First Program & Quantum Cybernetics

15 December 2011 Kyoto

Development of Optical Lattice Quantum Simulator

Kyoto University, JST

Y. Takahashi

First Program :
Analogue Quantum Computer/Quantum Simulation

Kyoto Group : ultracold atoms in optical lattice

Osaka Group : cold ions in ion-traps

Tokyo Group : exciton(-polaritons) in semiconductors

Quantum Cybernetics : Quantum Control of Cold Atoms

Kyoto Group : ultracold atoms in OL

NTT(Mukai) Group : cold atoms in atom chips

Gakushuin Group : BEC in optical trap

Kyoto Group:

Quantum Simulation of Hubbard Model

This presentation

Poster by Dr. Yamazaki

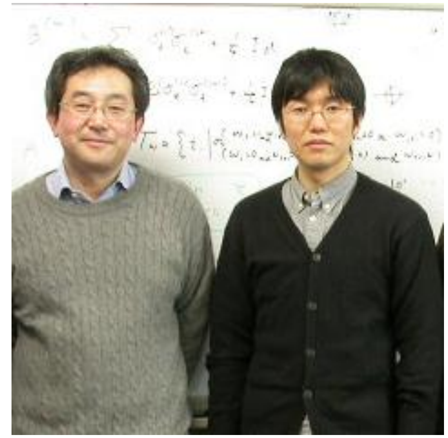
Poster by Mr. Taie

Quantum Feedback Control

Poster by Dr. Inoue

Collaborators

Optical Lattice:



NTT:
K. Inaba
M.Yamashita

Geneva:
A. Tokuno, T. Girmarchi

Ben Li, Y. Nakamura, R. Yamazaki, S. Sugawa, YT, Y. Takasu, R. Inoue,
H. Shimizu, S. Nakajima, S. Uetake, Y. Yoshikawa, H. Hara, (S. Kato, K. Takahashi)
H. Konishi, Y. Kikuchi, H. Yamada, R. Yamamoto, S. Taie, R. Namiki, K. Shibata,
(Undergraduate: K. Nishimura, T. Nishio, T. Seki, S. Watanabe)

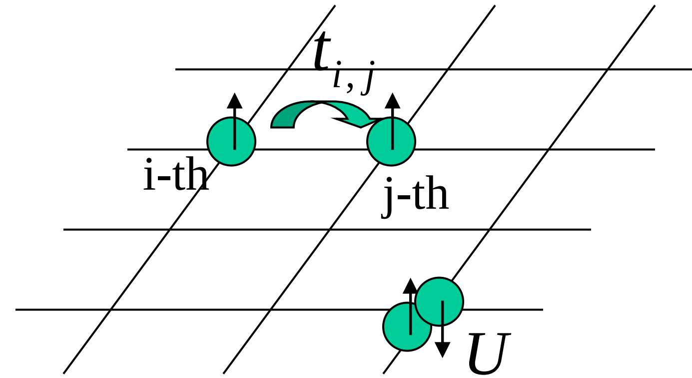
Outline of Talk

- **Quantum Simulation of Hubbard Model**
  - ***Realization of SU(6) Mott Insulator***
  - ***High-Resolution Spectroscopy***
- **Prospects**

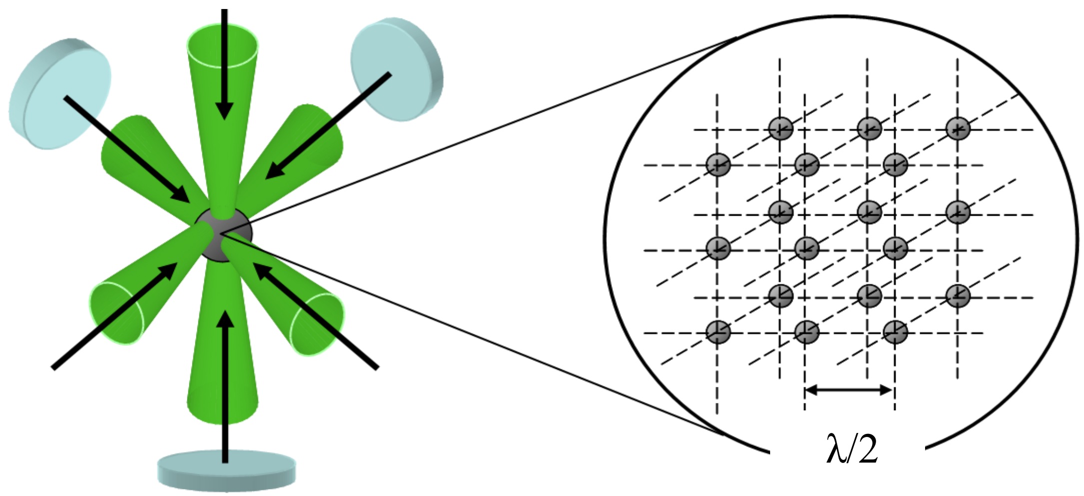
Quantum Simulation

Hubbard Model:

