益川塾セミナー

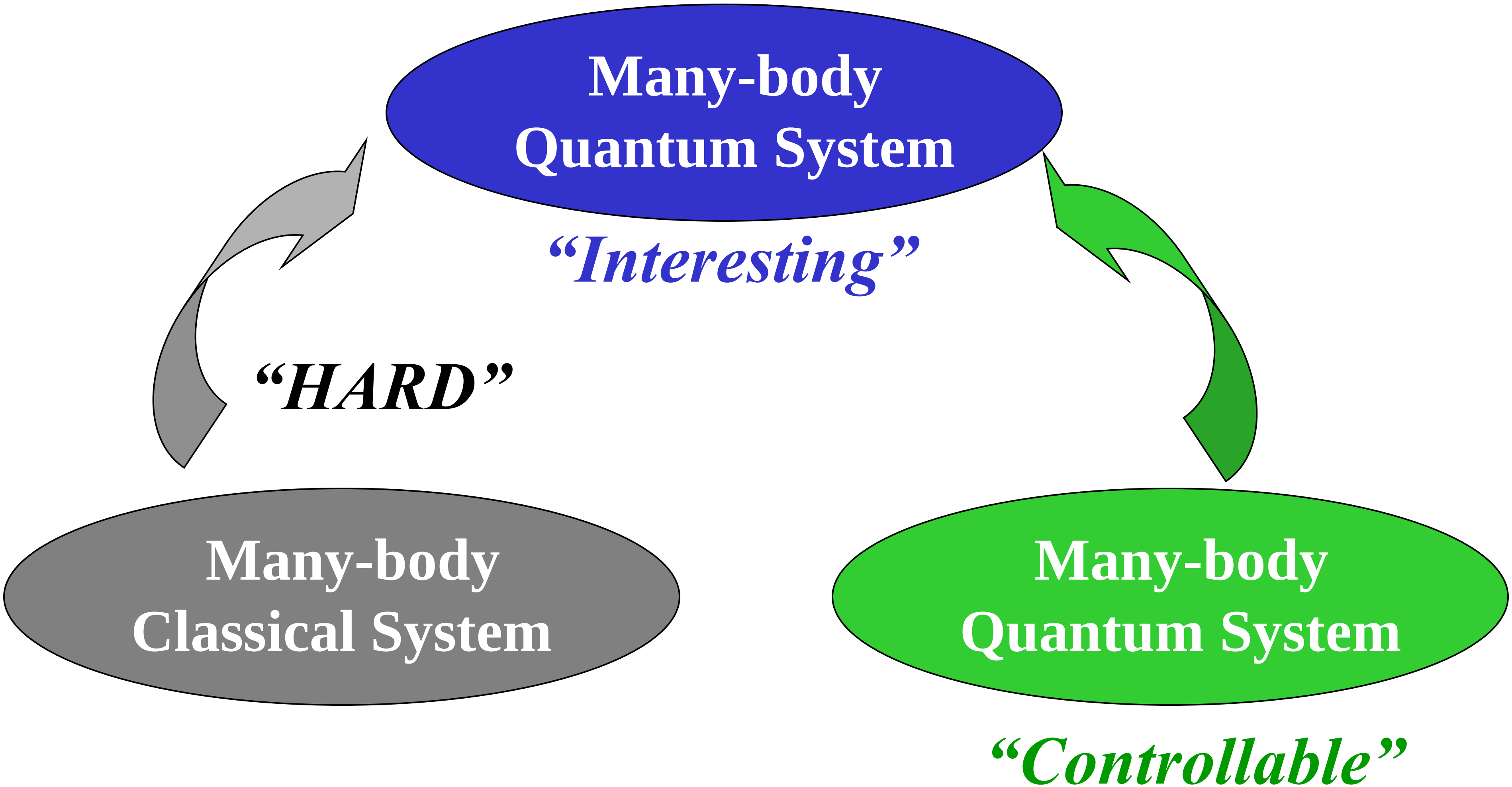
14 July 2012, 京都産業大学

超低温原子気体の精密量子制御:
強相関量子多体系の量子シミュレーションと基礎物理学への応用

Kyoto University, JST

Y. Takahashi

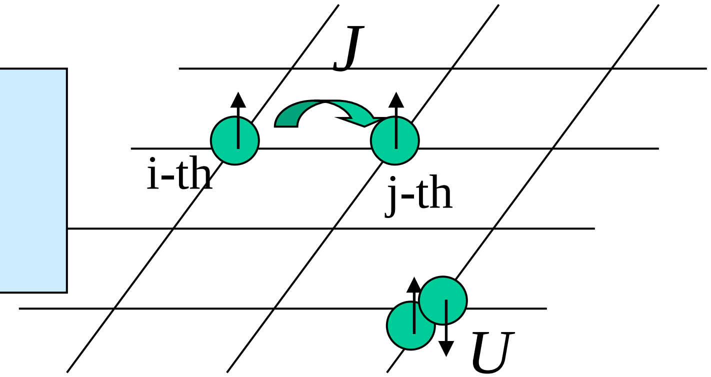
Quantum Simulation



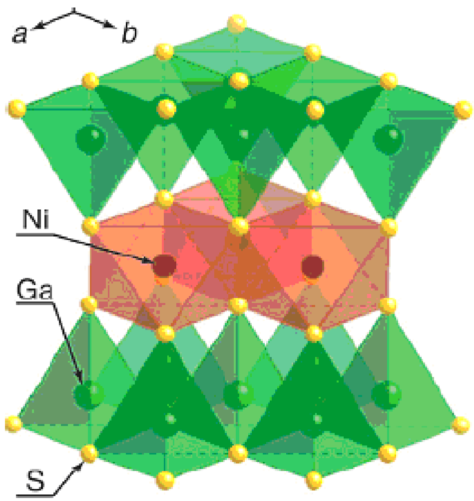
Quantum Simulation

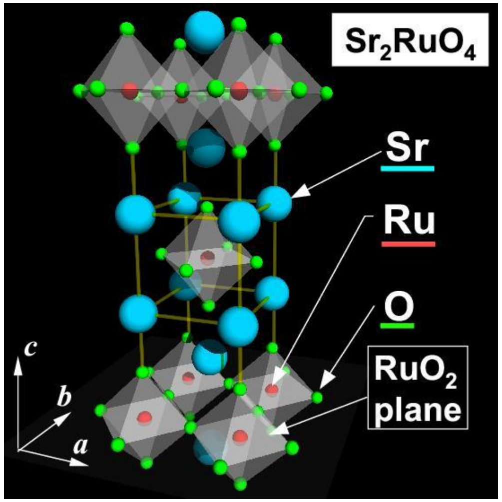
Hubbard Model:

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



→ Magnetism, Superconductivity





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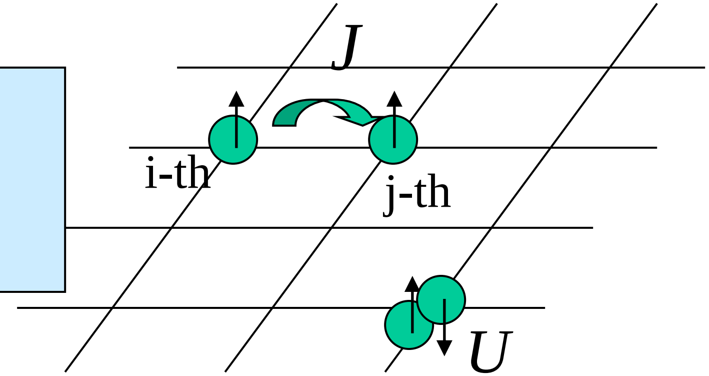


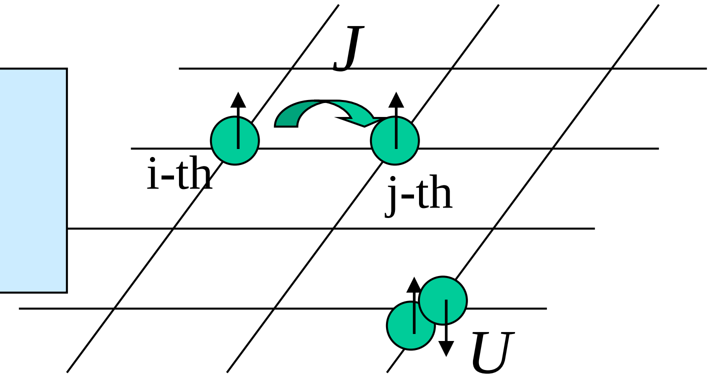
→ Numerical Calculation

DMFT(動的平均場)
Gutzwiller
QMC(量子モンテカルロ)
DMRG(密度行列繰り込み群)
Exact Diagonalization (厳密対角化)

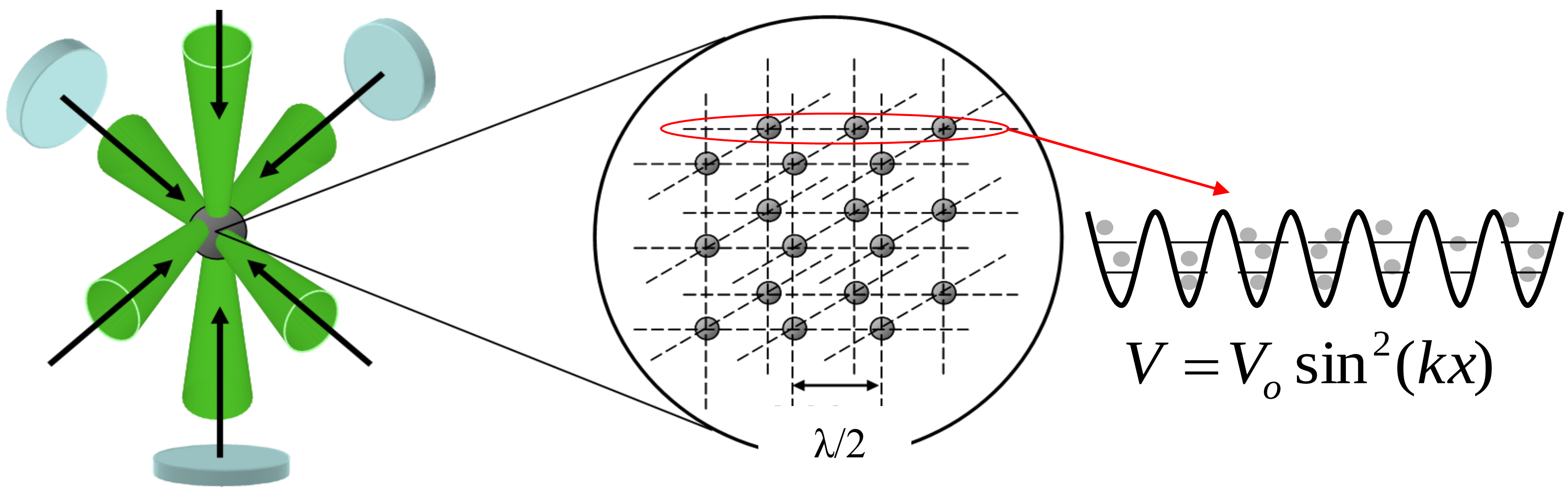
Quantum Simulation

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



Outline

Atom Manipulation Technique

Laser Cooling and Trapping

Optical Lattice

Tuning Interatomic Interaction

Quantum Simulation of Hubbard Model Using Alkali Atoms in an Optical Lattice

1)Bose-Hubbard Model

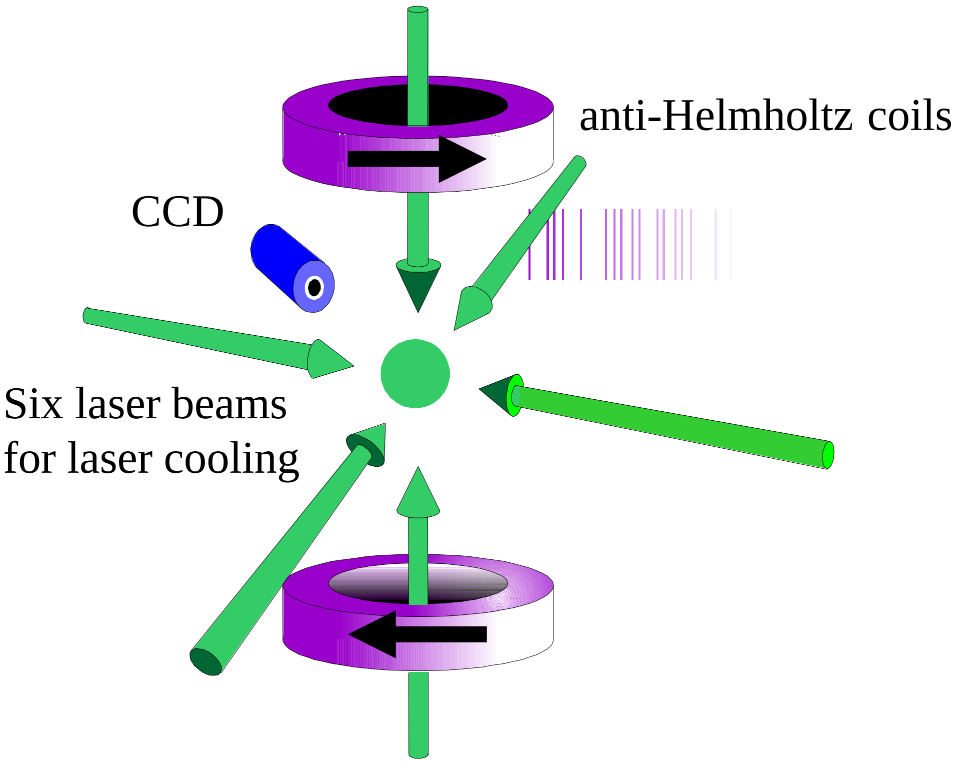
Superfluid-Mott Insulator Transition

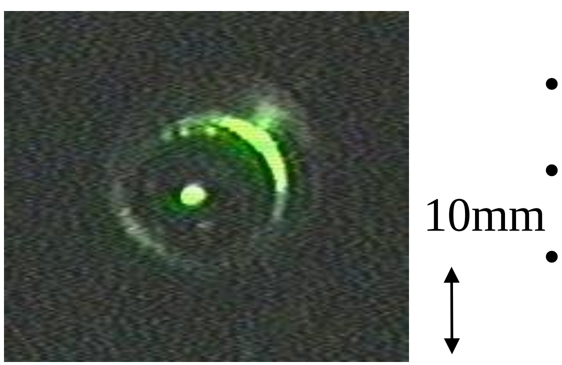
Quantum Gas Microscope

2)Fermi-Hubbard Model

Mott insulator

Laser Cooling and Trapping



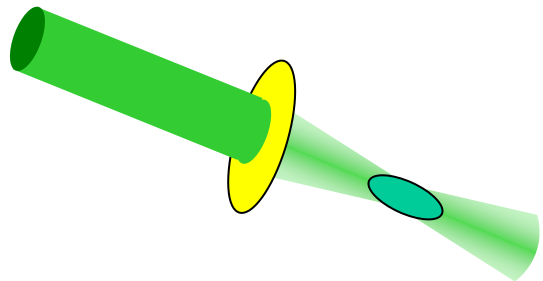


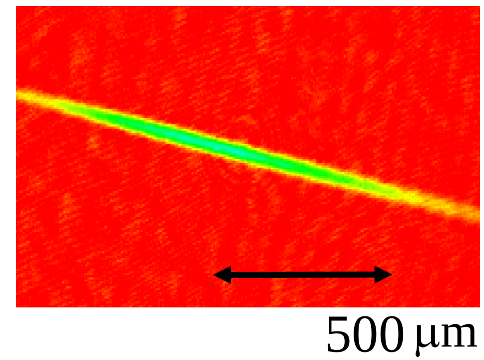
- Number: 10^7
- Density: $10^{11}/\text{cm}^3$
- Temperature: 10μK

"Magneto-optical Trap"

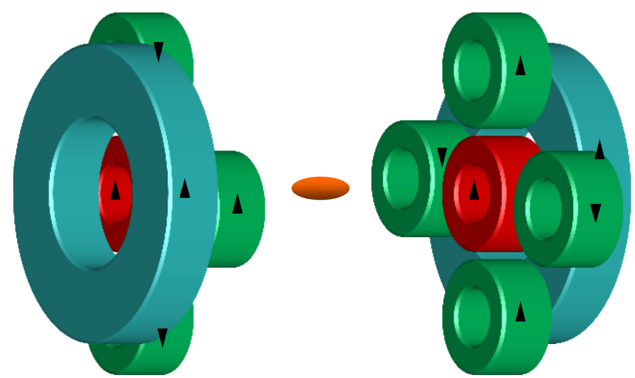
"optical trap"

