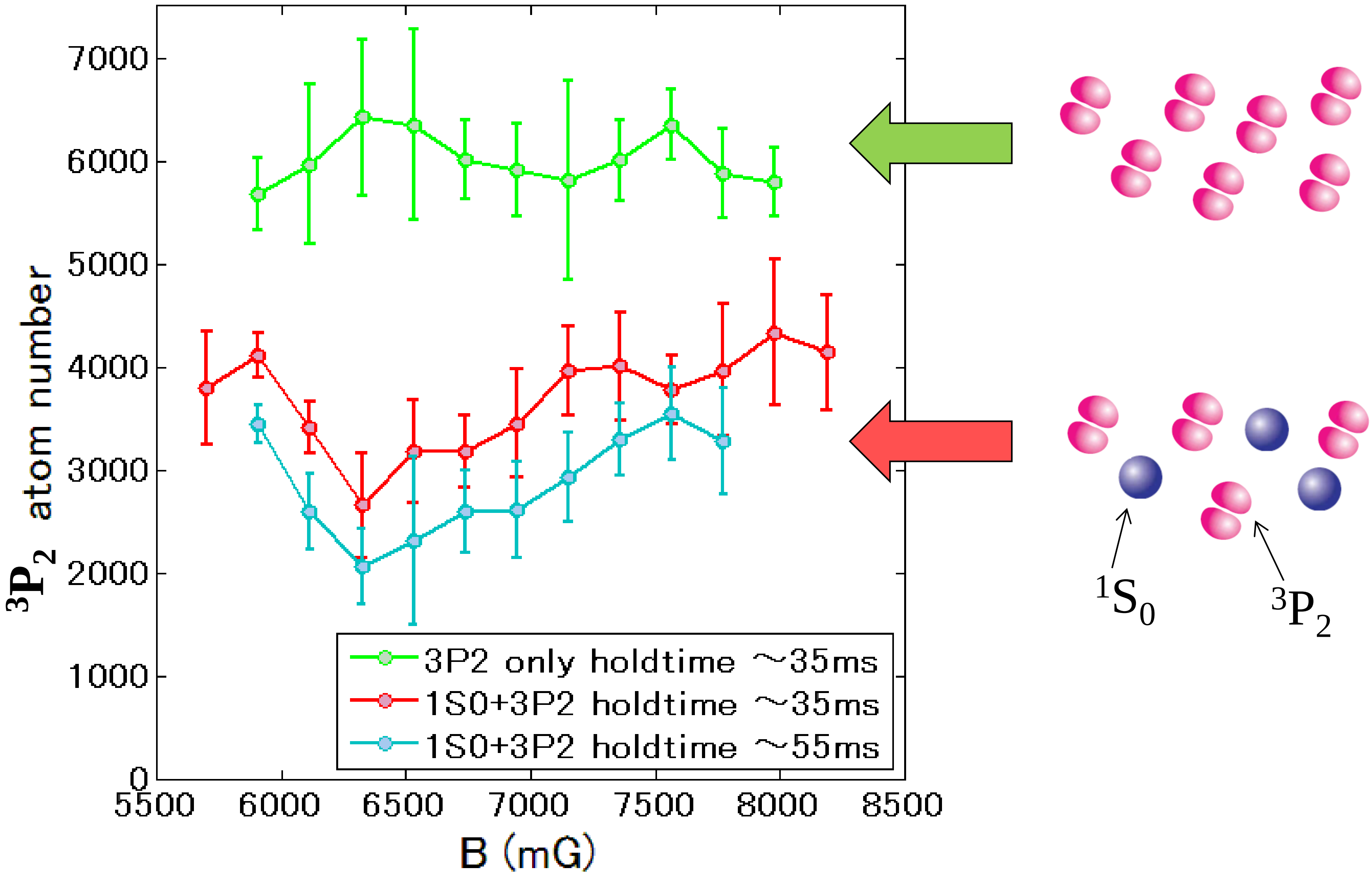




Anisotropy-induced Feshbach Resonance

[A. Petrov, E. Tiesinga, and S. Kotochigova, PRL(2012)]