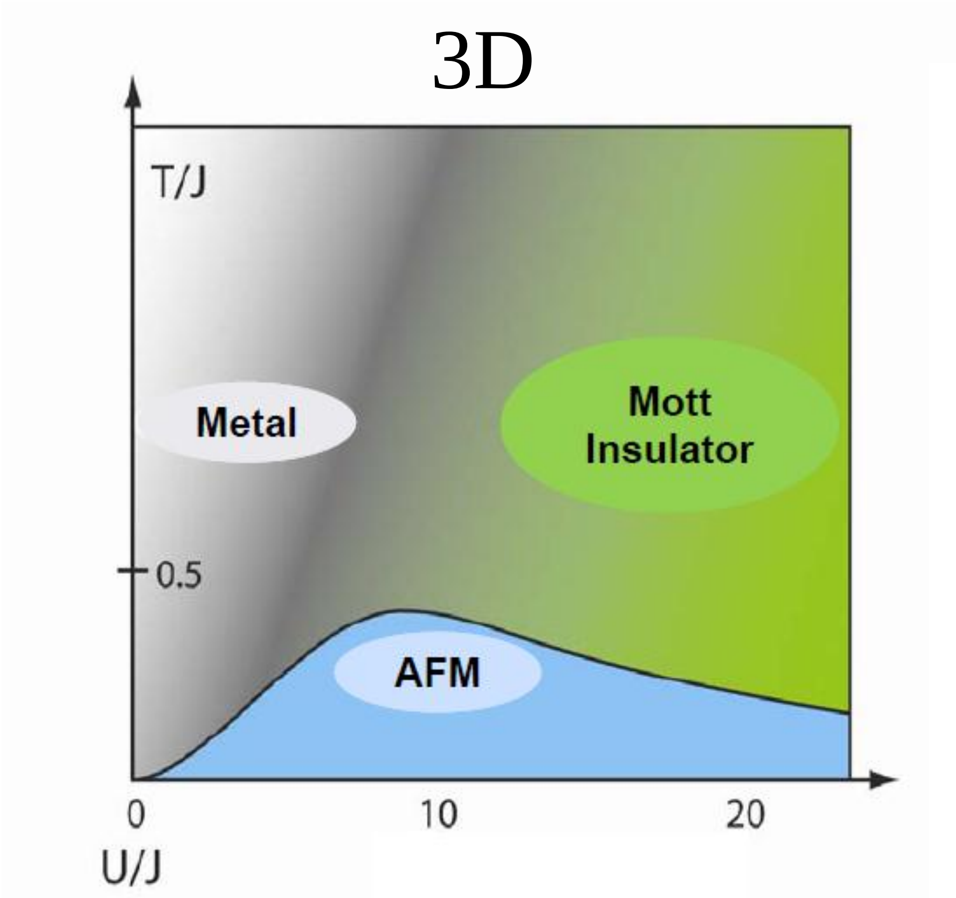
$$H = -J \sum_{<i,j>} c_i^+ c_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

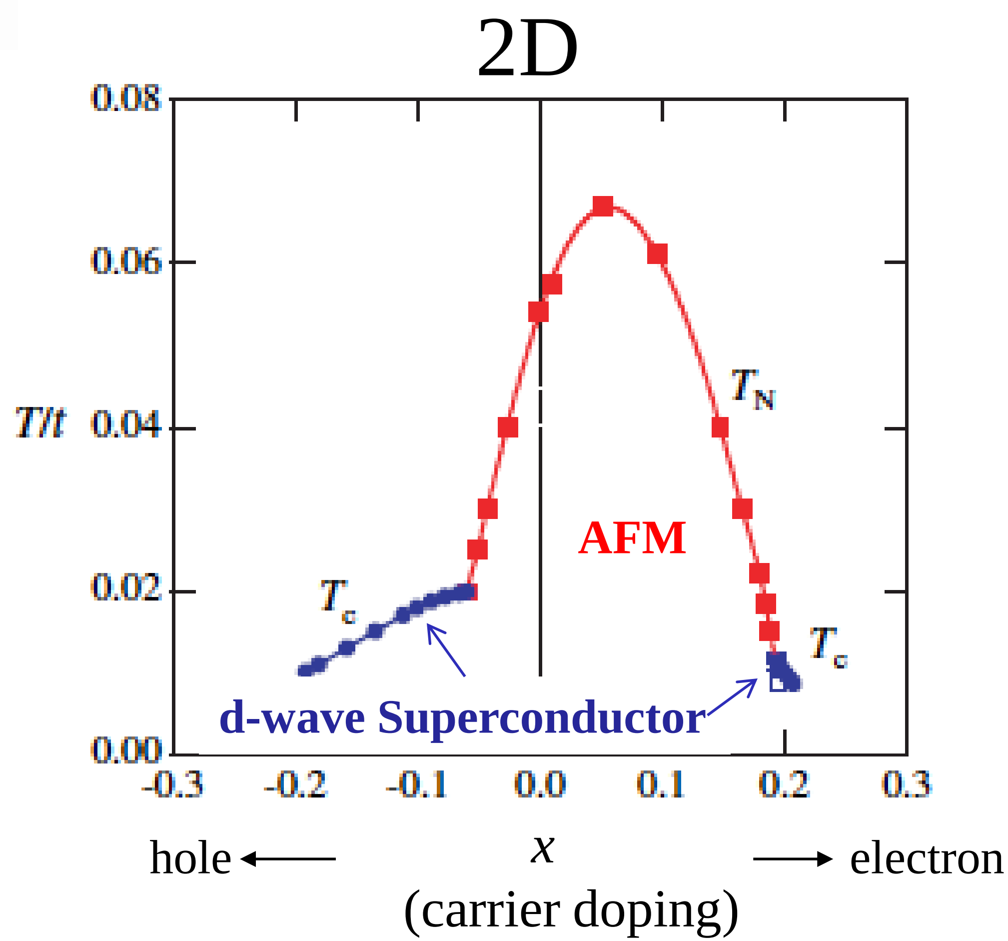


→ Cold Atoms in Optical Lattice



Phase Diagram of Repulsive Fermi Hubbard Model





[T. Esslinger, Annu. Rev. Condens. Matter Phys. 2010. 1:129-152]