$$V_{\text{int}} = -p \cdot E \qquad U_{pot}(r) = -\frac{\chi E(r)^2}{2}$$

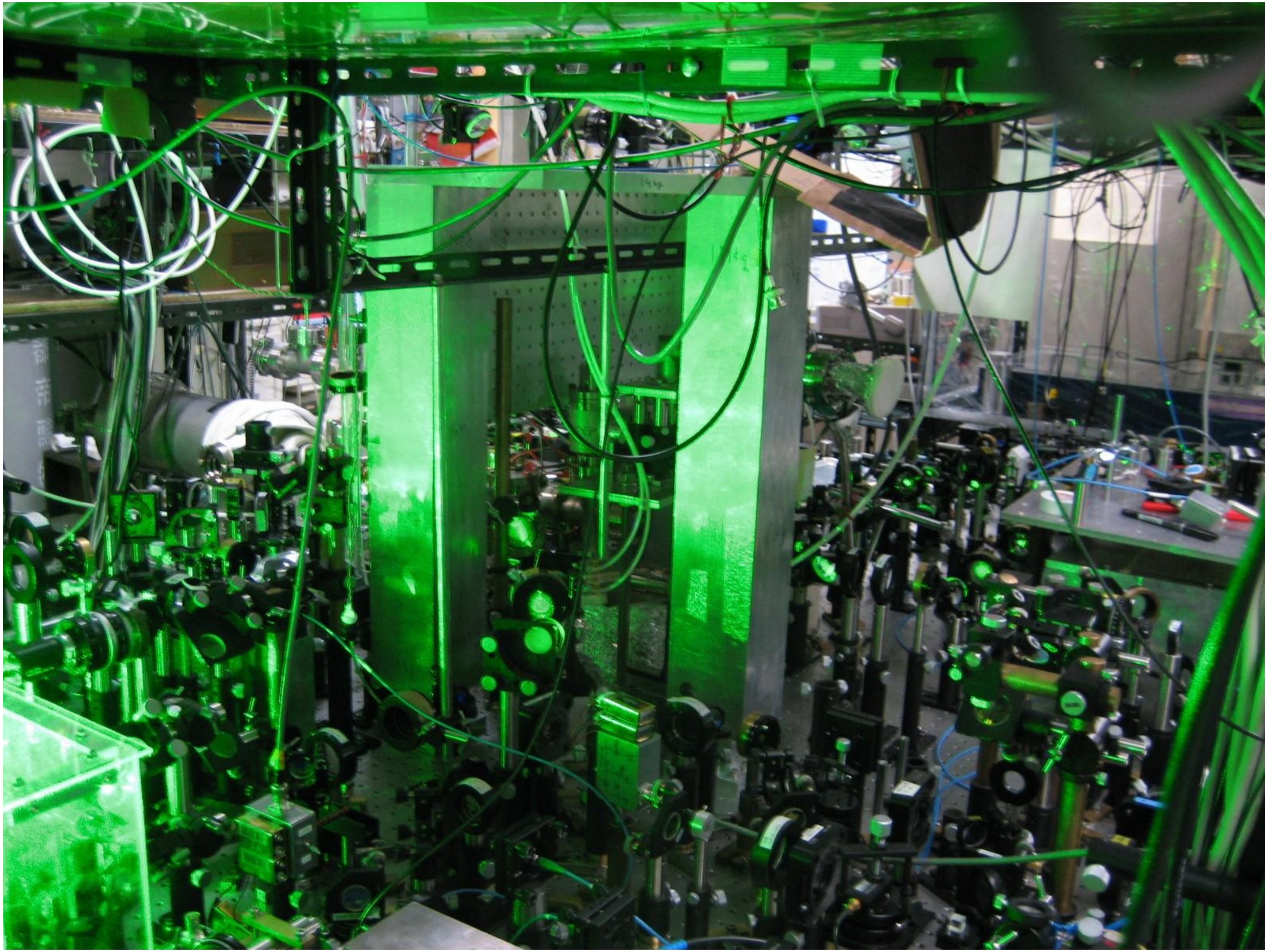




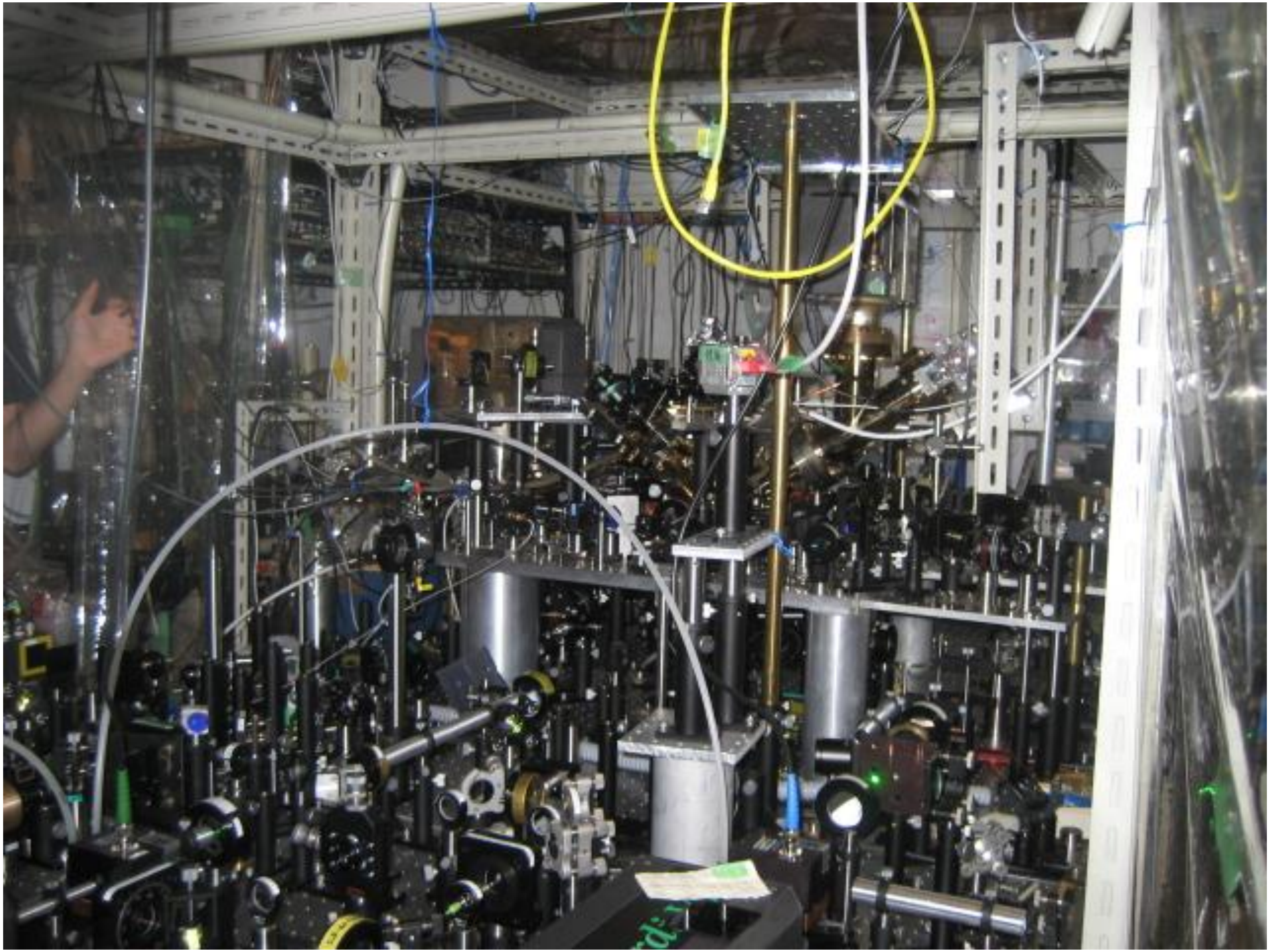
"magnetic trap" $V_{\text{int}} = -\mu \cdot B$



Experimental Setup for Cold Atom

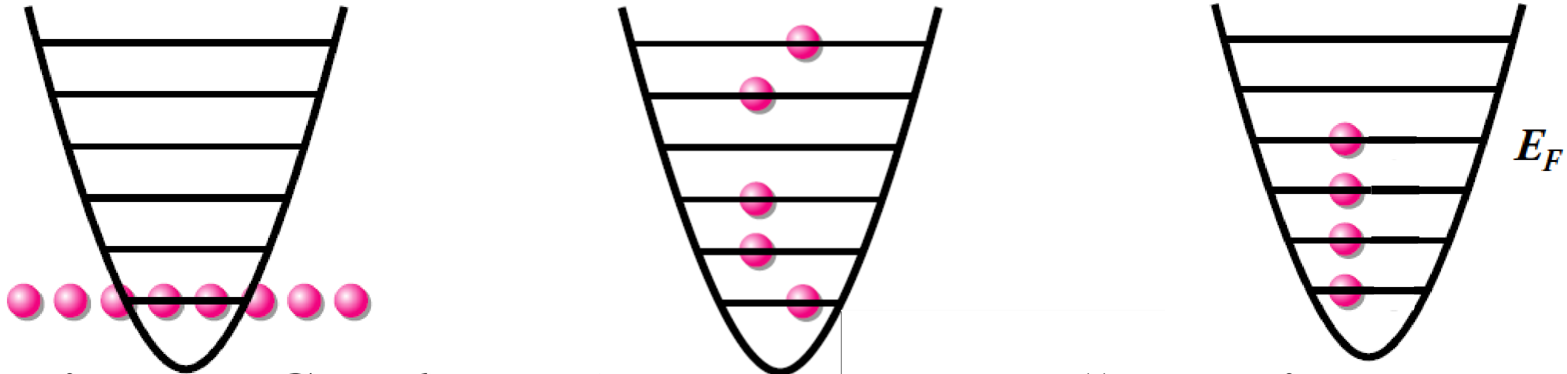


Experimental Setup for Cold Atom



Atomic Gases Reach the Quantum Degenerate Regime

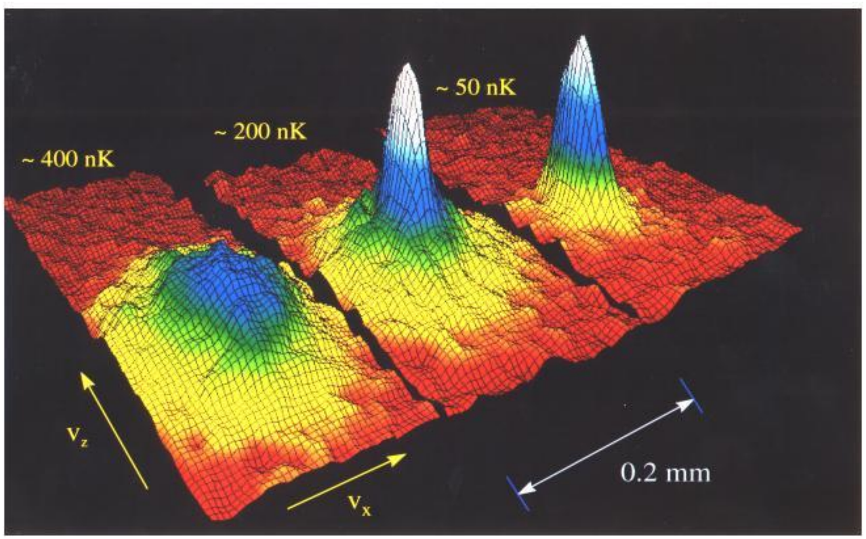
“Boson versus Fermion”



“Bose-Einsten Condensation”

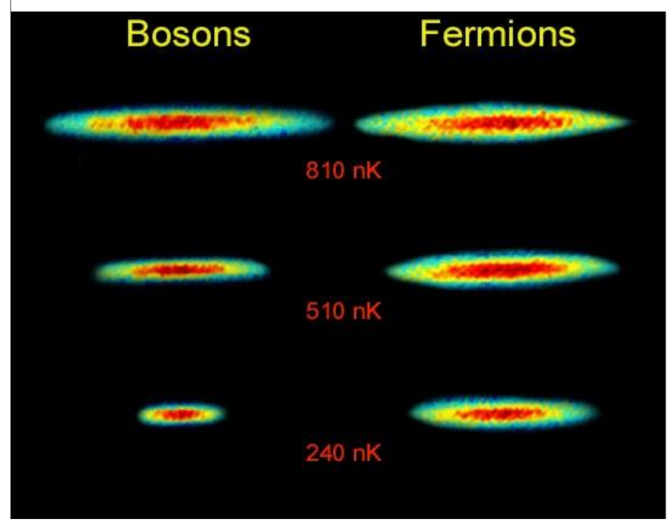
“Fermi Degeneracy”

^{87}Rb



Momentum Distribution

[E. Cornell et al, (1995)]

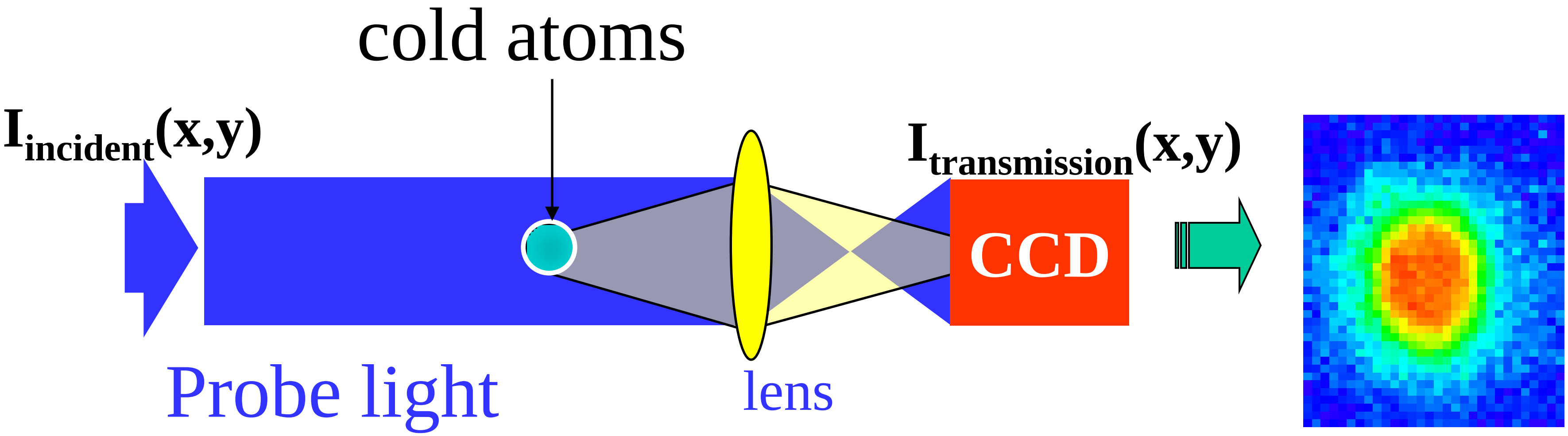


^{6}Li and ^{7}Li

Spatial Distribution

[R. Hulet et al, (2000)]

Optical Absorption Imaging of Atoms



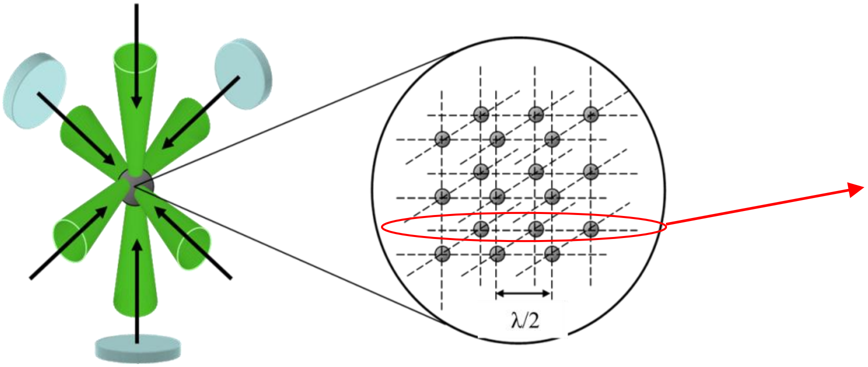
- *In-Situ* Image: ⟶ Reflect "**density**" distribution in a trap
- Time-of-Flight Image: ⟶ Reflect "**momentum**" distribution in a trap

t=0 release atoms from a trap

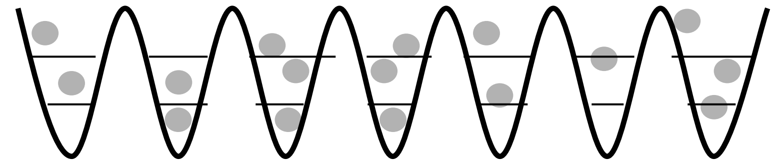
$t=t_{TOF}$ observe atom density distribution

$$x = p / M \cdot t_{TOF}$$

Optical Lattice

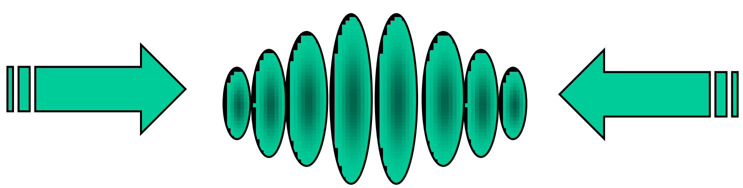


$$V_o(x) = V_o \sin^2(k_L x)$$

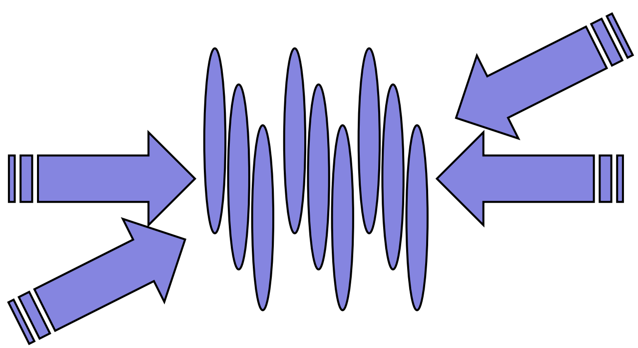


$$V_o(\mathbf{x}) = \sum_{j=1}^{3} V_{oj} \sin^2(k_L x_j) = V_o \sum_{j=1}^{3} \sin^2(k_L x_j)$$

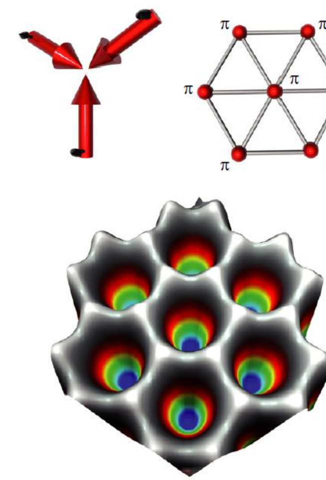
$$E_R = \frac{(\hbar k_L)^2}{2m}, s = \frac{V_0}{E_R}$$



2D gas
(pancake)



1D gas
(tube)

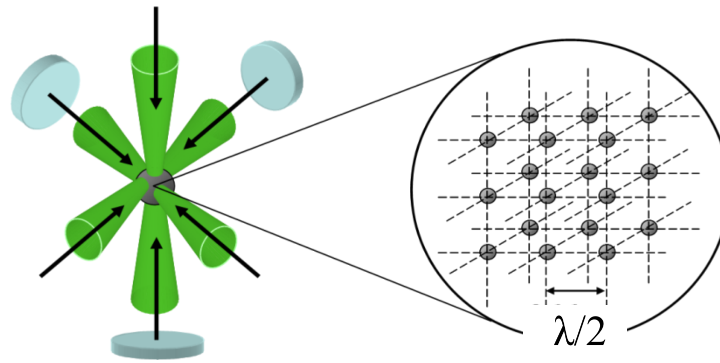


[C. Becker *et al.*,
New J. Phys. **12** 065025(2010)]

Quantum Simulation of Hubbard Model using "Cold Atoms in Optical Lattice"

[D. Jaksch *et al*., PRL, **81** , 3108(1998)]

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



$$J = E_R (2/\sqrt{\pi}) s^{3/4} \exp(-2\sqrt{s})$$

$$U = E_R a_s k_L \sqrt{8/\pi}\, s^{3/4}$$

$s \equiv V_o / E_R$, $E_R \equiv (\hbar k_L)^2 / 2m$, a_s : scattering length

Controllable Parameters

hopping between lattice sites	: J		lattice potential	: V_0
On-site interaction	: U	⇒	Feshbach Resonance	: a_s
filling factor (e- or h-doping)	: n		atom density	: n

Various geometry

Feshbach Resonance:
ability to tune an inter-atomic interaction

Collision is in Quantum Regime

It is described by s-wave scattering length *a_s*

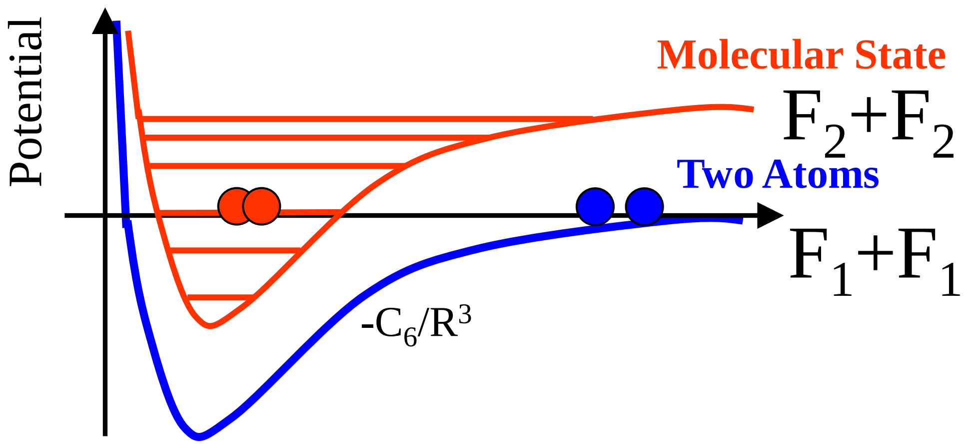
$$a_s = -\delta_l / k$$

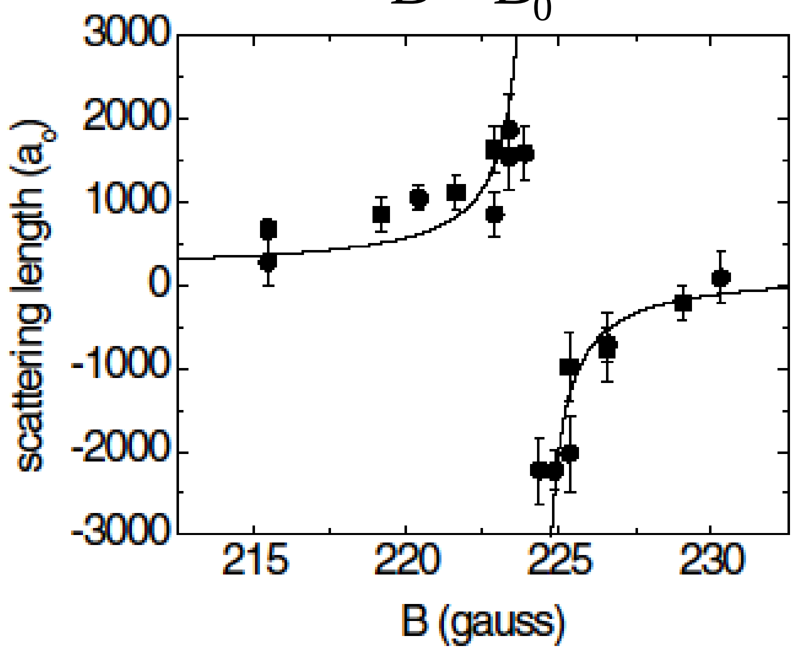
$$\sigma_0 = 4\pi |f_0|^2 = 4\pi |a_s|^2$$

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

→ Control of Interaction(a_s)