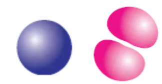
# Magnetic Feshbach Resonance ($^{171}$Yb)

"$^1S_0 \longleftrightarrow {}^3P_2(F=3/2,\ m_F= -3/2)$" :$^{171}$Yb:Fermion



# Various Applications

Cooper Pairing between Different Electronic States;

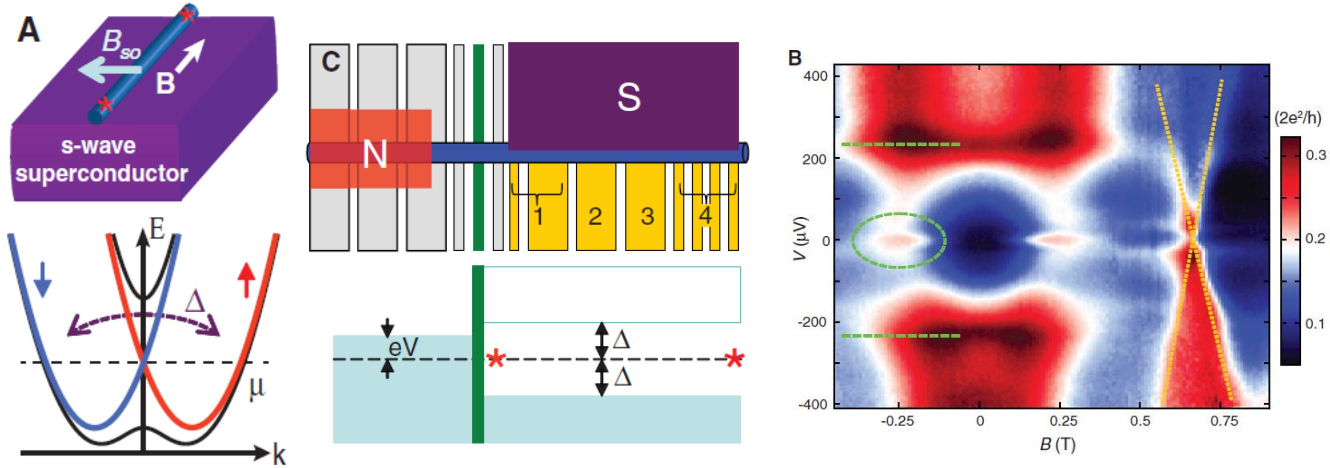
s-state:  :p-state

Topological Superfluids:

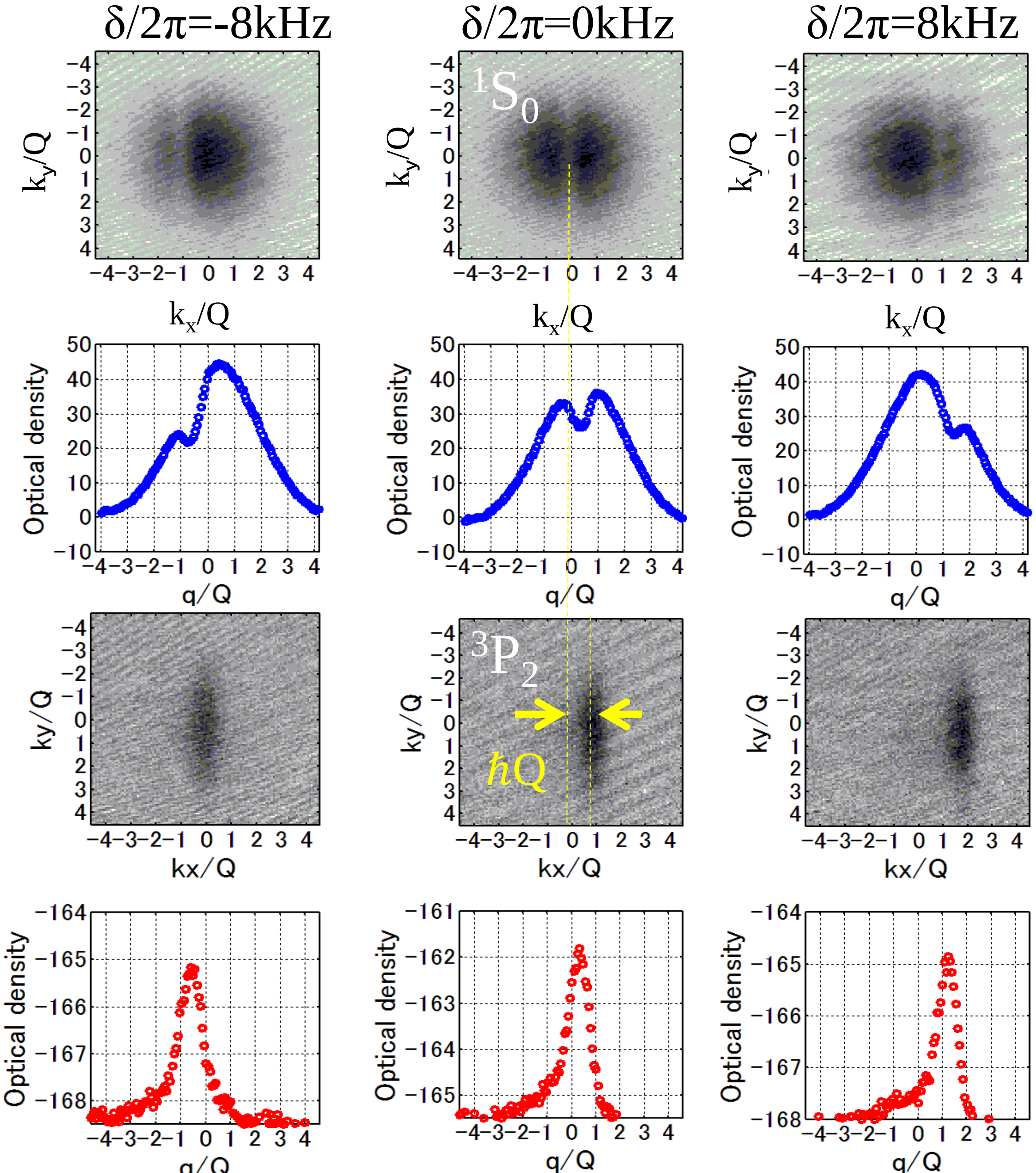
strong s-wave interaction + Spin-Orbit Interaction

**"Non-Abelian Topological Order in s-wave Superfluids of Ultracold Fermionic Atoms"** M. Sato, et al, PRL, **103**, 020401(2009)

**"Signature of Majorana fermions in hybrid superconductor-semiconductor nanowire devices",**
V. Mourik et al., Science(2012)



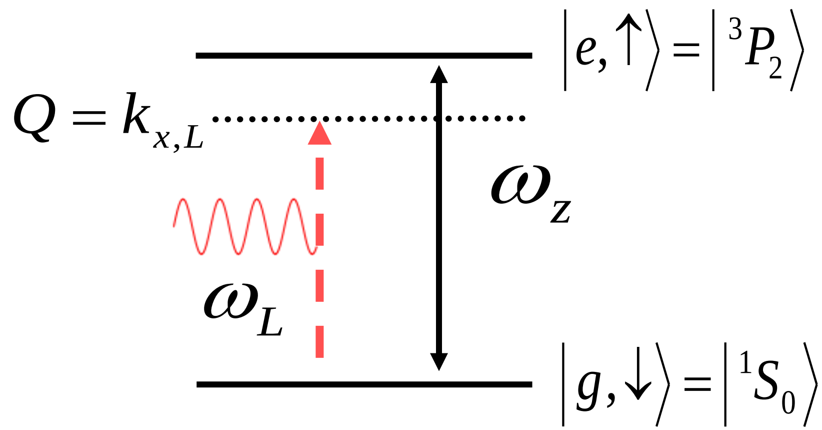
# Implementing Spin-Orbit Interaction between $^1S_0 - {}^3P_2(^{174}Yb)$