[T. Moriya and K. Ueda, Rep. Prog.Phys. 66(2003)1299]

Beyond SU(2) Physics: Extension to Larger Spin Degrees of Freedom

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

SU(N) algebra:

spin permutation operators (generators of SU(N) rotations)

$$S_n^m = c_n^+ c_m \qquad [S_n^m, S_q^p] = \delta_{mq} S_n^p - \delta_{pn} S_q^m$$

$$\longrightarrow \qquad [H_{\text{int}}, S_n^m] = 0$$

Physics of large-spin Fermi gas:

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, …

^{173}Yb: +5/2 +3/2 +1/2 -1/2 -3/2 -5/2

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

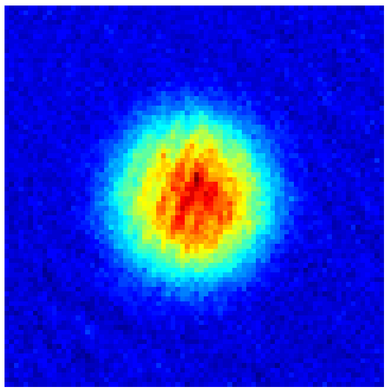
SU(6) Fermion :Realized

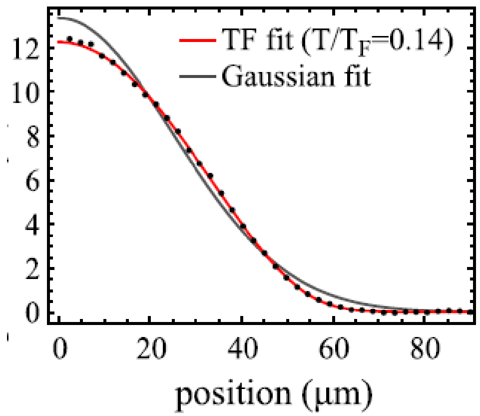
The first quantum gas with SU(N>2) symmetry

^{173}Yb:SU(6)

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

+5/2 +3/2 +1/2 -1/2 -3/2 -5/2

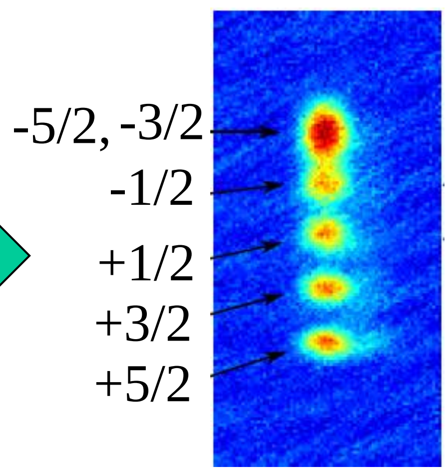




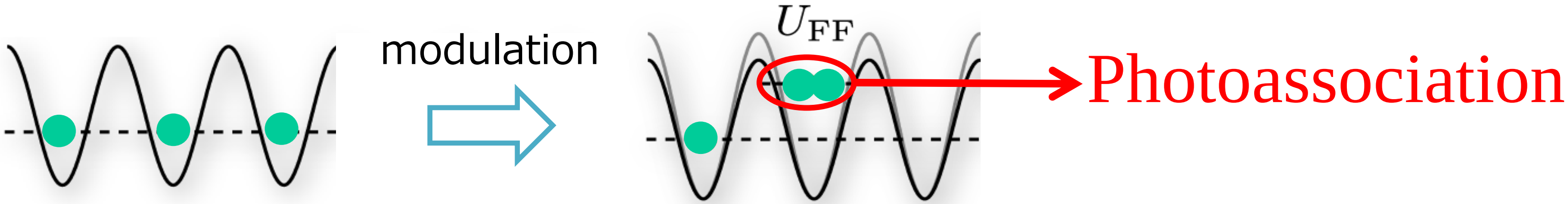
T/T_F =0.14
(6-component)