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





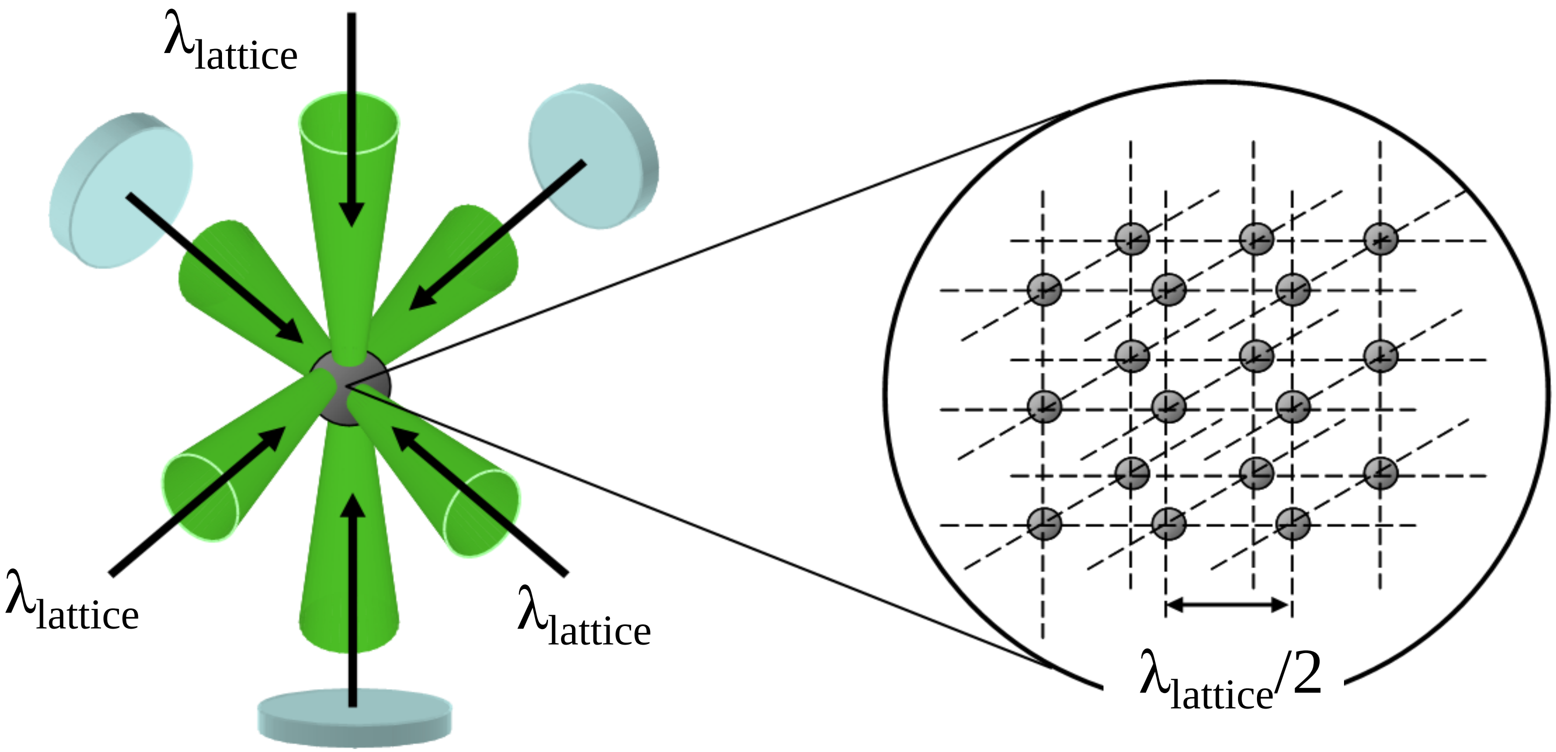
[C. Regal and D. Jin, PRL**90**, 230404(2003)]

Quantum Simulation of Hubbard Model Using Ultracold Alkali Atoms in an Optical Lattice

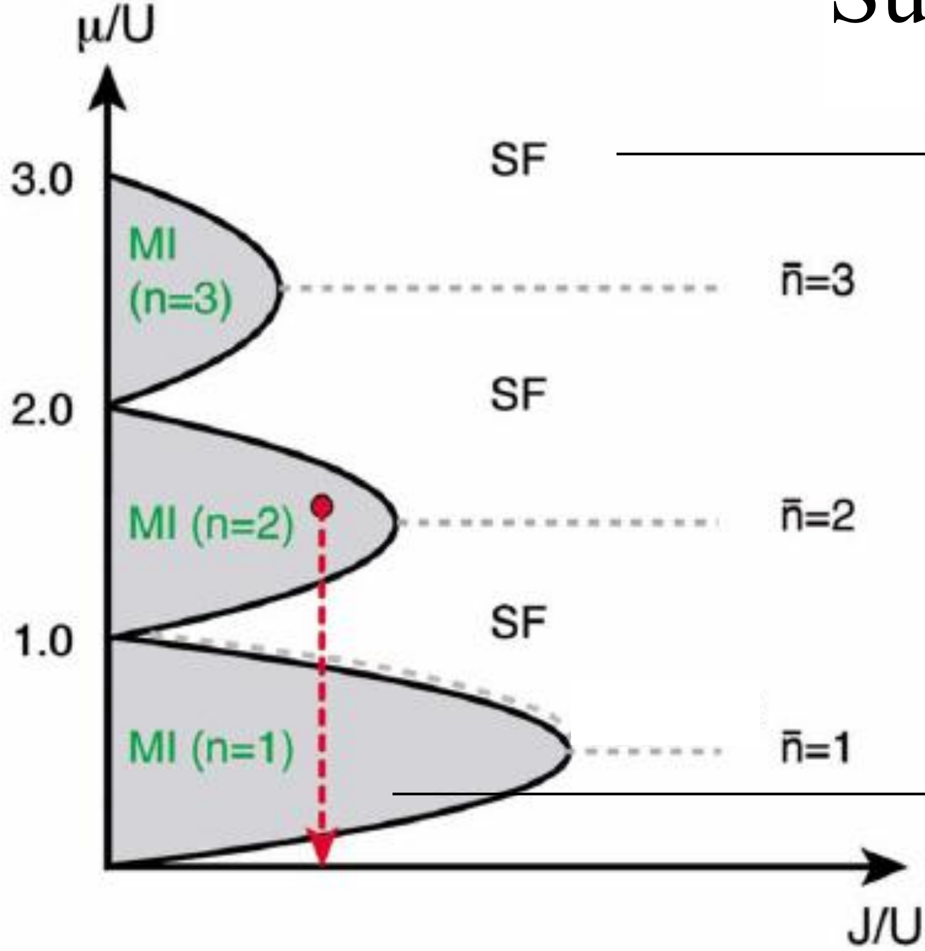
Bosons in a 3D optical lattice

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

"Bose-Hubbard Model"

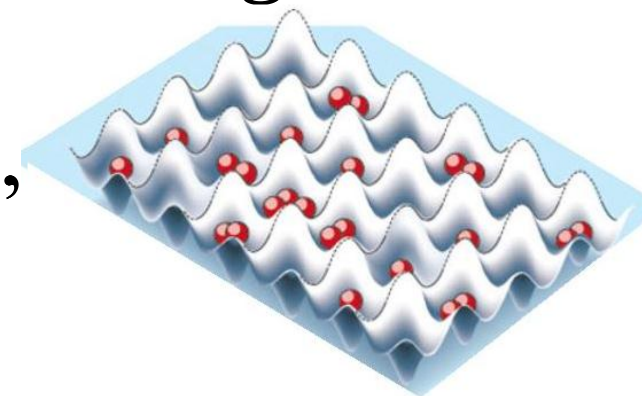


Phase Diagram of Repulsively Interacting Bosons



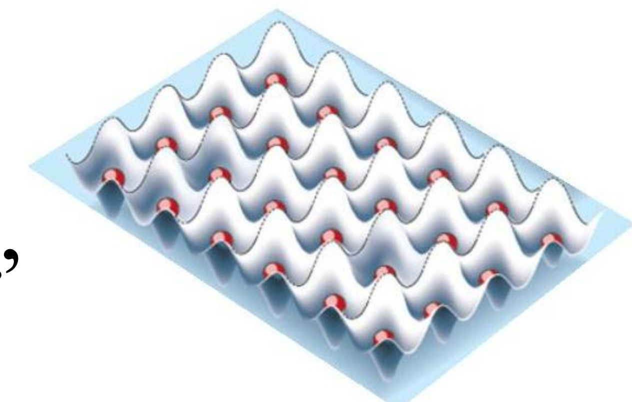
[RMP**80**,885(2008)]

"Superfluid"



$$|\Psi_{SF}\rangle \propto \left(\frac{1}{\sqrt{M}} \sum_{i=1}^{M} a_i^{+} \right)^{N} |0\rangle$$

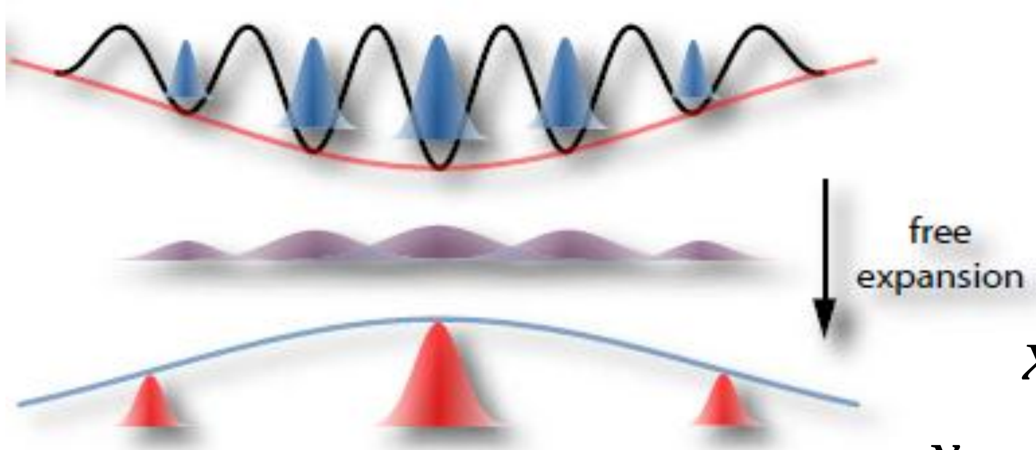
"Mott Insulator"



$$|\Psi_{MI}\rangle \propto \prod_{i=1}^{M} \left(a_i^{+} \right)^{n} |0\rangle$$

Interference Fringe : the direct signature of the phase coherence

"Sudden Release"



t_{TOF}

$x \leftrightarrow \hbar k$

$x = (\hbar k / M) t_{TOF}$

$$n(k) \propto \left|\tilde{w}(k)\right|^2 G(k)$$

Fourier Transform of the Wannier function

$$G(k) = \sum_{R,R'} \exp(ik \cdot (R - R')) \left\langle \hat{a}_R^+ \hat{a}_{R'} \right\rangle$$

no long-range order: $\left\langle \hat{a}_R^+ \hat{a}_{R'} \right\rangle = \delta_{R,R'} \rightarrow G(k) = N$

uniform long-range order: $\left\langle \hat{a}_R^+ \hat{a}_{R'} \right\rangle = 1 \rightarrow G(k) = \dfrac{\sin^2(kdN/2)}{\sin^2(kd/2)}$

peaks at $\pm 2n\hbar k_L$ (n=0,1,2...)

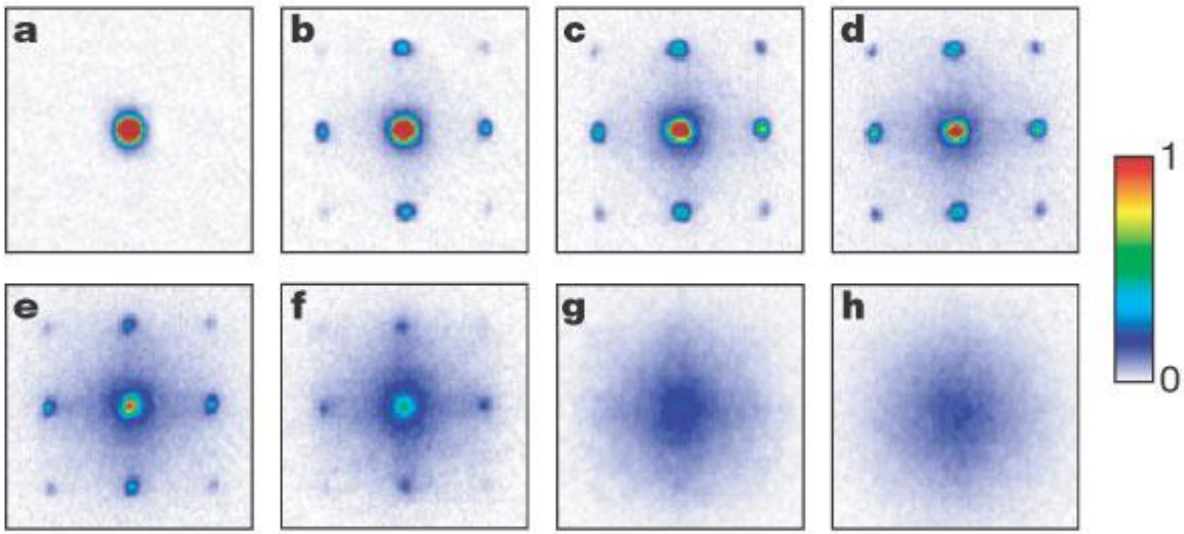
Bose-Hubbard Model:

"Superfluid - Mott-insulator Transition"

[M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, Nature 415,39 (2002)]

No lattice $V_0 / E_R =$ 3 7 10

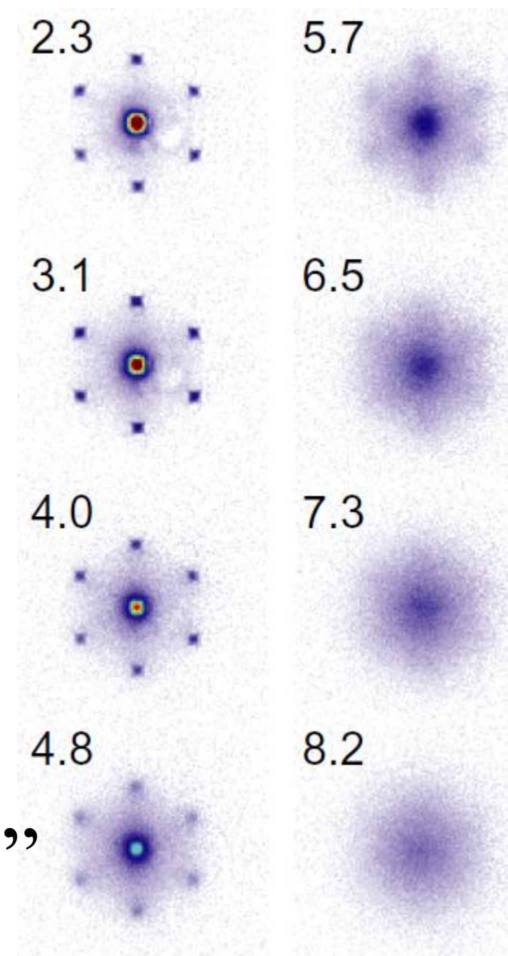
^{87}Rb



13 14 16 20

"cubic lattice"

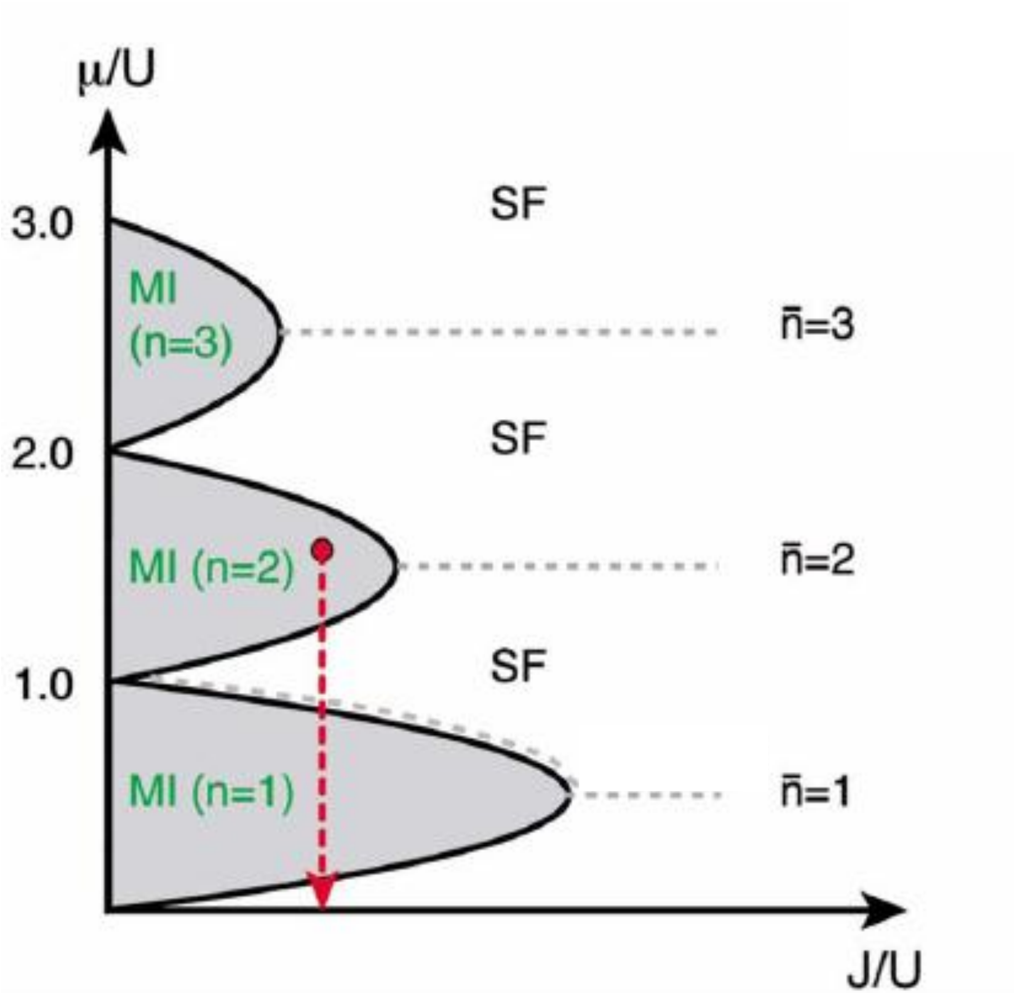
$s=$



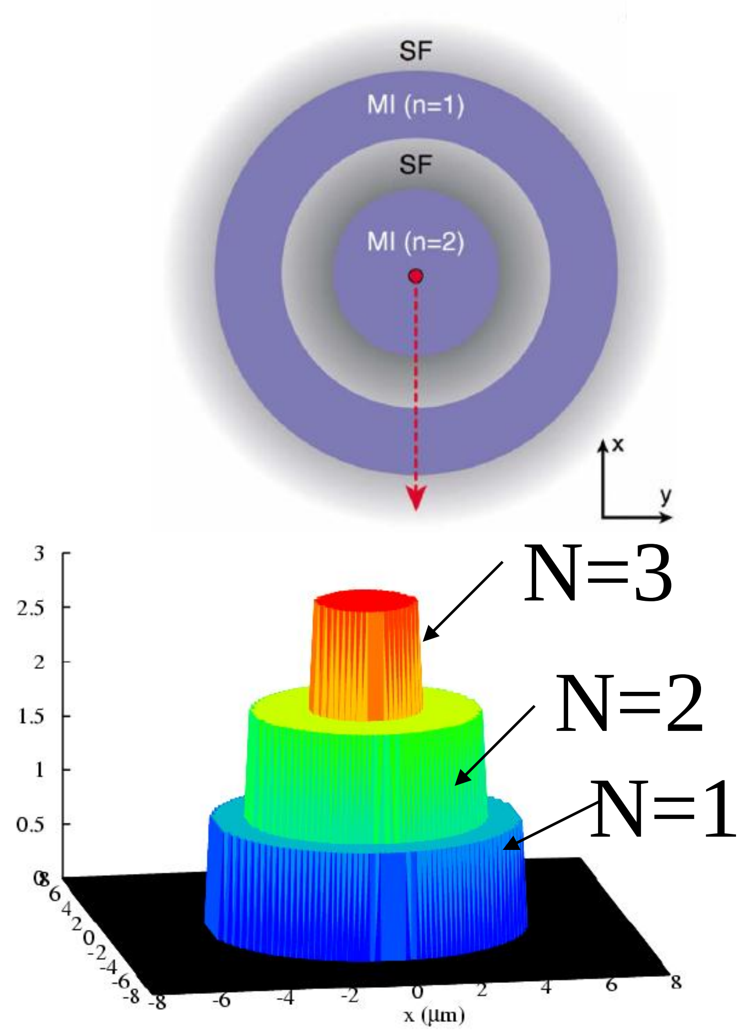
"triangular lattice"