$SOI \propto \sigma_y k_x$

"Boson: $^{87}$Rb" "Fermion: $^6$Li, $^{40}$K"

Y. –J. Lin, et al., Nature (2011)
P. Wang et al., PRL (2012),
L. W. Cheuk et al.,PRL(2012)




$$\hat{P}^{(quasi)} \equiv \begin{cases} P_0 - \dfrac{\hbar Q}{2}, |{}^3P_2\rangle \\ P_0 + \dfrac{\hbar Q}{2}, |{}^1S_0\rangle \end{cases}$$

$q = P^{(quasi)}/\hbar$

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## Prospects:

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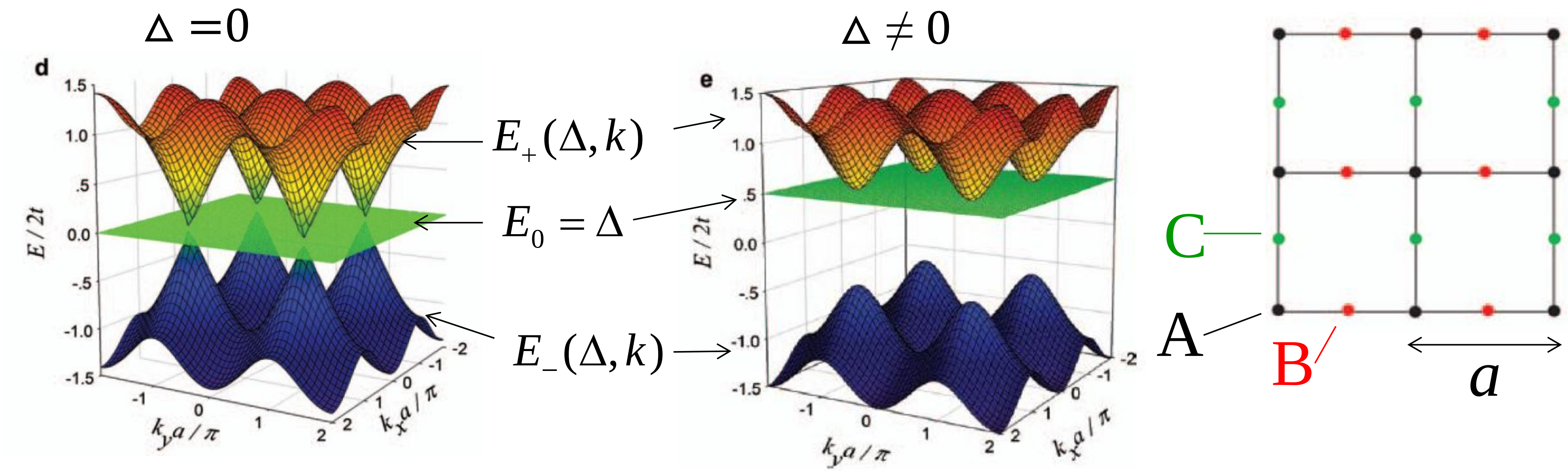
Yb-Li atomic mixture