Optical Stern-Gerlach Spin-Separator

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



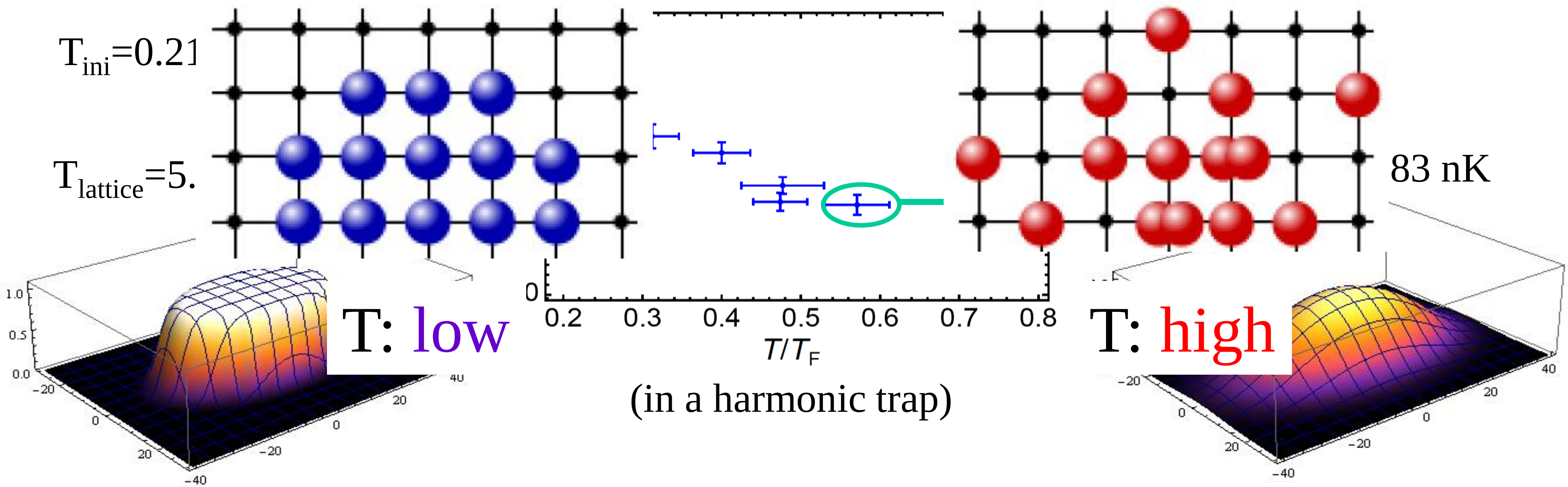
Doublon Production Rate Measurement by lattice modulation



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

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

N=1.9× 10^4, $11E_R$, 18%pp mod. U/J=62.4



Spin Degrees of Freedom *is Cool*

Pomeranchuk Cooling

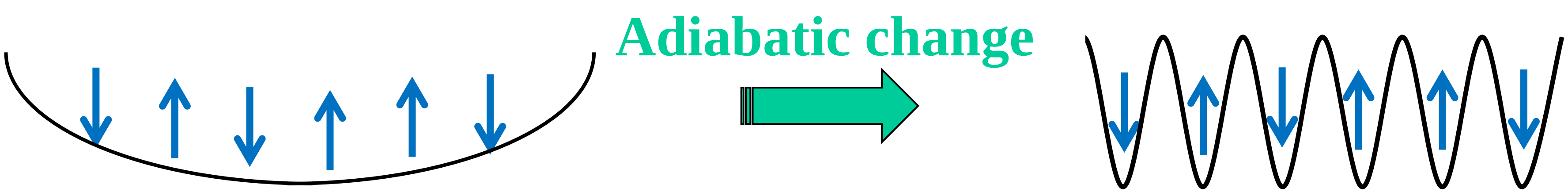
[Pomeranchuk, (1950)]

→ Discovery of Superfluid ^{3}He by Osheroff, Lee, Richardson

→ "Pomeranchuk Cooling of an Atomic Gas"

Initial state: Spin *de*polarized and also with *degeneracy*:

Final state: Spin *de*polarized and also with *localization*



$s \sim k_B \pi^2 T/T_F$

liquid ^{3}He atoms in a trap

$s \sim k_B \ln(N)$

solid ^{3}He atoms in Mott Insulator

"entropy flows from **motional** degrees of freedom to **spin**, which results in the low temperature"

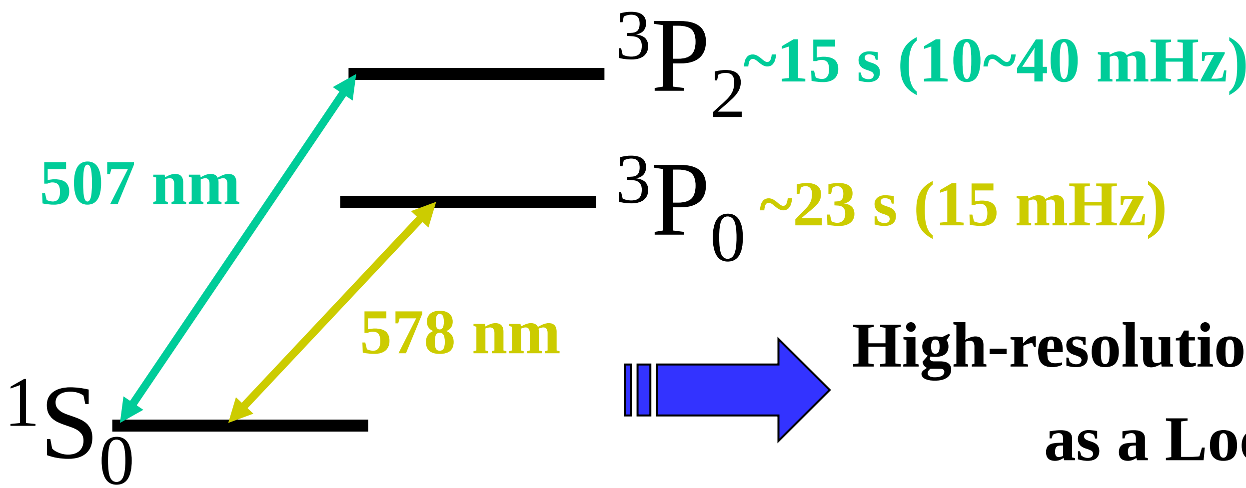
Next Step: If $T/T_F = 0.14$ then $s_{ini} \sim k_B \pi^2 T/T_F < s_{fin} \sim k_B \ln(N)$