[C. Becker *et al.*, New J. Phys. **12** 065025(2010)]

Phase Diagram of Repulsively Interacting Bosons



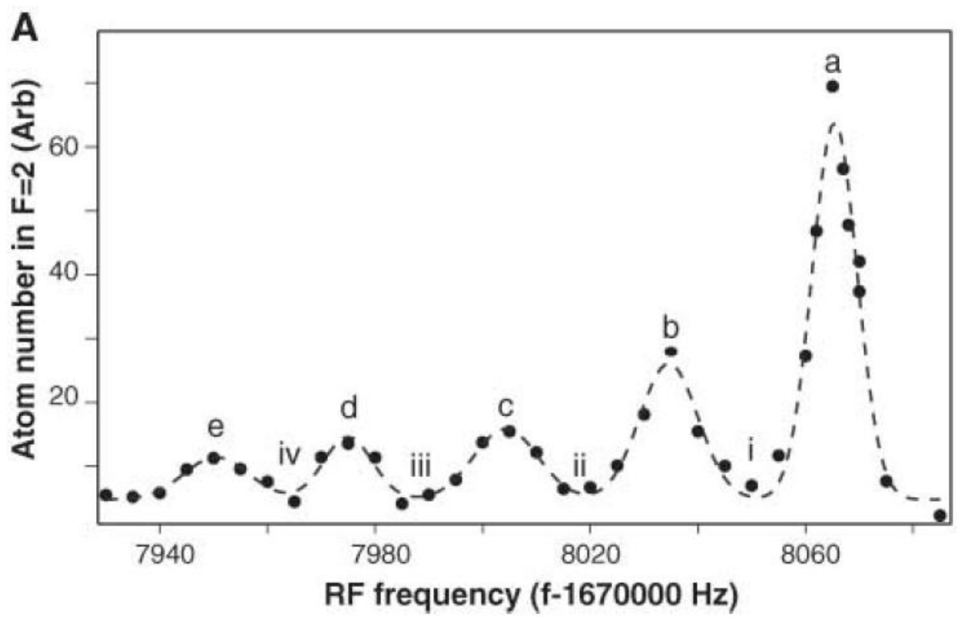
[RMP**80**,885(2008)]



Shell Structure of Mott States

High-Resolution RF Spectroscopy: Observation of Mott Shell Structure

[G. K. Campbell et al., Science 313, 649 (2006)]



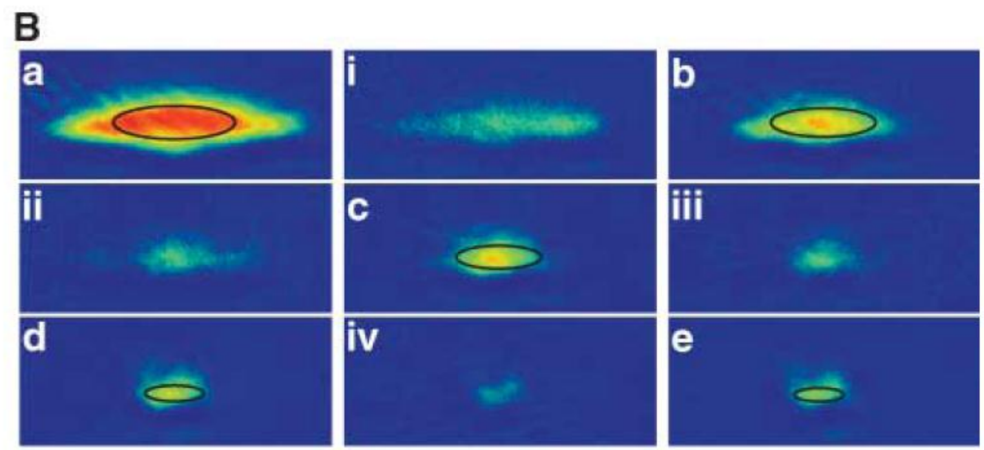


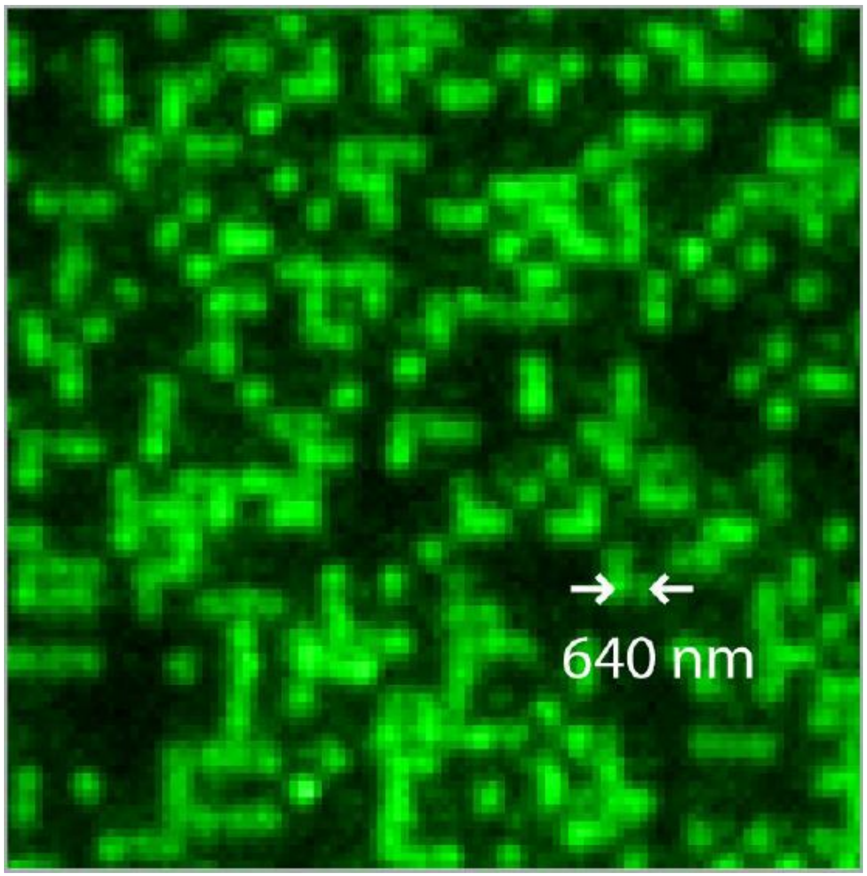
Fig. 3. Imaging the shell structure of the MI. (**A**) Spectrum of the MI at V = $35E_{rec}$. (**B**) Absorption images for for decreasing rf frequencies. Images a to e were taken on resonance with the peaks shown in (A) and display the spatial distribution of the n =1 to n = 5 shells. The solid lines shows the predicted contours of the shells. Absorption images taken for rf frequencies between the peaks (images i to iv) show a much smaller signal. The field of view was 185 μm by 80 μm.

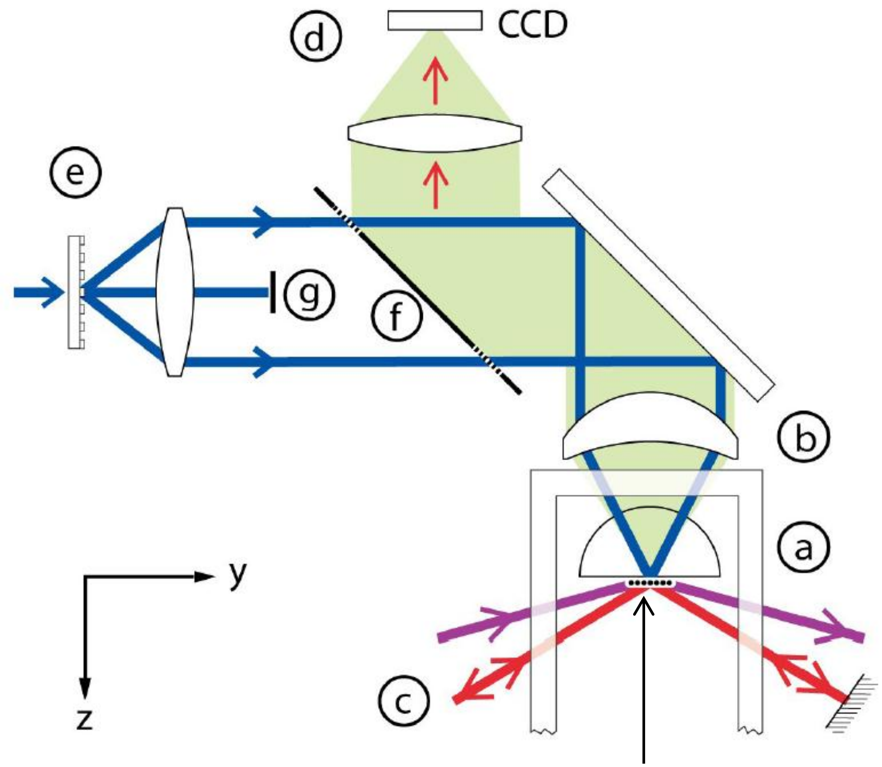
$$h\nu_n = \frac{U}{a_{11}}(a_{12} - a_{11})(n-1)$$

New Technique: Single Site Observation

[WS. Bakr, I. Gillen, A. Peng, S. Folling, and M. Greiner, Nature 462(426), 74-77(2009)]

Fluorescence Imaging





^{87}Rb

Single Site Resolved Detection of MI

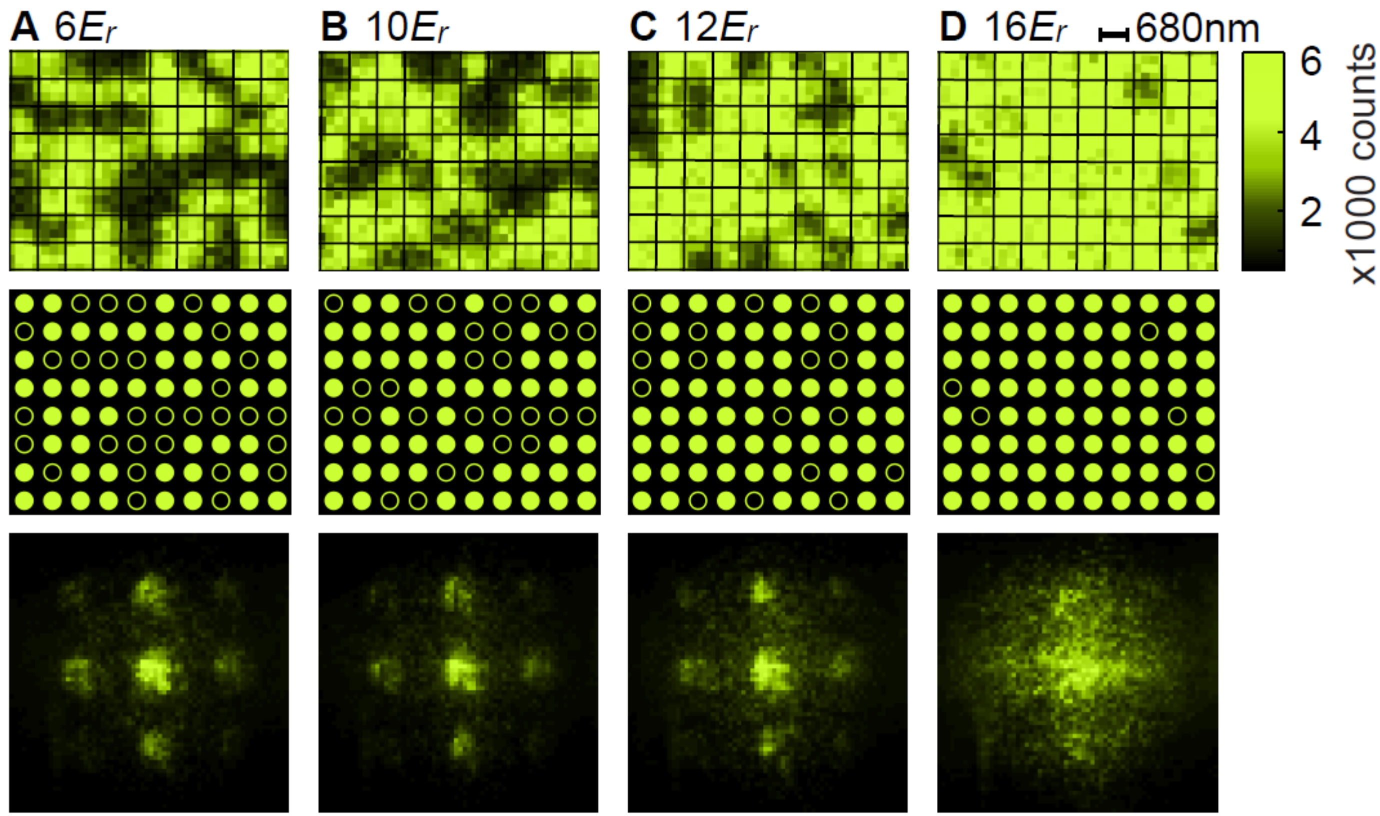
[WS Bakr, et al., Science 329, 547–550 (2010)]

SF ⟷ MI

In Situ-image

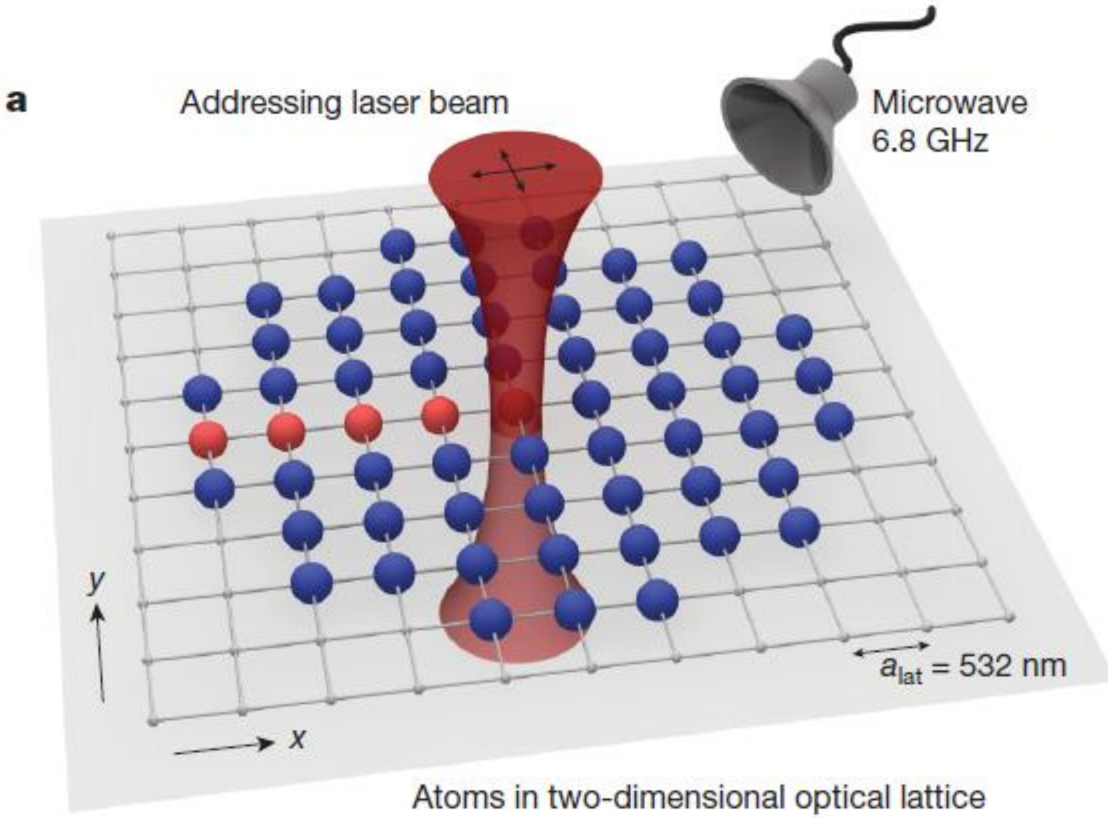
after analysis

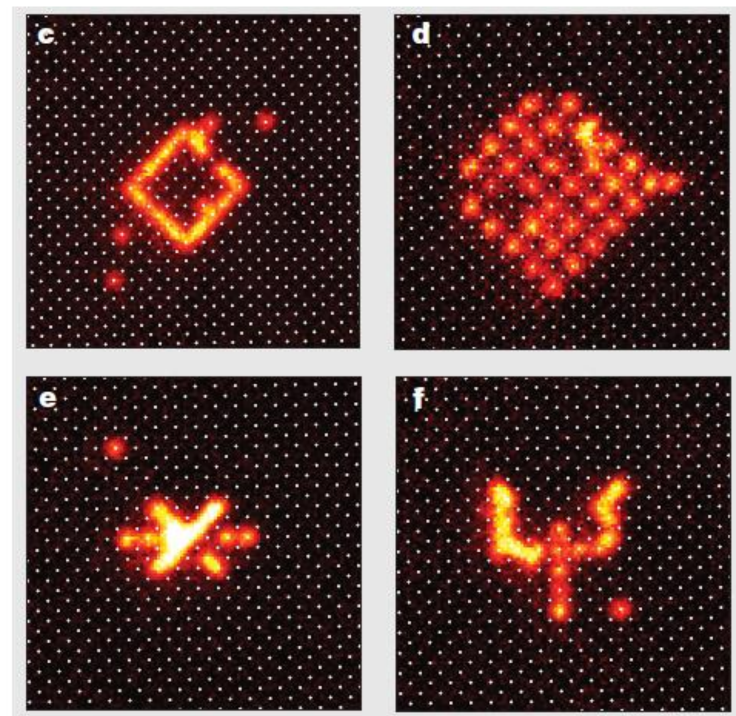
TOF-image



New Technique: Single Site Manipulation

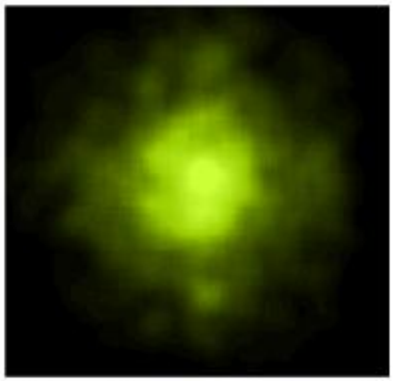
[C. Ewitenberg *et al*, Nature 471, 319(2011)]



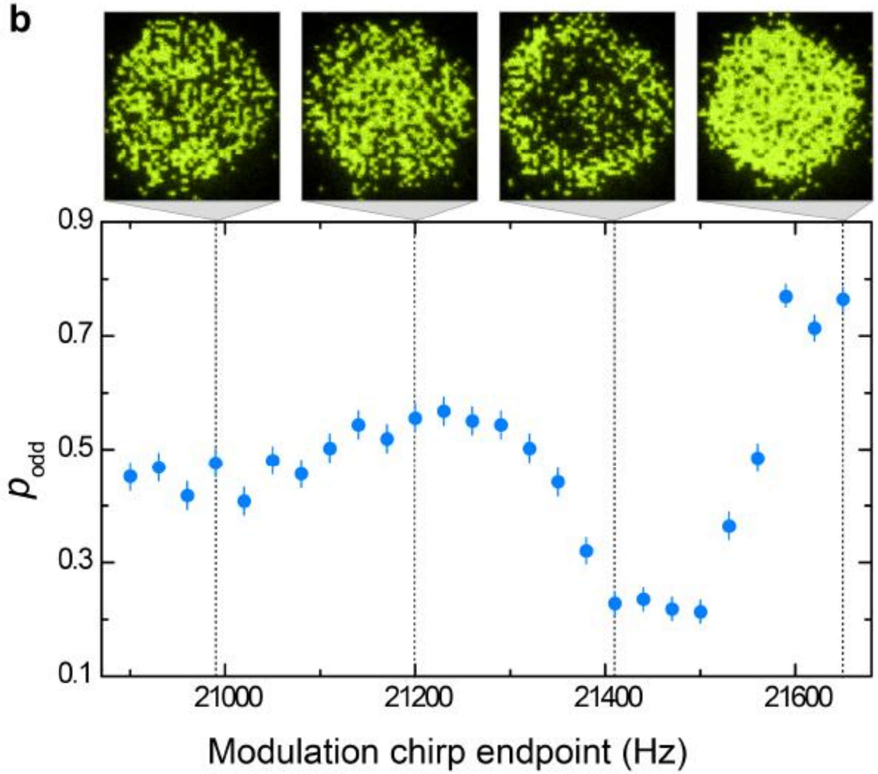


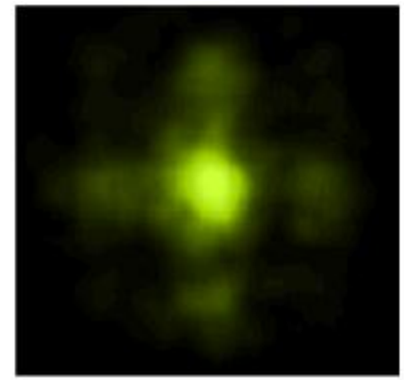
Manipulation of Mott Shell / Filter Cooling (Maxwell Demon)