# “Non-Standard Lattice-Lieb Lattice-”

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

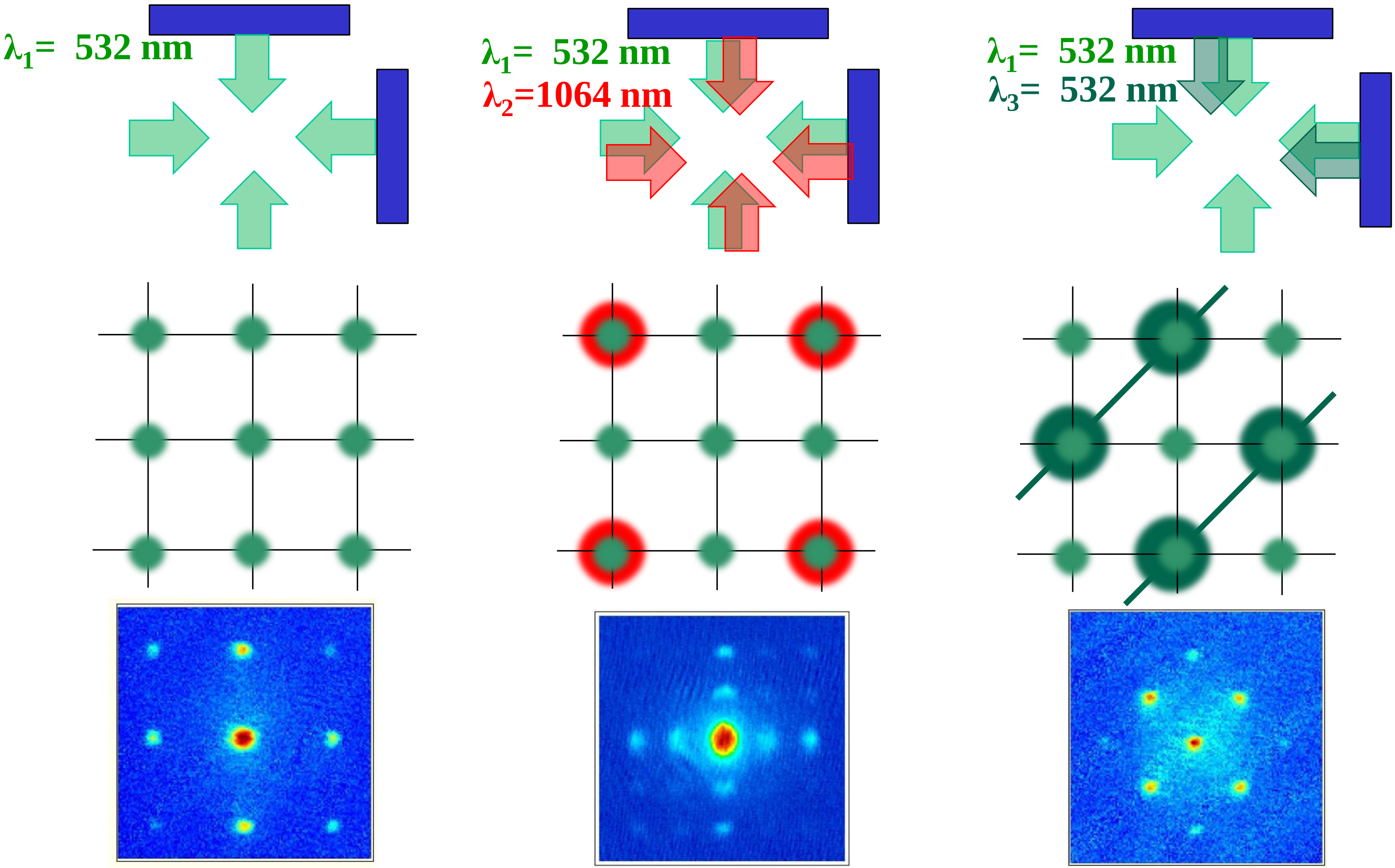



$$E_{\pm} = \pm\sqrt{\Delta^2 + 4t^2\{\cos^2(k_x a/2) + \cos^2(k_y a/2)\}}$$

$$V(x,y) = V_1(\sin^2 k^L x + \sin^2 k^L y + \sin^2 2k^L x + \sin^2 2k^L y) + V_2\left(\sin^2\left[k^L(x+y) + \frac{\pi}{2}\right] + \sin^2\left[k^L(x-y) + \frac{\pi}{2}\right]\right)$$