Outline of Talk

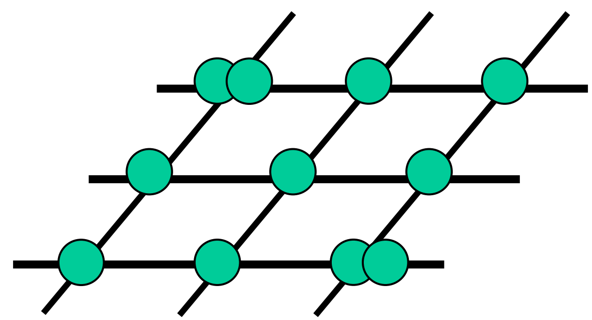
- **Quantum Simulation of Hubbard Model**
  - ***Realization of SU(6) Mott Insulator***
  - ***High-resolution spectroscopy***
- **Prospects**

New Possibility:
High-Resolution Laser Spectroscopy of Strongly Correlated Quantum Many-body System

Ultra-narrow Optical Transitions in Yb

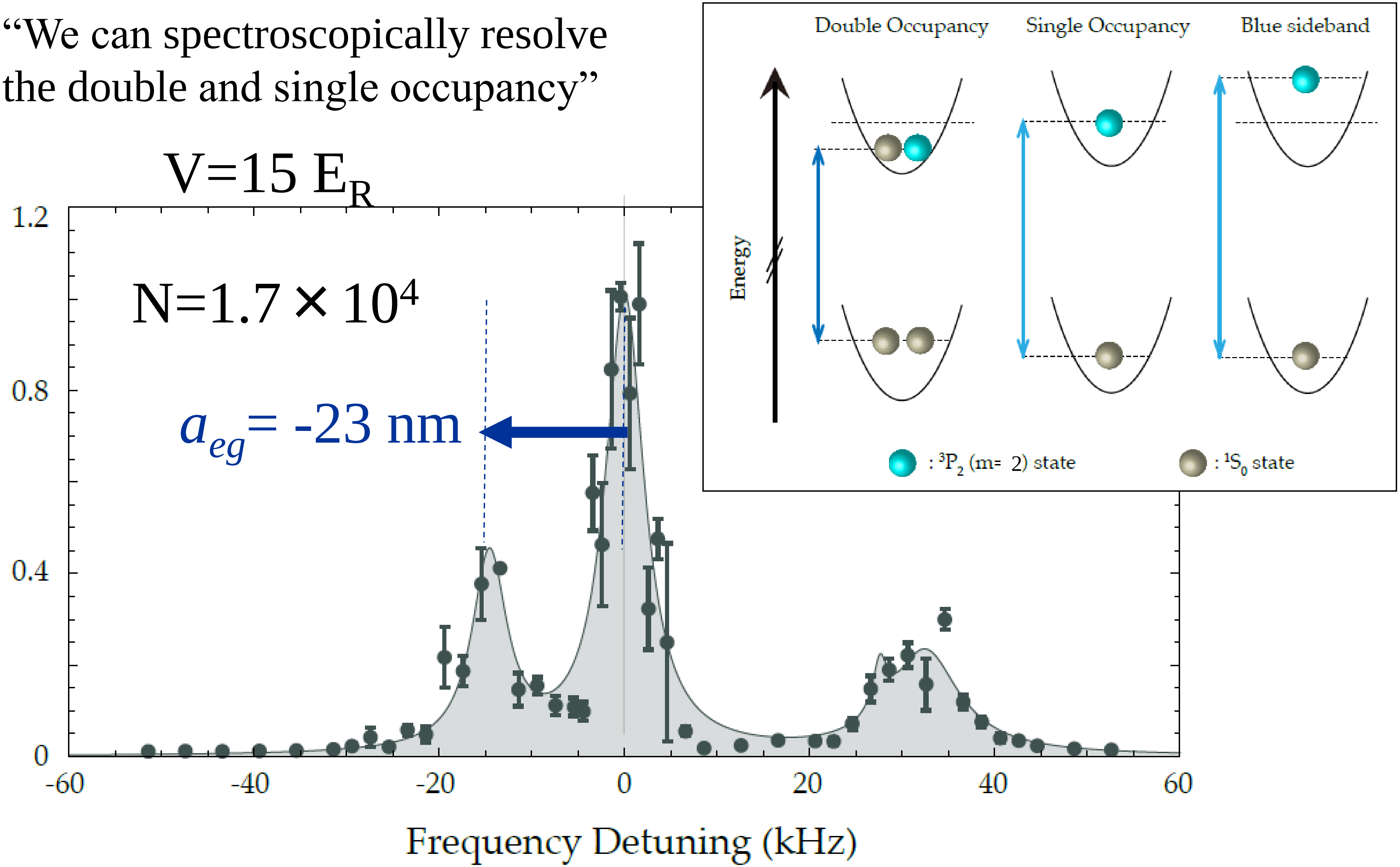


High-resolution laser spectroscopy as a Local Probe



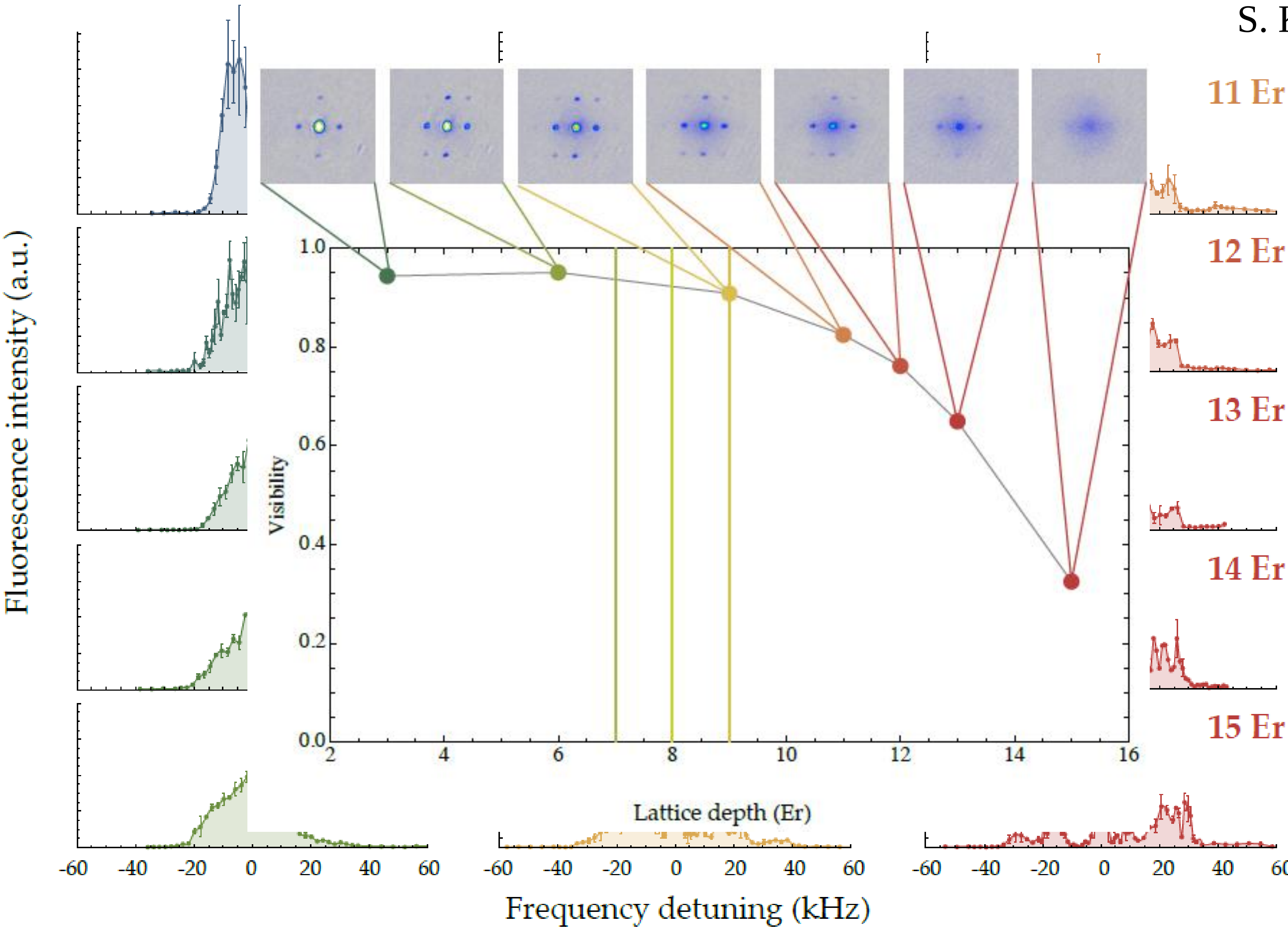
Spectroscopy of Atoms in a Mott Insulating State

"We can spectroscopically resolve the double and single occupancy"