[arXiv:1105.5834v1, W. S. Bakr, *et al*.,]



Dephased cloud



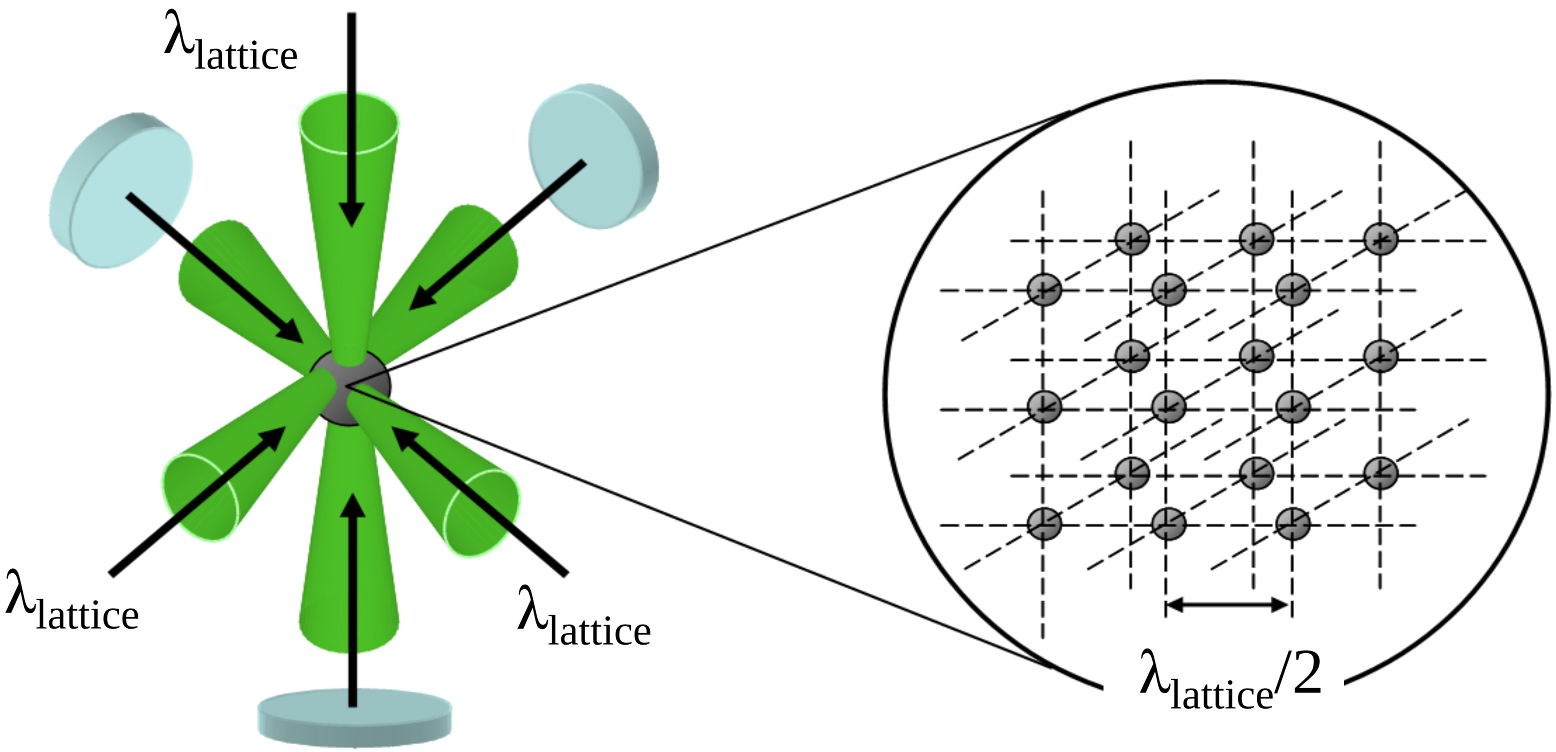


Recooled superfluid

Fermions in a 3D optical lattice

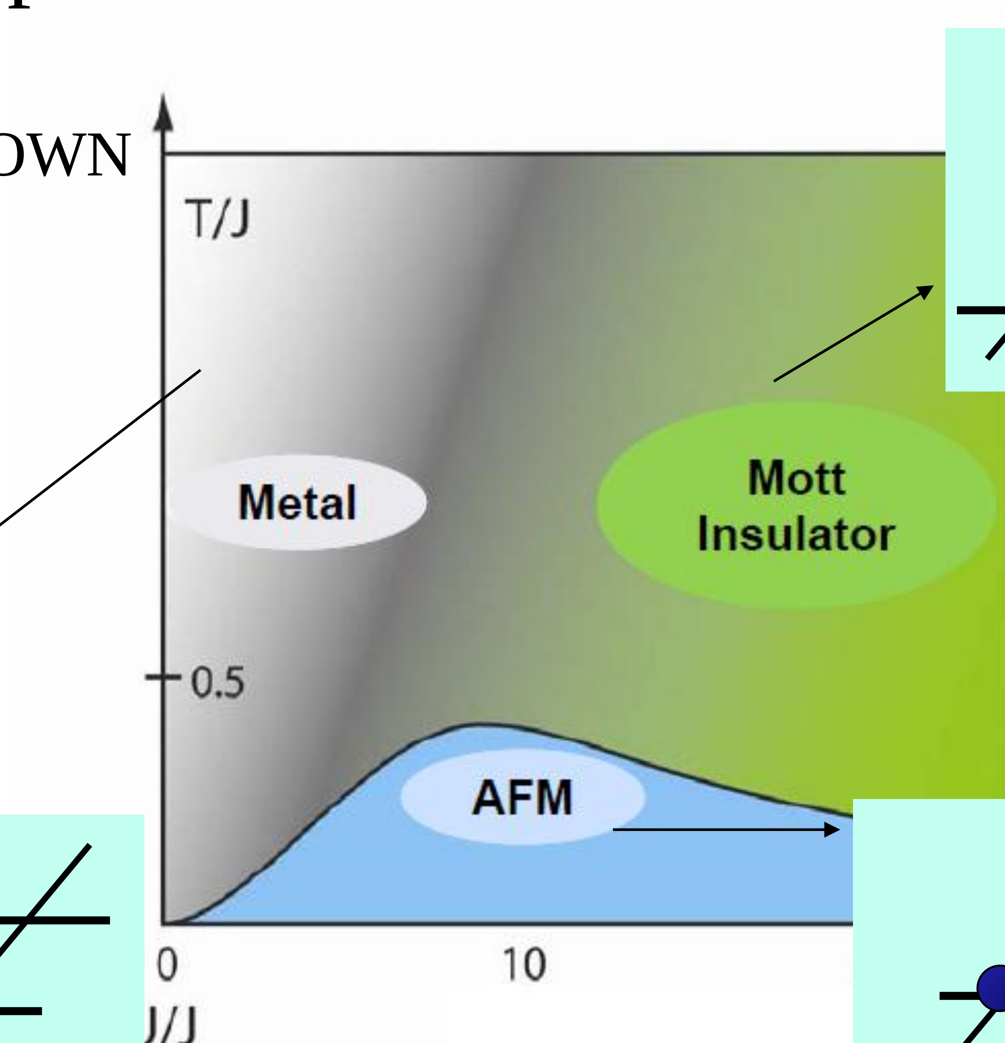
$$H = -J\sum_{<i,j>} c_i^{+} c_j + U\sum_i n_{i,\uparrow} n_{i,\downarrow} + \sum_i \varepsilon_i n_i$$

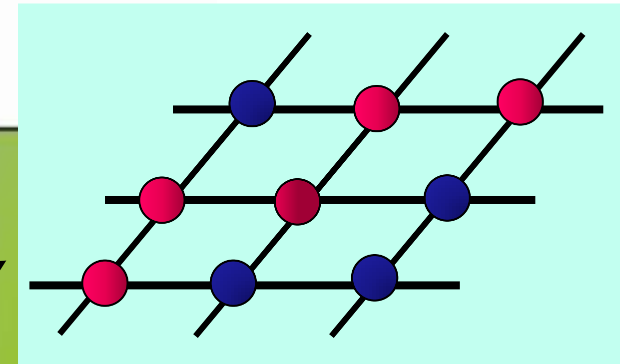
"Fermi-Hubbard Model"



Phase Diagram of
Repulsive Fermi-Hubbard Model

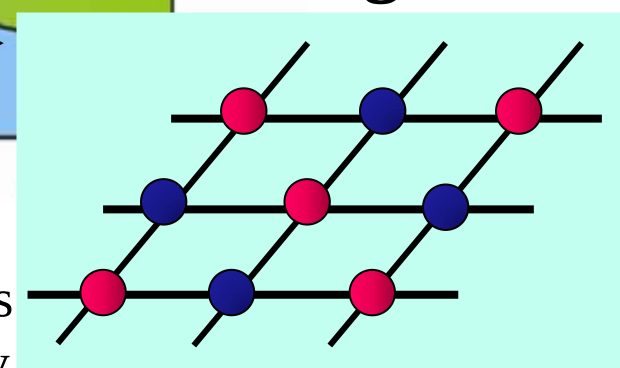
Spin UP Spin DOWN



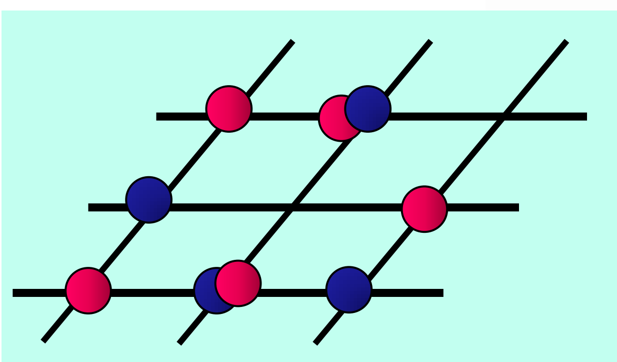


Mott Insulator

Anti-Ferro Magnetism



Metal

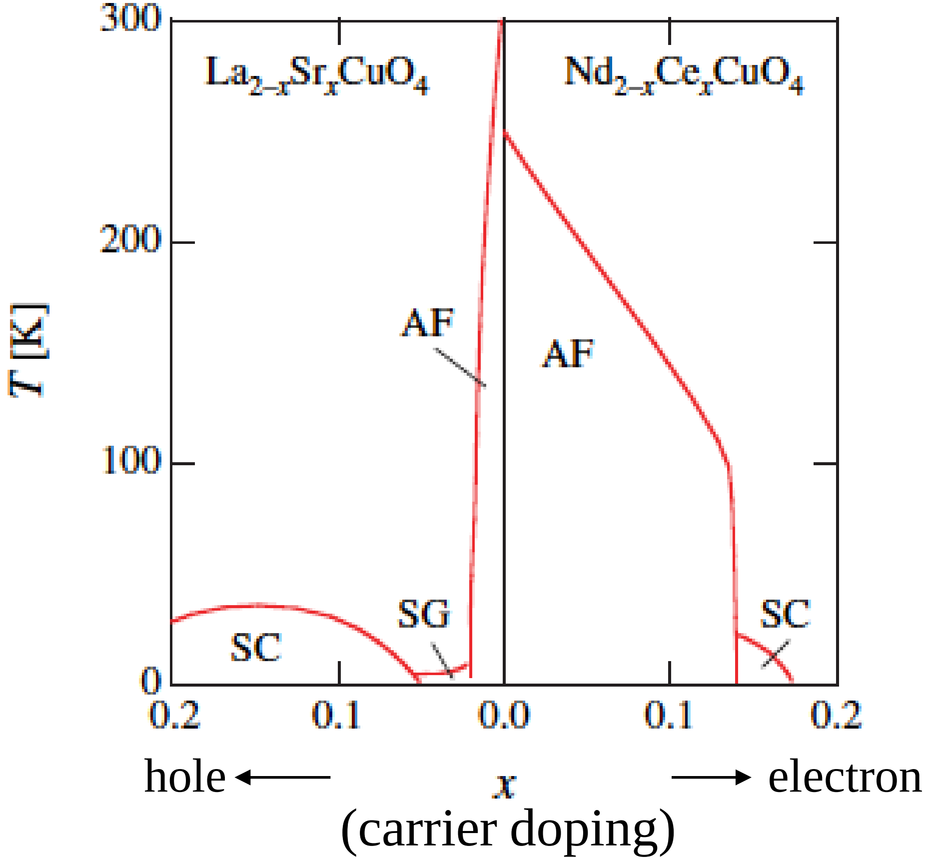


Annu. Rev. Condens. Matter Phys

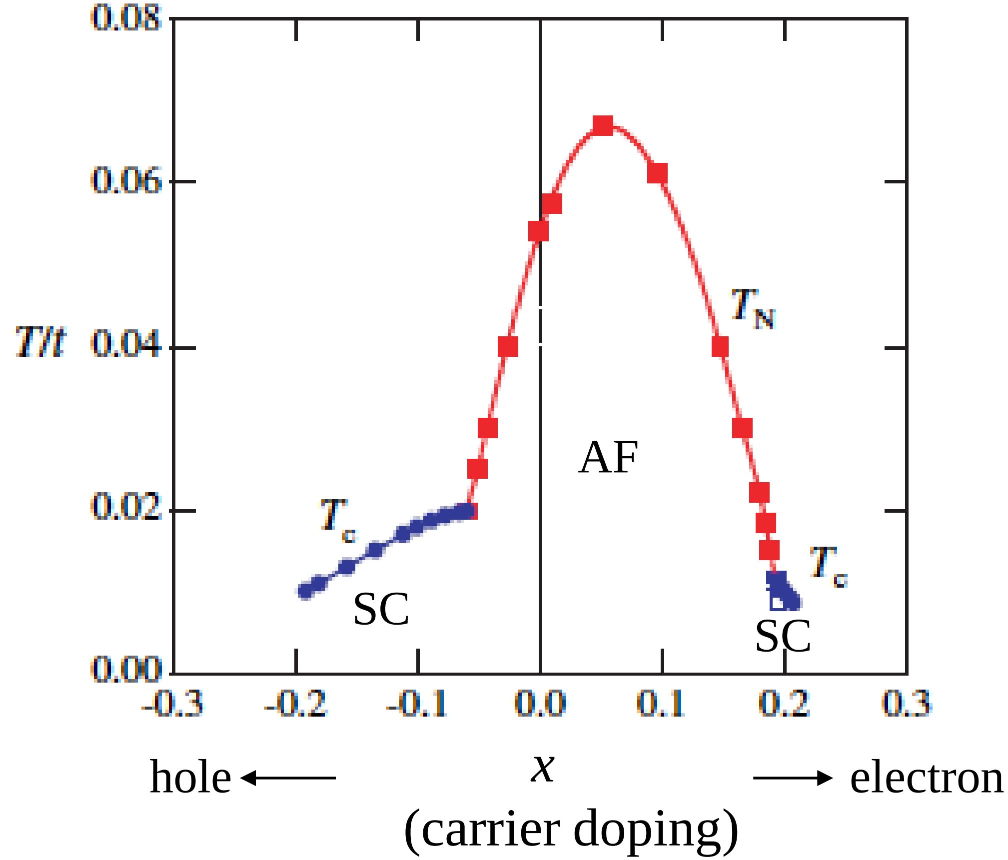
Ranninger, S. Roaszkiewicw, Rev.

Phase Diagram of High-T_c Cuprate Superconductor

experiment



theory



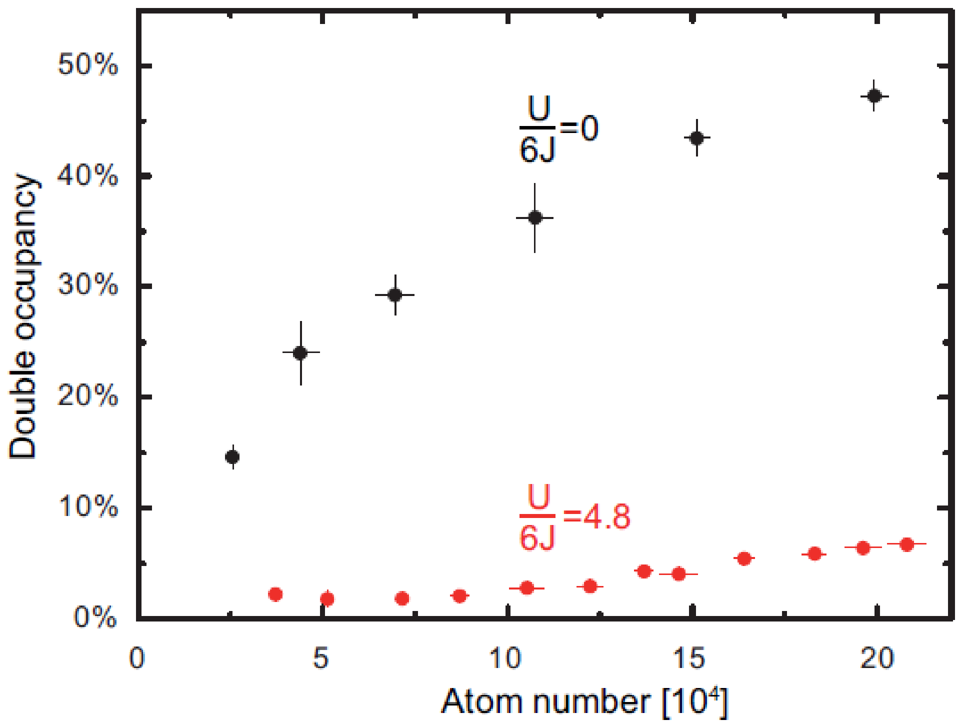
[in T. Moriya and K. Ueda, Rep. Prog.Phys.66(2003)1299]

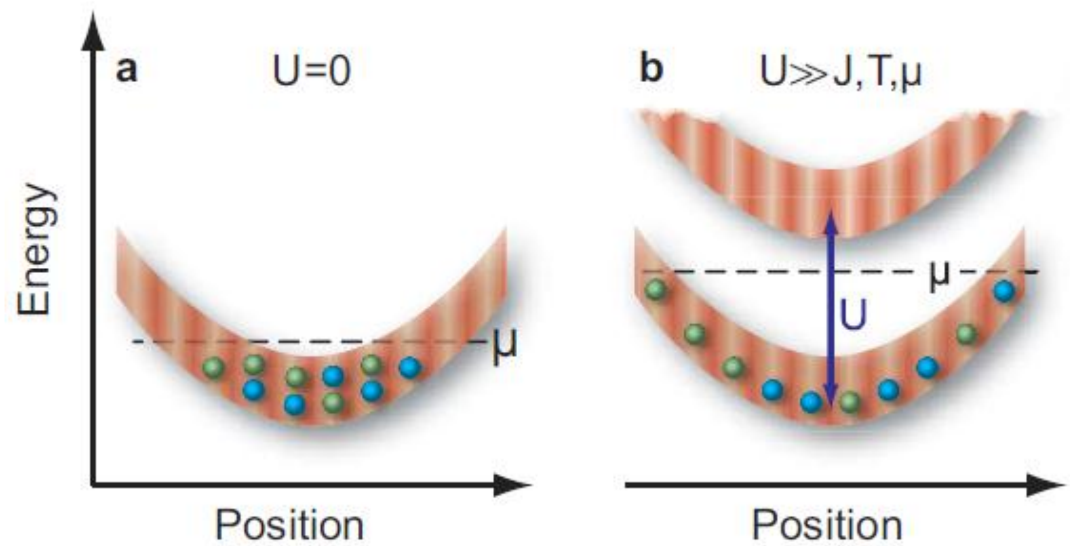
There is controversy in the under-dope region