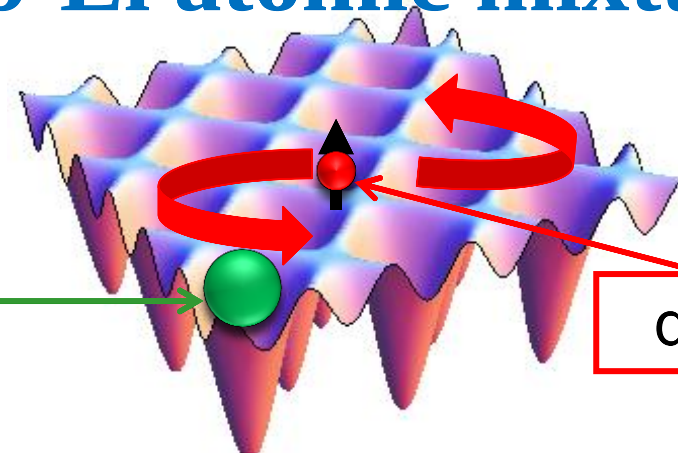
“proposal for optical lattice implementation” R. Shen et al., PRB**81**, 041410(R),2010

# Towards Lieb-Lattice



# Simulation of Impurity System with Yb-Li atomic mixture

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



localized impurity

Yb

Li

delocalized carrier

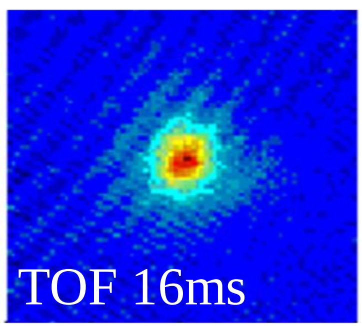
***Anderson Hubbard Model***

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

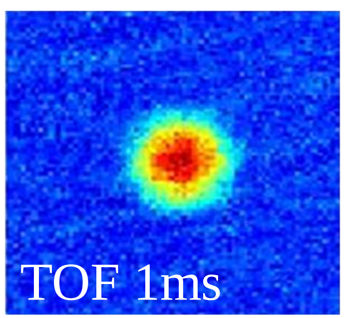
"Random Potential"

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

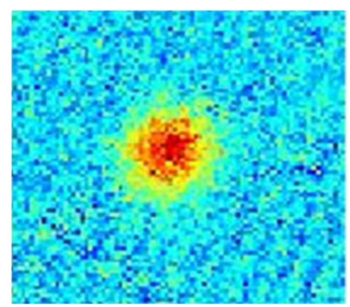
$^{174}$Yb:BEC



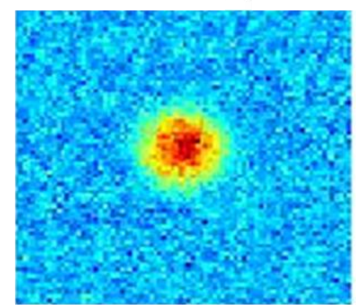

$^{6}$Li:$T/T_F$=0.08




$^{174}$Yb:$T/T_F$=0.52



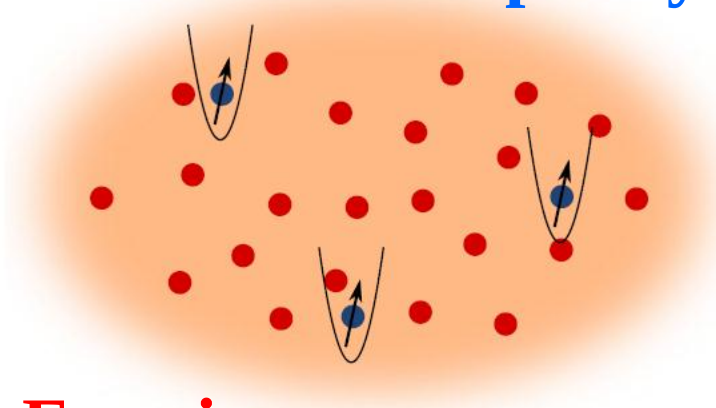
$^{6}$Li:$T/T_F$=0.07



[H. Hara *et al.* ,PRL **106**, 205304, (2011)]