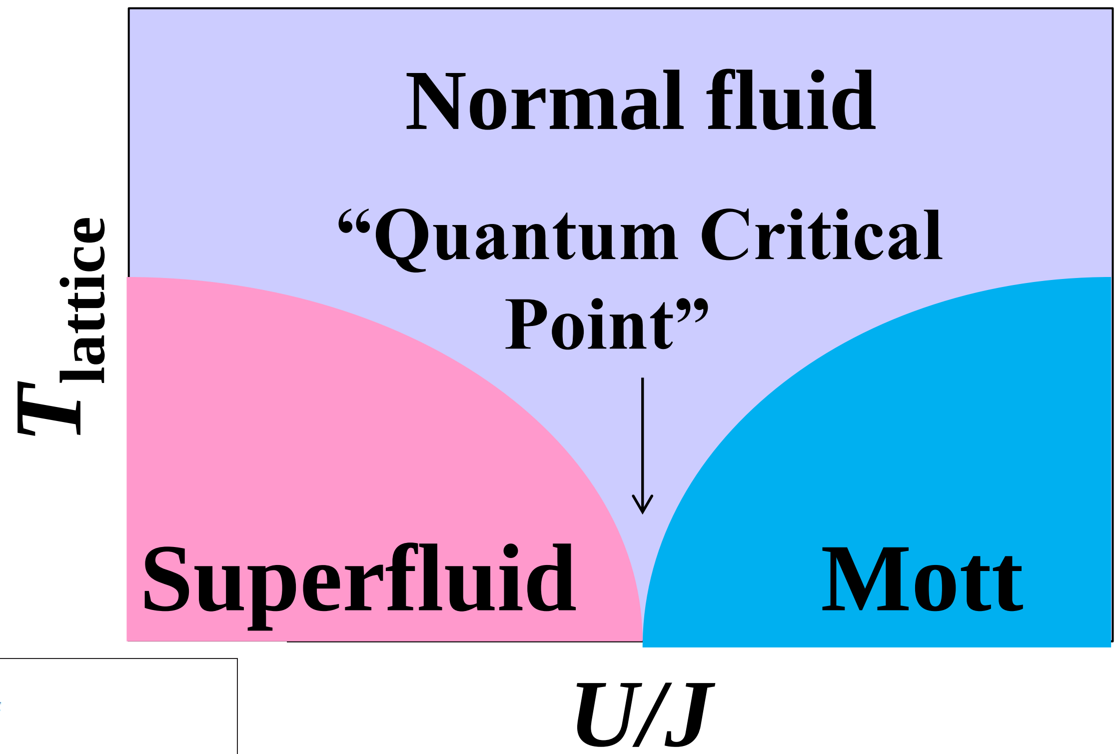


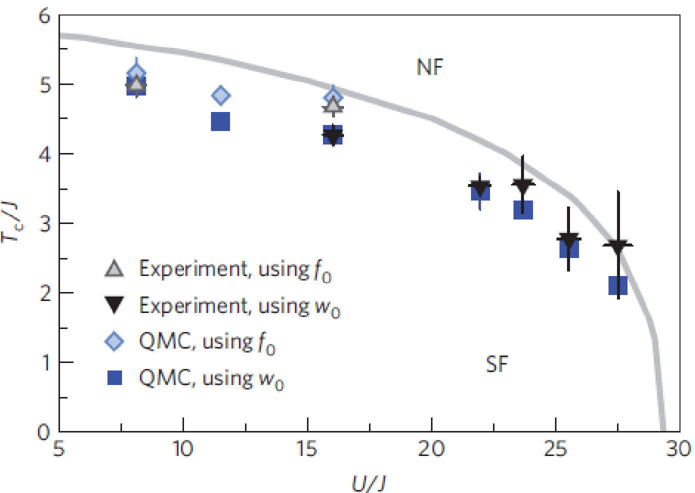
Superfluid-Mott Insulator Transition

S. Kato *et al*



Phase Diagram of Bose Gas (homogeneous)





[S. Trotzky et al., Nature Physics, **6**, 998(2010)]

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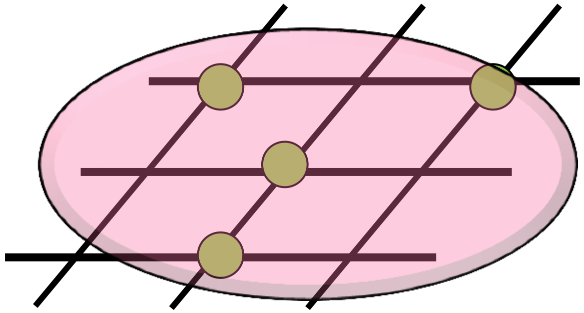
Prospects: Simulation of Impurity in Superfluid

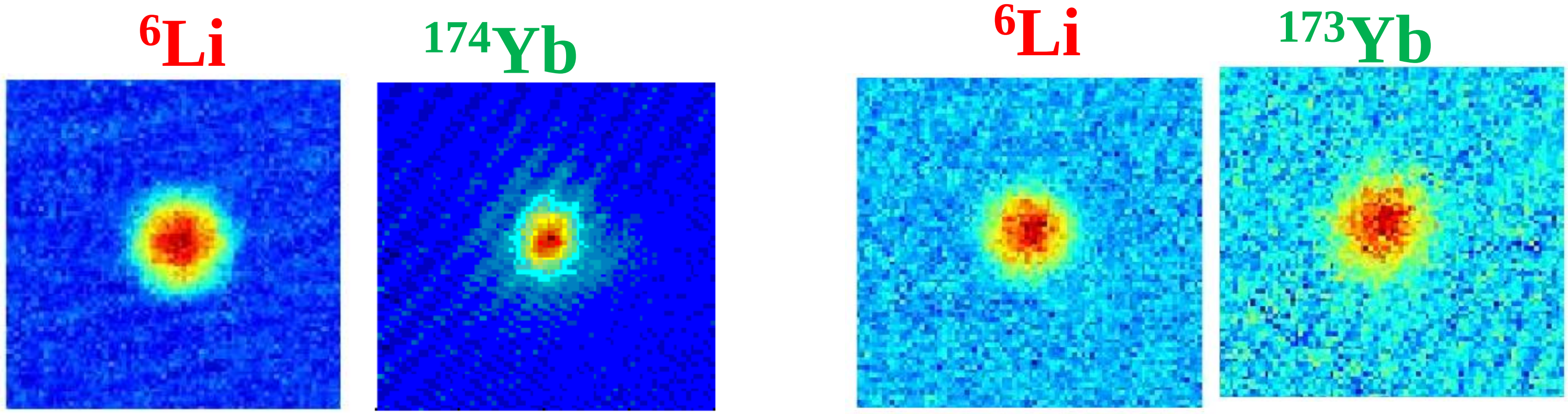


[F. M.Spiegelhalder,*et a*l, PR L(2009). K. Targonska and K. Sacha, PR A(2010) R. B. Diener and M. Randeria,PRA(2010) E. Vernier, *et al*, arXiv(2010).]