Current Status of
Quantum Simulation of Fermi Hubbard Model:
"Formation of (paramagnetic) Mott insulator"

"A Mott insulator of ^{40}K atoms (2-component) "

[R. Jördens *et al.*, Nature **455**, 204 (2008)] [U. Schneider, *et al.*, Science **322**,1520(2008)]

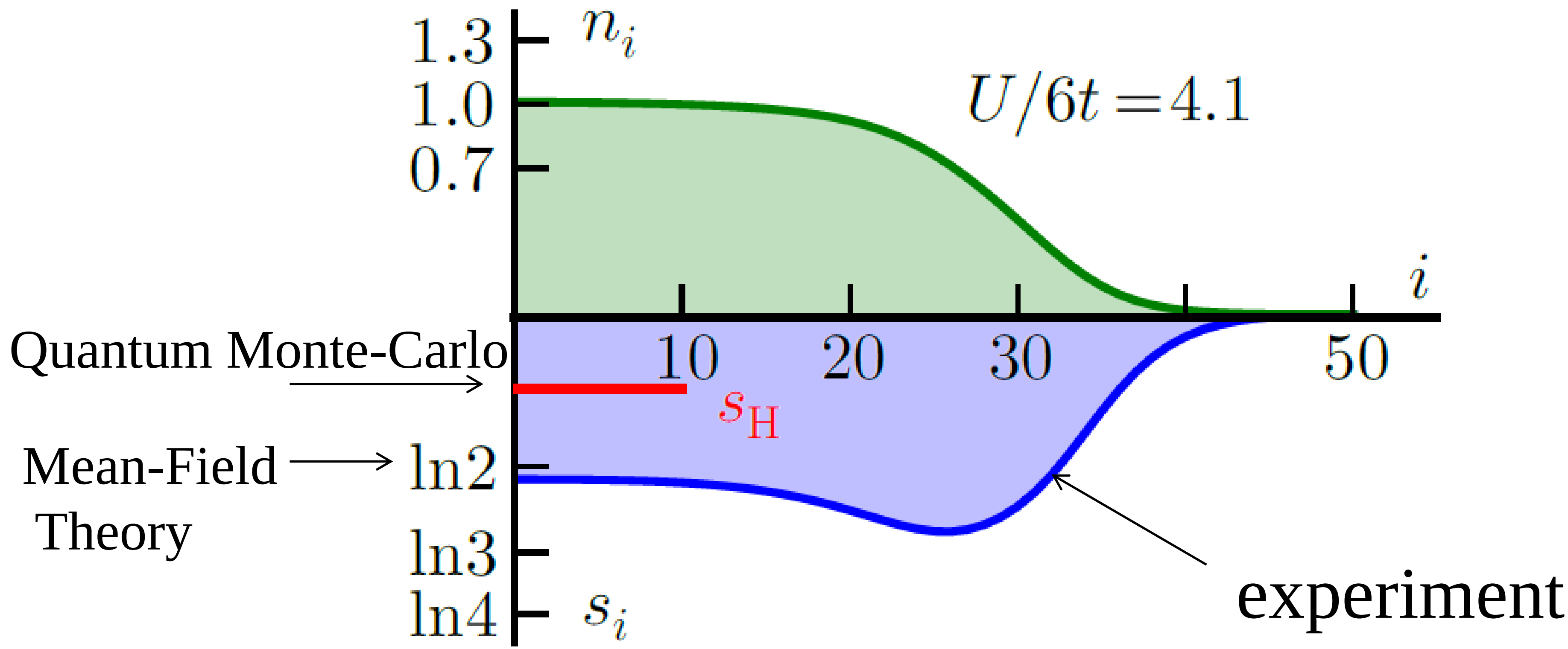




Current Status of
Quantum Simulation of Fermi Hubbard Model:
"Formation of (paramagnetic) Mott insulator"

[R. Jördens *et al.*, PRL **104**, 180401 (2010)]

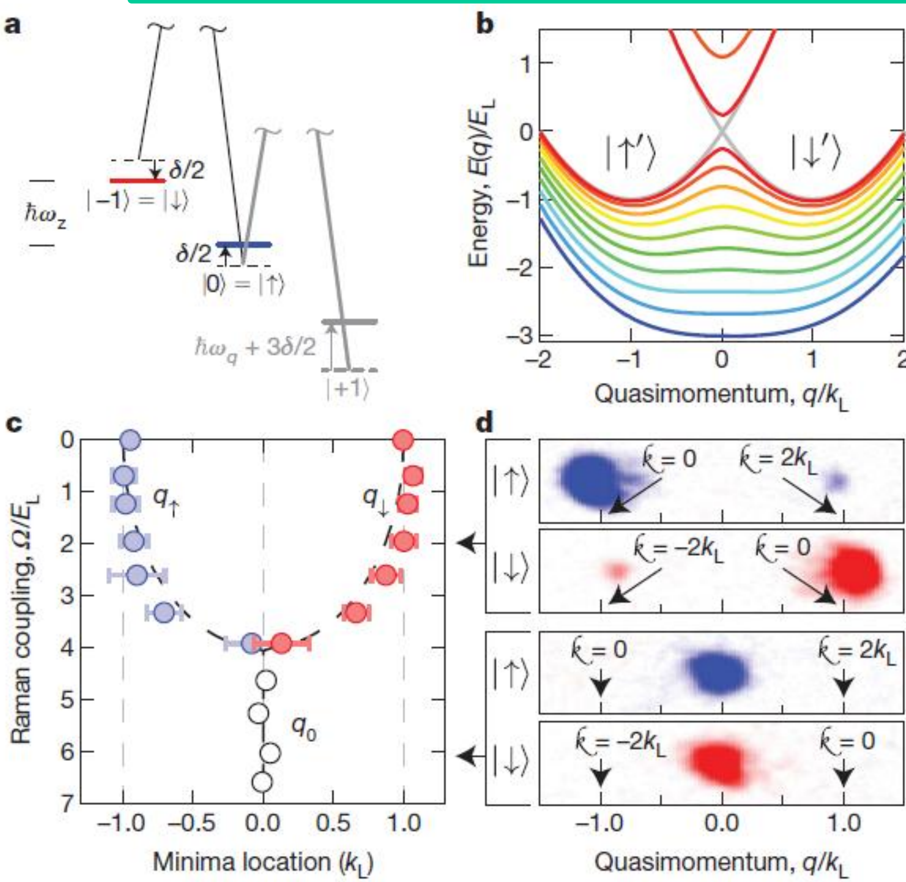
^{40}K atoms (2-component)



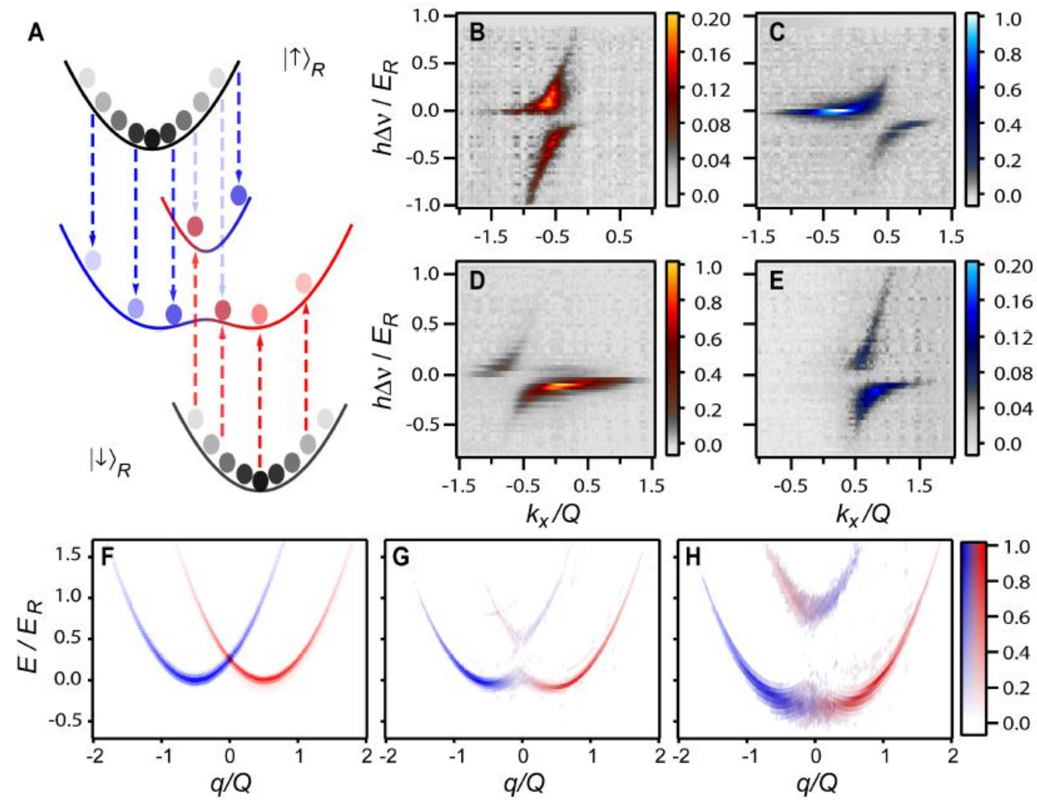
Other Progress

Spin-Orbit Interaction in Cold Atoms:

$$\mathcal{H} = \frac{\hbar^2 k^2}{2m} - \frac{g\mu_B}{\hbar}\mathbf{S}\cdot\left(\mathbf{B}^{(D)} + \mathbf{B}^{(R)} + \mathbf{B}^{(Z)}\right), \quad \begin{aligned}\mathbf{B}^{(R)} &= \alpha(-k_y, k_x, 0)\\ \mathbf{B}^{(D)} &= \beta(k_y, k_x, 0)\end{aligned}$$



“Boson: ^{87}Rb”



“Fermion: ^{6}Li”

Summary1

Quantum Simulation of Hubbard Model Using Alkali Atoms in an Optical Lattice

Tuning Interatomic Interaction:

magnetic Feshbach resonance

Superfluid-Mott Insulator Transition

matter-wave interference, spectroscopy

Quantum Gas Microscope

SF-Mott insulator transition, Single-site manipulation,
entropy reduction by Maxwell demon

Fermi Mott Insulator

SU(2) Mott insulator

Spin-Orbit Inteaction

BEC, Fermi gas

Quantum Simulation of Hubbard Model Using Ultracold Ytterbium Atoms in an Optical Lattice

1)Bose-Hubbard Model:

SF-Mott Insulator Transition by Laser spectroscopy

2)Fermi-Hubbard Model: *Fermi Mott Insulator*

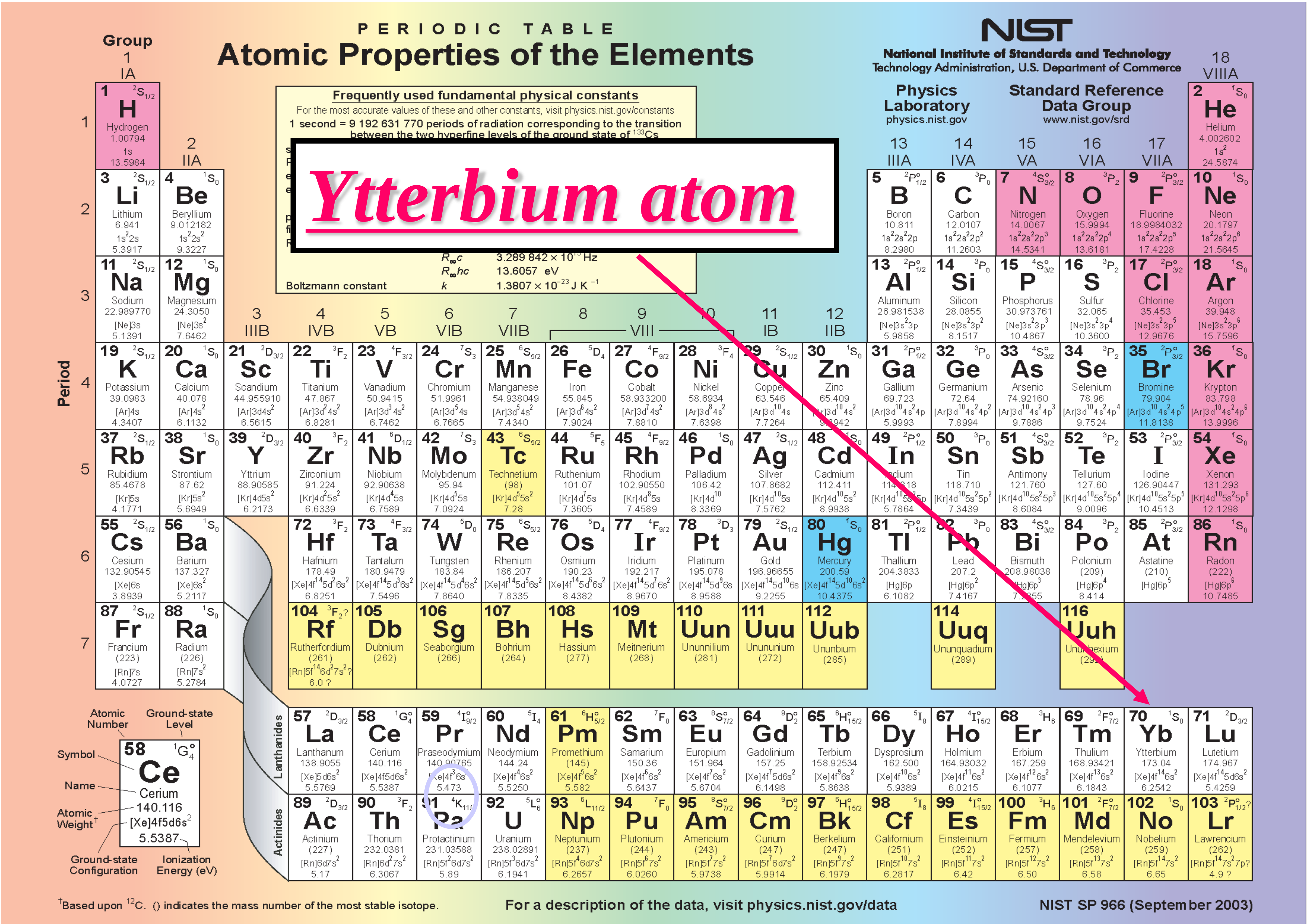
SU(6) Mott insulator, Pomeranchuk Cooling,

3)Bose-Fermi-Hubbard Model:

Mixed Mott Insulator

4)Plan

Ytterbium atom



Unique Features of Ytterbium Atoms

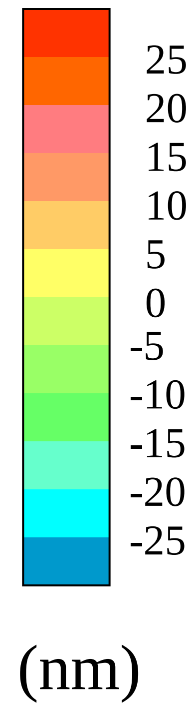
Rich Variety of Isotopes

^{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**

Isotopic Tuning of Interatomic Interaction

Scattering Length

Mass number	168	170	171	172	173	174	176
168	**13**						
170	**6.2**	**3.4**					
171	**4.7**	**1.9**	**-0.1**				
172	**3.4**	**-0.1**	**-4.3**	**-30**			
173	**2.0**	**-4.2**	**-29**	**22**	**11**		
174	**0.2**	**-26**	**23**	**11**	**7.3**	**5.5**	
176	**-18**	**11**	**7.5**	**5.6**	**4.2**	**2.9**	**-1.2**



[M. Kitagawa, *et al*, PRA**77**, 012719 (2008)]

Collaboration with R. Ciurylo, P. Naidon, P. Julienne

Unique Features of Ytterbium Atoms

Rich Variety of Isotopes

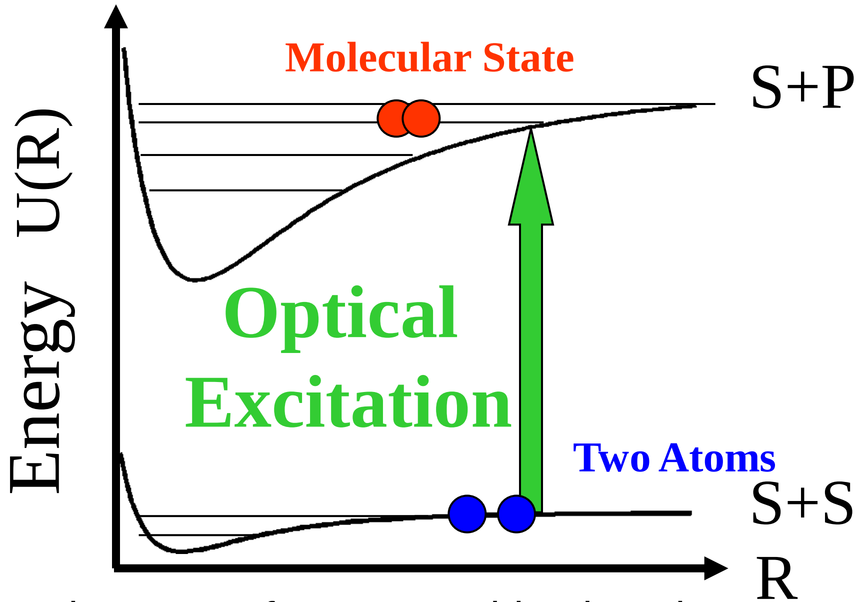
^{168}Yb (0.13%)	^{170}Yb (3.05%)	^{171}Yb (14.3%)	^{172}Yb (21.9%)	^{173}Yb (16.2%)	^{174}Yb (31.8%)	^{176}Yb (12.7%)
Boson	**Boson**	**Fermion**	**Boson**	**Fermion**	**Boson**	**Boson**

^{173}Yb (I=5/2) $$H_{\text{int}} = \frac{4\pi\hbar^2 a_s}{M}\delta(\vec{r}_1 - \vec{r}_2)$$ **SU(6) system**

$\longrightarrow$ novel magnetism

[M. A. Cazalilla, *et al.*, N. J. Phys**11**, 103033(2009), Hermele, et al., PRL 103, 130351 (2009); A. V. Gorshkov, *et al.*, Nat. Physics, 6, 289(2010)]

Optical Feshbach Resonance



$$S_{00} = \frac{\Delta - i\Gamma_S/2 + i\gamma/2}{\Delta + i\Gamma_S/2 + i\gamma/2}$$

$$\Gamma_S \propto \left| \langle b | V_{las} | f \rangle \right|^2$$

γ :spontaneous decay rate

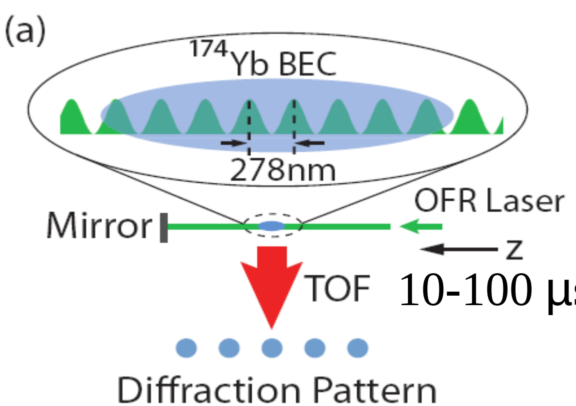
Δ :detuning from the PA resonance

[J. Bohn and P. Julienne PRA(1999)]