# *Application to* Anderson Orthogonality Catastrophe

[M, Knap, *et al.*, *Physical Review X.* **2,** 041020 (2012)]

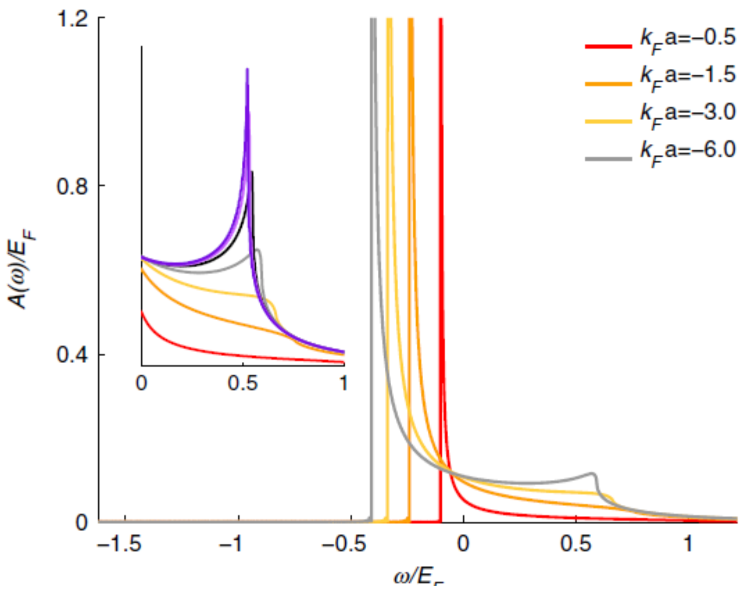



$$S(t) = \langle \psi_0 | e^{i\hat{H}_i t/\hbar} e^{-i\hat{H}_f t/\hbar} | \psi_0 \rangle$$

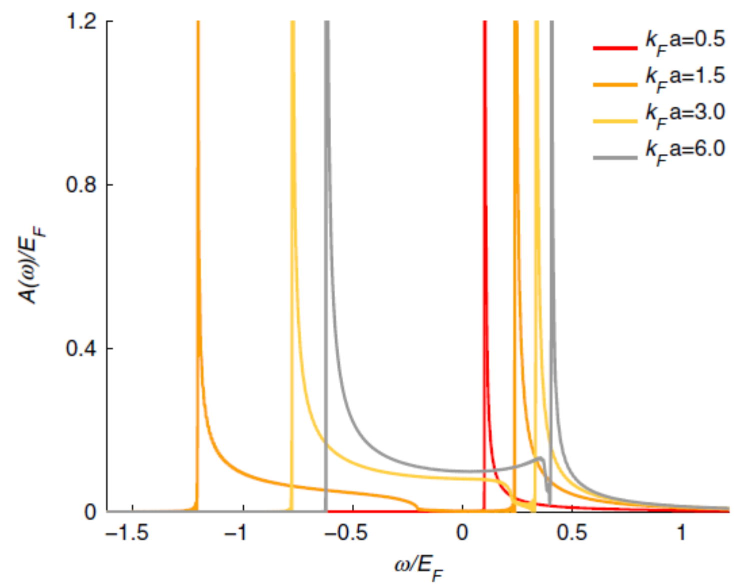
$$= \langle \psi_i | \psi_f \rangle = N^{-(\sin(\delta))^2/(3\pi^2)} \longrightarrow 0$$

[P. W. Anderson, *PRL* **18,** 1049 (1967)]

## Attractive Interaction




## Repulsive Interaction



# Summary

## Quantum Simulation of Strongly-Correlated States

*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

Yb-Li atomic mixture

## Precision Measurement:

***quantum feedback control of atomic spin ensemble***

[R. Inoue et al, arXiv:quant-ph 1301.1016v2 PRL accepted]

***test of gravity at short range with photo-association spectroscopy***

# *Thank you very much for attention*

16 August Mount Daimonji at Kyoto