“Anderson Localization” **T_c vs Impurities**

Poster by Dr. Nakajima

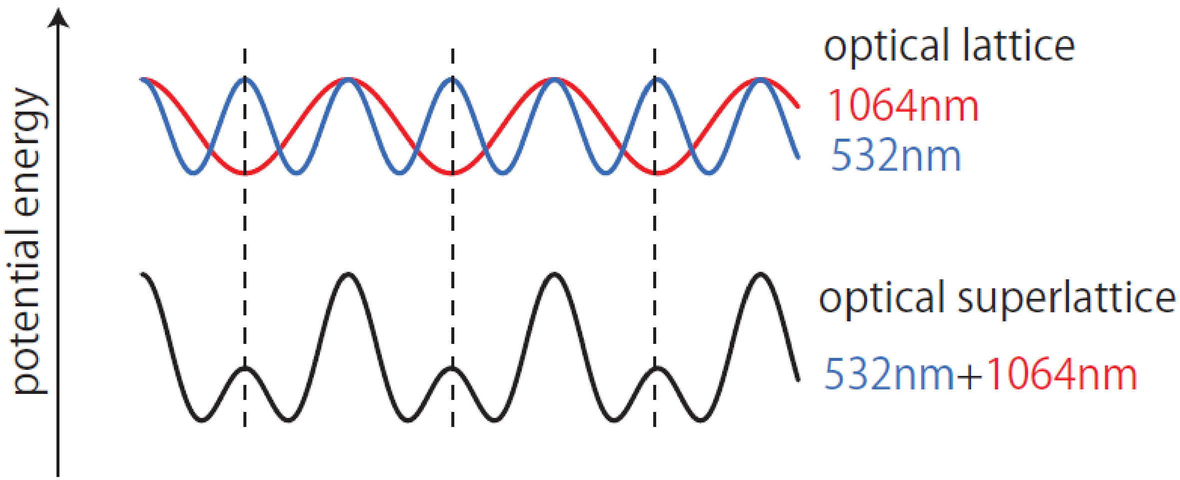
Heavy Impurity (Yb) in a Superfluid (Li) “$M_{Yb}/M_{li} \sim 29$”

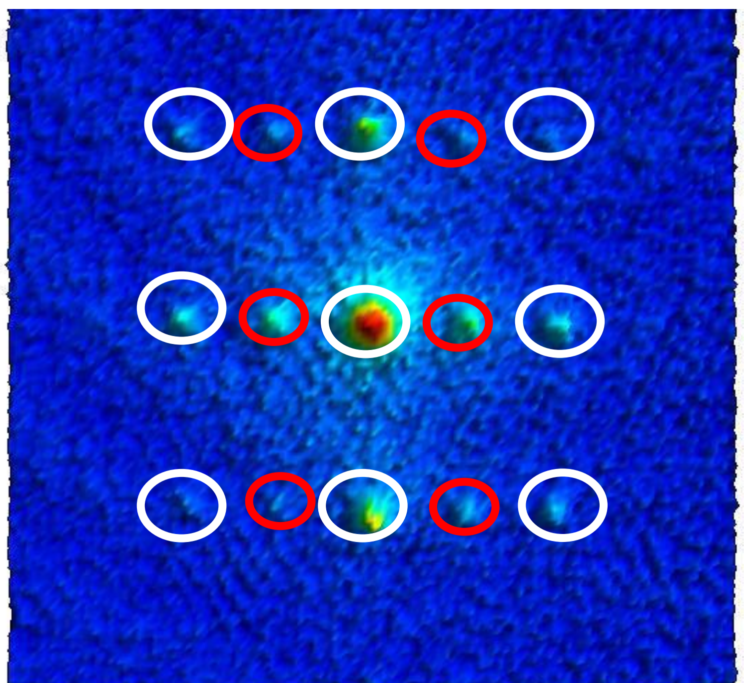


$T/T_F = 0.08 \pm 0.02$ **$T = 280 \pm 20$ nK** **$T/T_F = 0.07 \pm 0.02$** **$T/T_F = 0.52 \pm 0.12$**

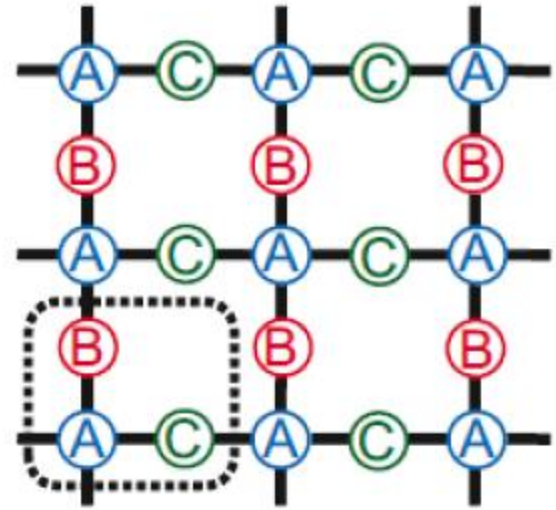
[H. Hara *et al.*, Phys. Rev. Letters **106**, 205304 (2011):Editor’s Suggestion]

Prospects: Super-Lattice





^{174}Yb BEC
N=8 × 10^{4}



"decorated square lattice"
[PRA**80**, 063622(2009)]

"dp model"

Summary

- **Quantum Simulation of Hubbard Model**

  — ***Realization of SU(6) Mott Insulator***

  Demonstration of New Atom Cooling :Pomeranchuk Cooling
  Starting Point Towards SU(6) Quantum Magnetism

  — ***High-resolution spectroscopy***

  Possible New Probe of Quantum Critical Behaviors

- **Prospects**

  Yb-Li Quantum Mixture : Simulation of Impurity problem
  Super-Lattice