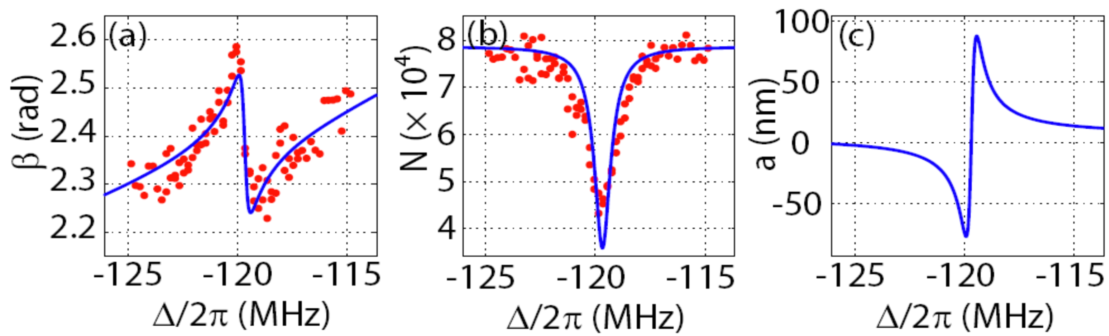
Advantages for Intercombination Lines

R. Ciurylo, *et al.* *Phys. Rev. A* **70**. 062710 (2004)

Nanometer-scale Spatial Modulation



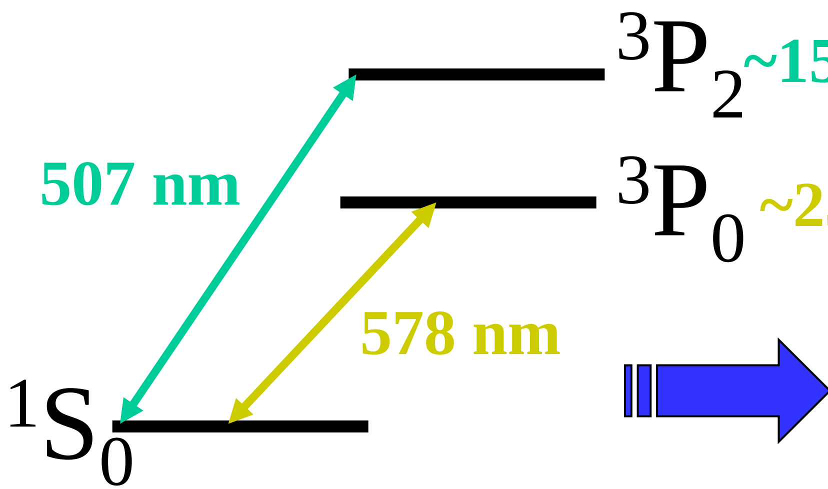
10-100 μs Pulse



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

Unique Features of Ytterbium Atoms

Ultra-narrow Optical Transitions



High-resolution laser spectroscopy as a Local Probe

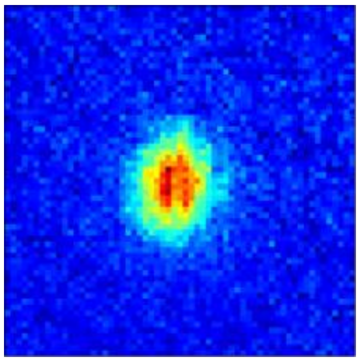
Another Useful Orbital States with Different Characters

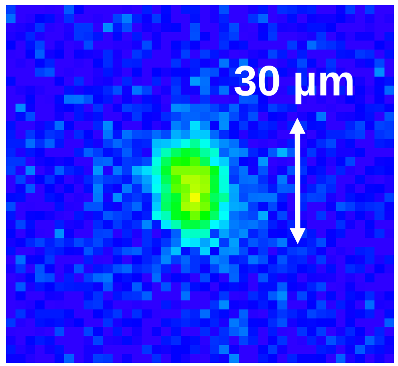
Quantum Degenerate Gases of Yb

[Y. Takasu *et al.*, PRL **91**, 040404 (2003)] [T. Fukuhara *et al.*, PRA **76**, 051604(R)(2007)]
[S. Sugawa *et al.*, PRA **84**, 011610(R)(2011)]

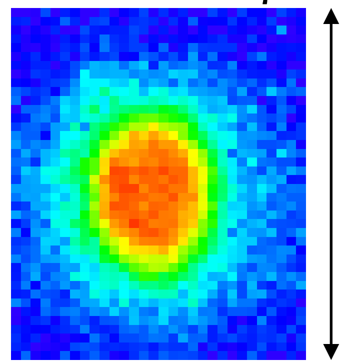
^{168}Yb(0.13%) ^{170}Yb ^{174}Yb ^{176}Yb

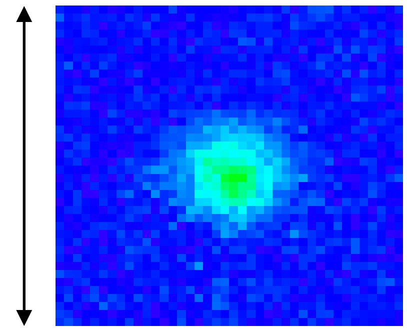
160μm 120 μm TOF: 8 ms





TOF:
10ms



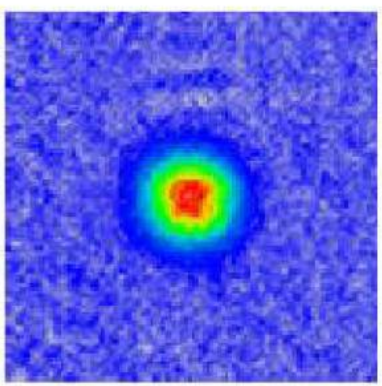


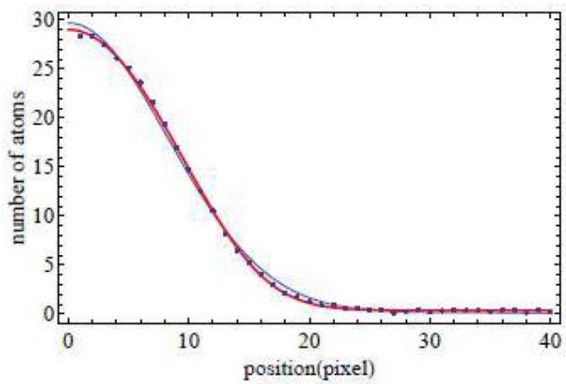
Fermion

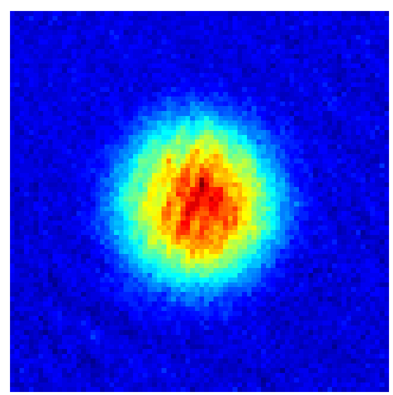
[T. Fukuhara *et al.*, PRL. **98**, 030401 (2007)] [S. Taie *et al* ., PRL**105**, 190401(2010)]

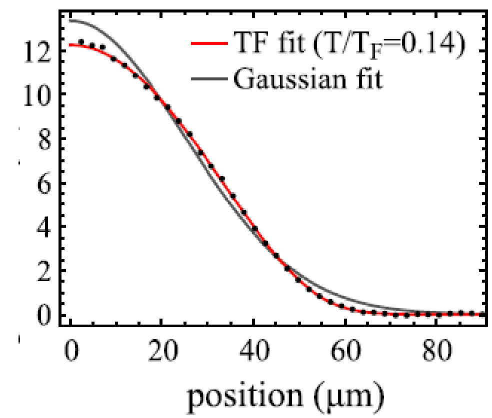
^{171}Yb(I=1/2) **T/T_F =0.3 (2-component)**

^{173}Yb(I=5/2):**SU(6)** **T/T_F =0.14 (6-component)**





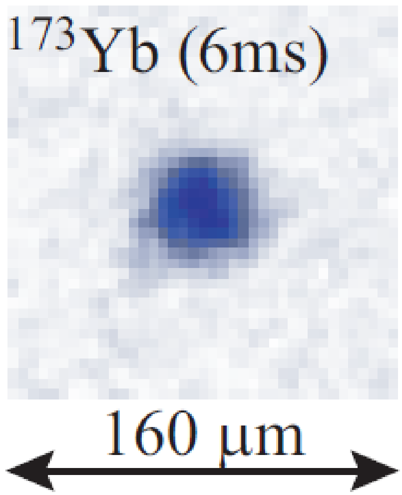


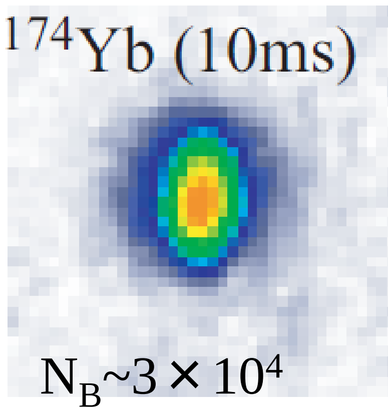


Quantum Degenerate Mixtures of Yb

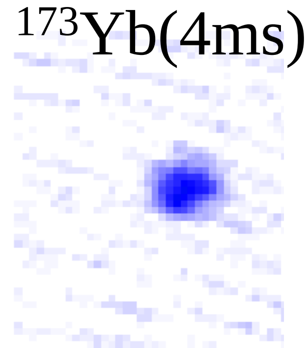
[T. Fukuhara *et al.*, Phys. Rev. A 79, 021601(R) (2008)] [S. Taie *et al.*, PRL**105**, 190401(2010)]

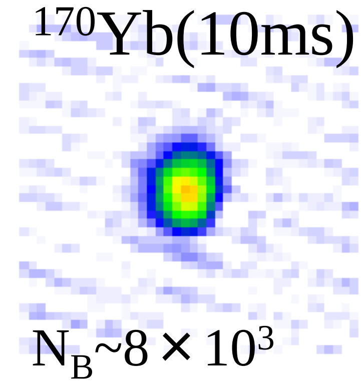
^{173}Yb(Fermion) + ^{174}Yb(Boson)



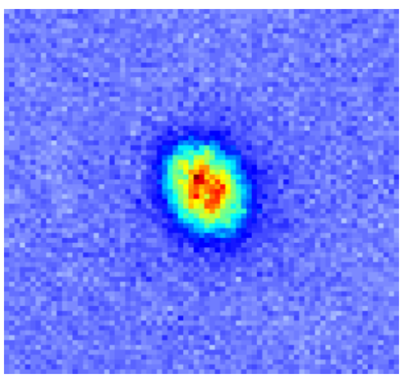


^{173}Yb(Fermion) + ^{170}Yb(Boson)

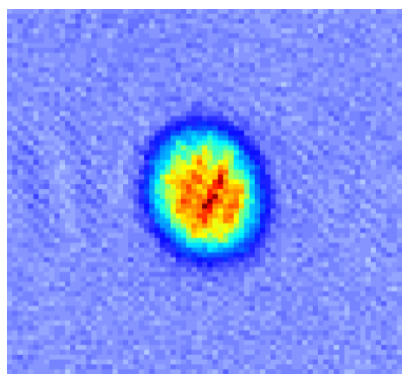




^{168}Yb(Boson)+ ^{174}Yb(Boson)

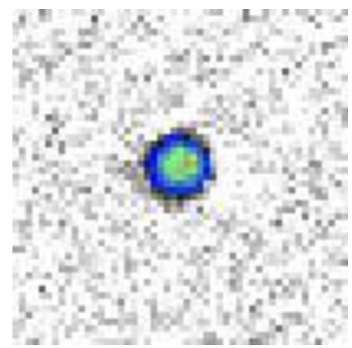


N_B~6×10^3

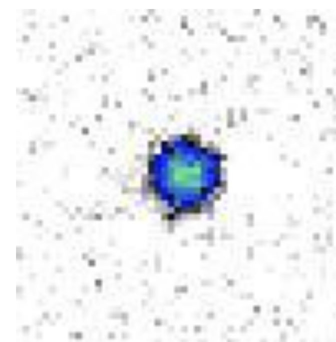


N_B~4.5×10^4

^{171}Yb(Fermion) + ^{173}Yb(Fermion)



$T/T_F = 0.33$



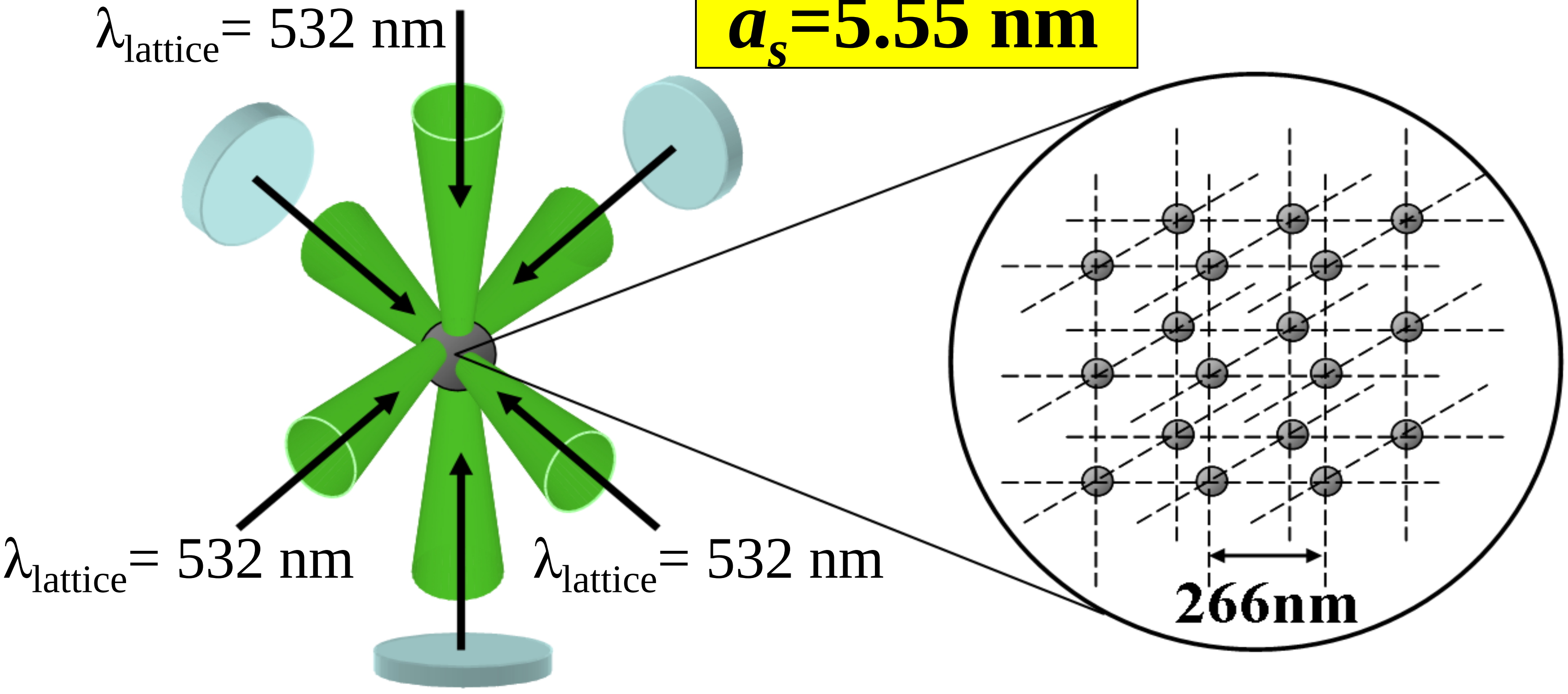
$T/T_F = 0.3$

Boson ^{174}Yb in a 3D optical lattice

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

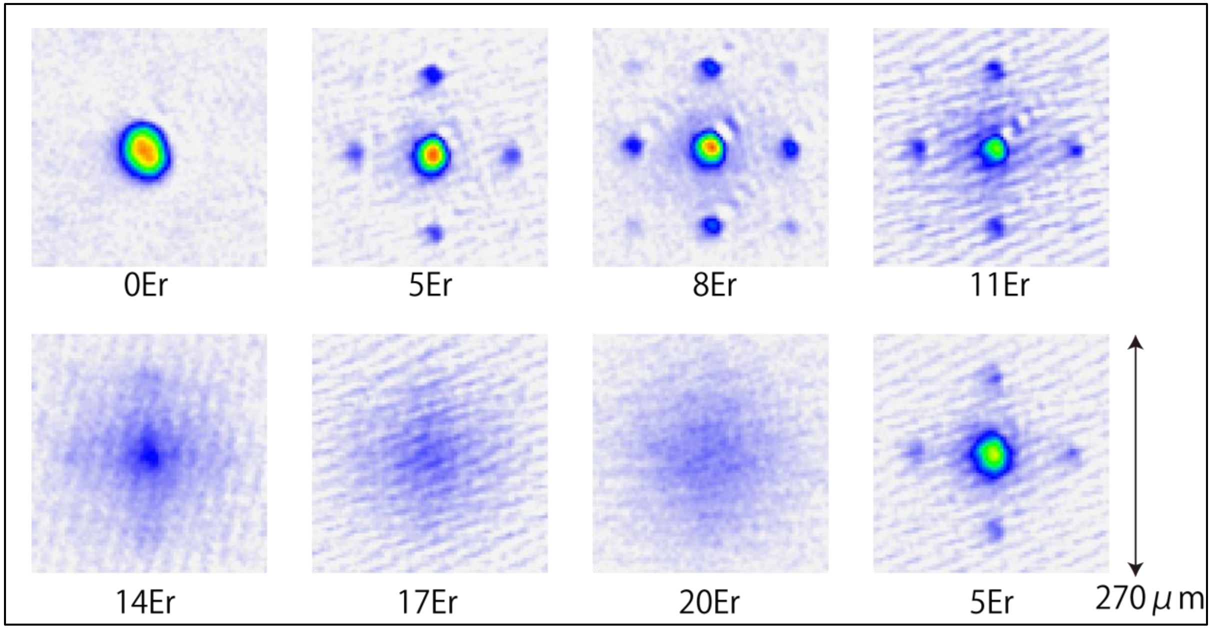
^{174}Yb

a_s=5.55 nm



Superfluid-Mott Transition

T. Fukuhara, *et al.*, *PRA*. **79**, 041604R (2009);H. Moritz and T. Esslinger, Physics **2**,31(2009)(Viewpoint)



→ Unique Applications to Quantum Computing

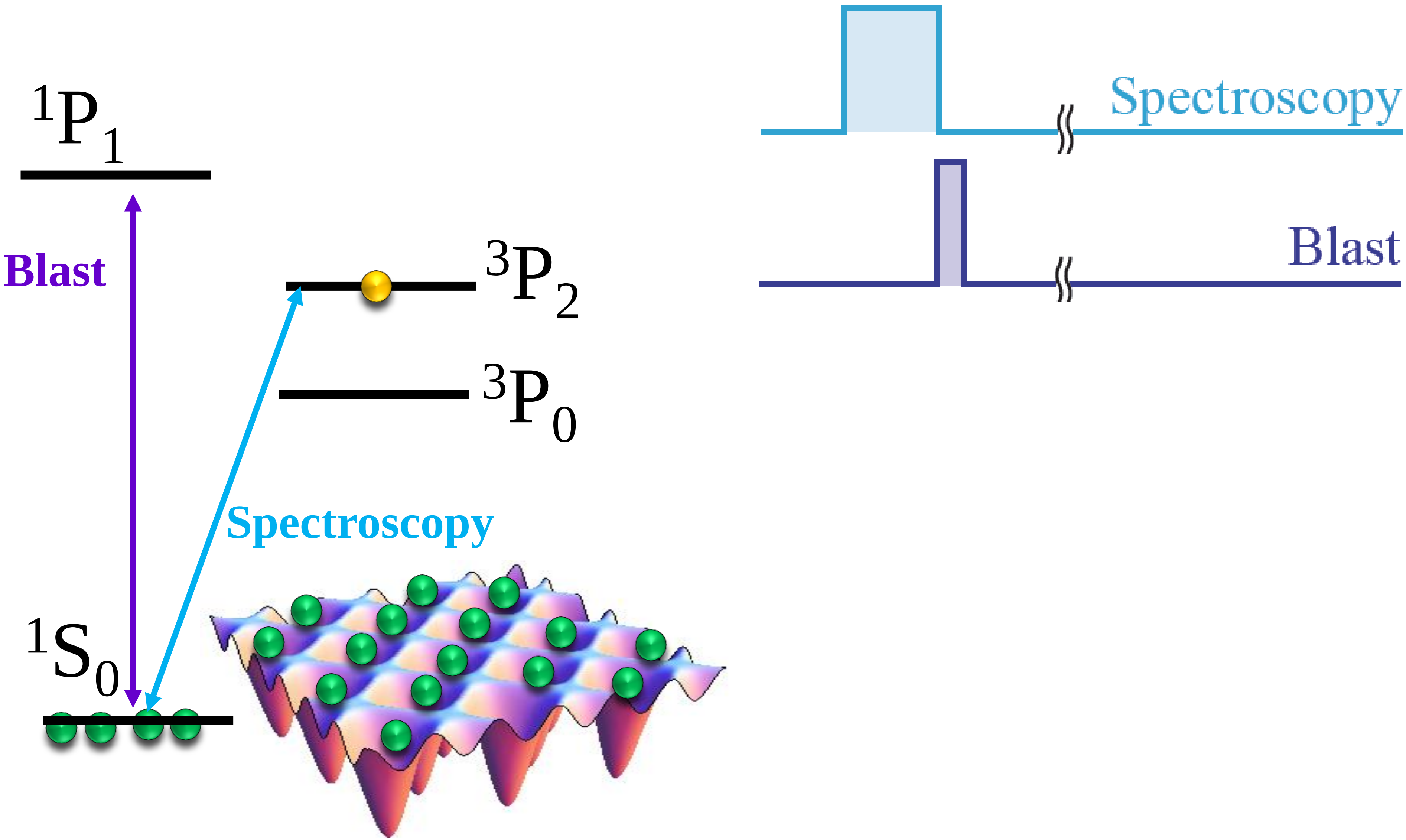
K. Shibata *et al*, Appl. Phys. B **97**, 753(2009). Single-Atom Addressing by MRI

A. J. Daley *et al*, PRL. **101**, 170504(2008). Dual Lattice Configuration

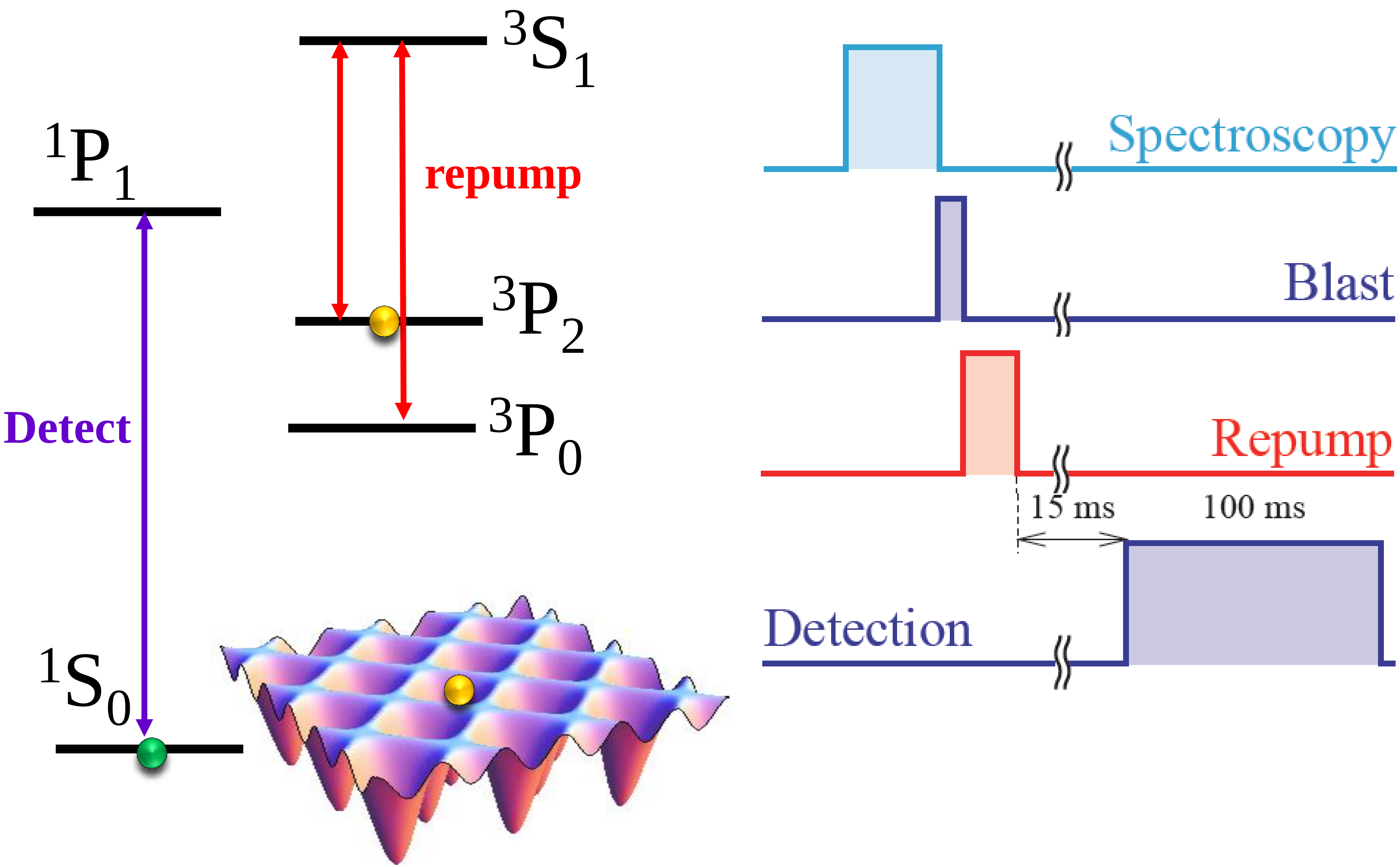
A. V. Gorshkov *et al*, PRL. **102**, 110503(2009). Few-Qubit Quantum Register

F. Gerbier and J. Dalibard, New J. Physics **12**, 033007(2010). Gauge fields

Spectroscopy of Atoms in an Optical lattice

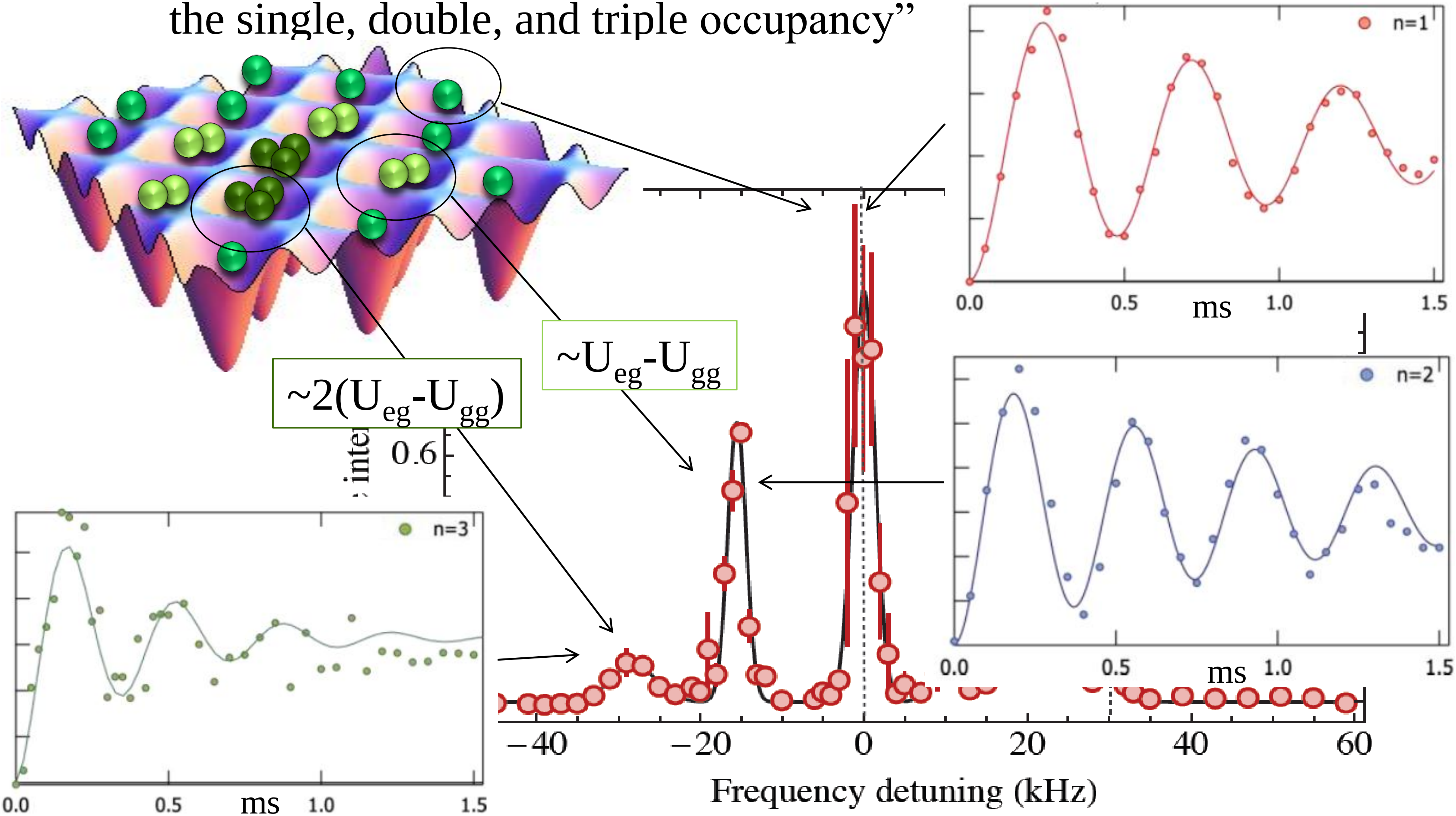


Spectroscopy of Atoms in an Optical lattice

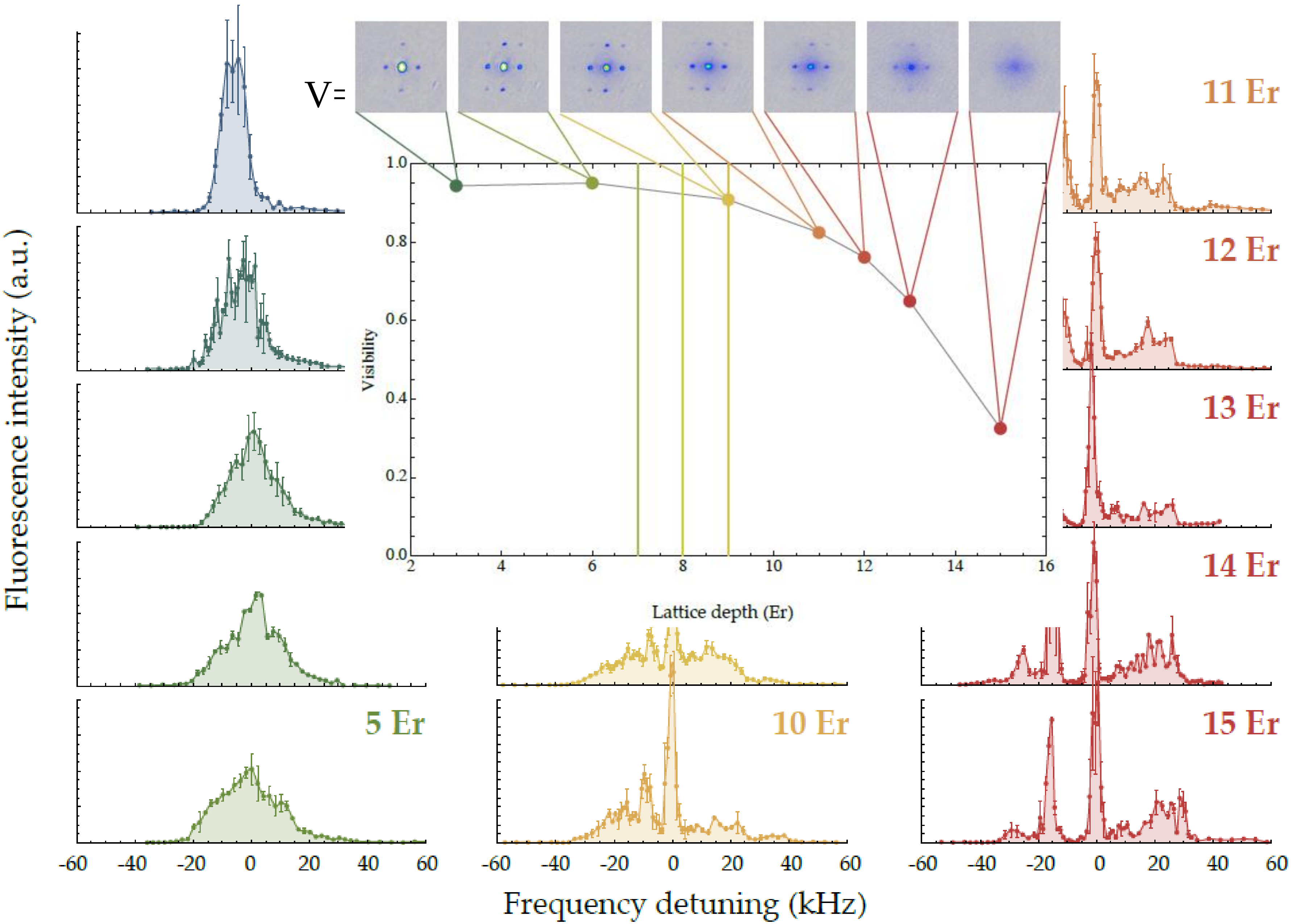


Spectroscopy of Atoms in a Mott Insulating State

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

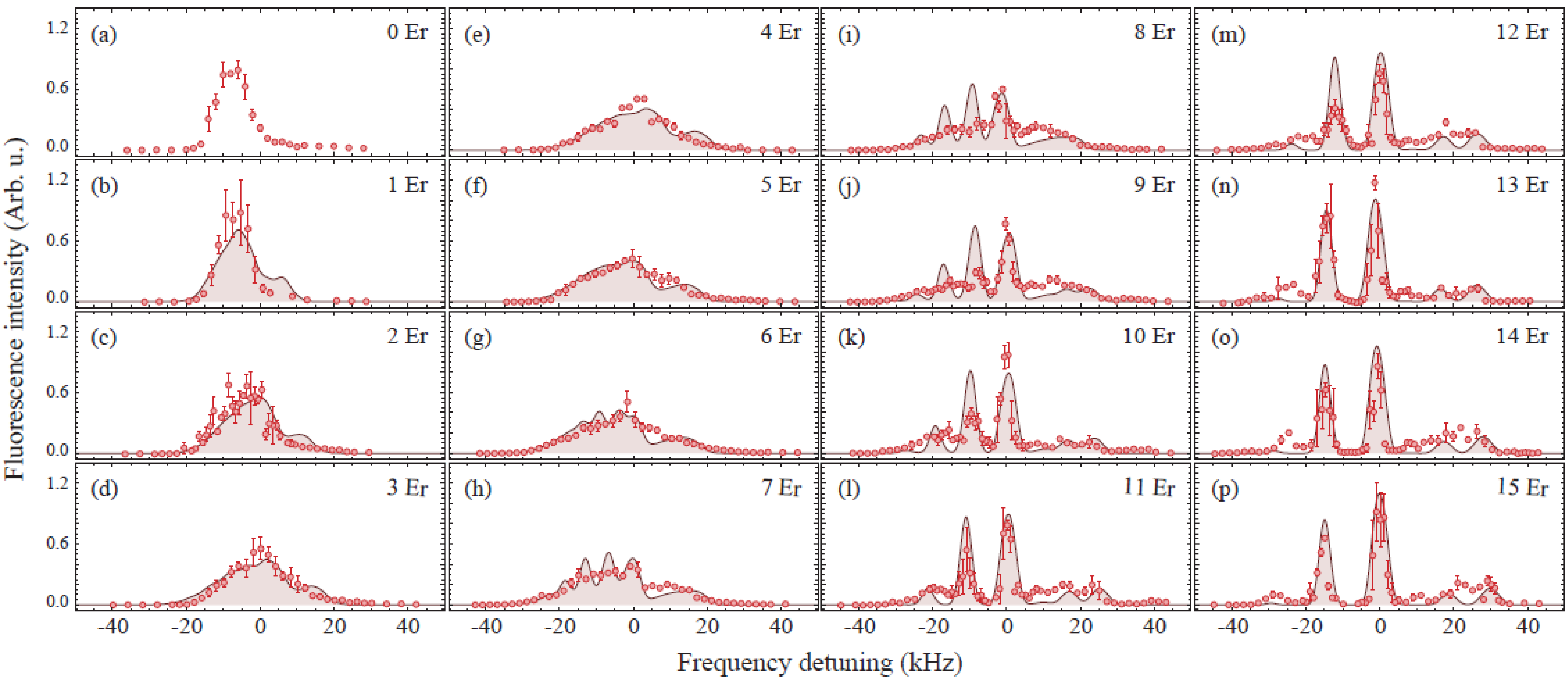


Spectroscopy of Superfluid-Mott Insulator Transition



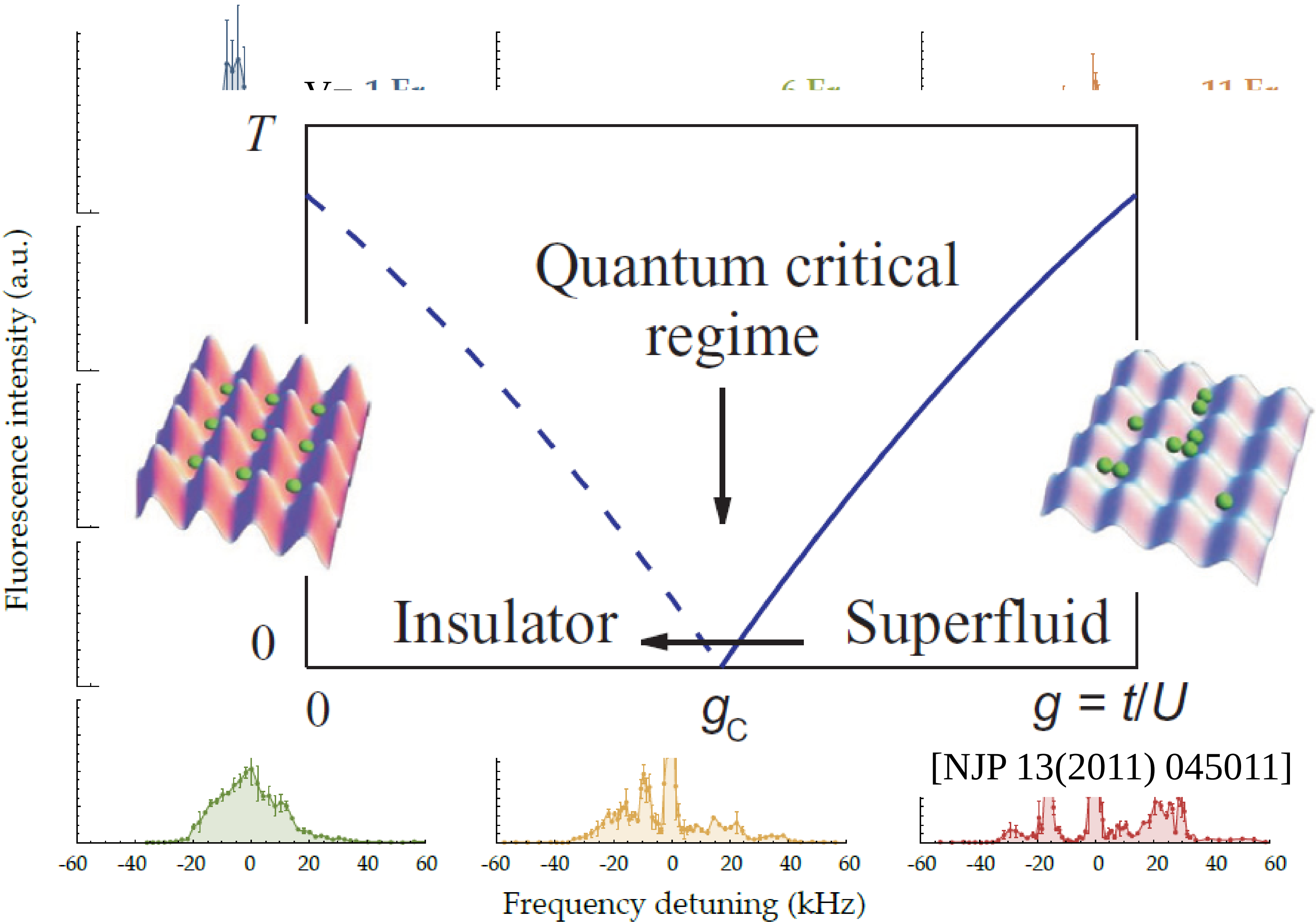
Spectroscopy of Superfluid-Mott Insulator Transition

"Comparison with finite temperature Gutzwiller calculation by Inaba"
(preliminary)



T_{init}=95 nK

Spectroscopy of Superfluid-Mott Insulator Transition



[NJP 13(2011) 045011]

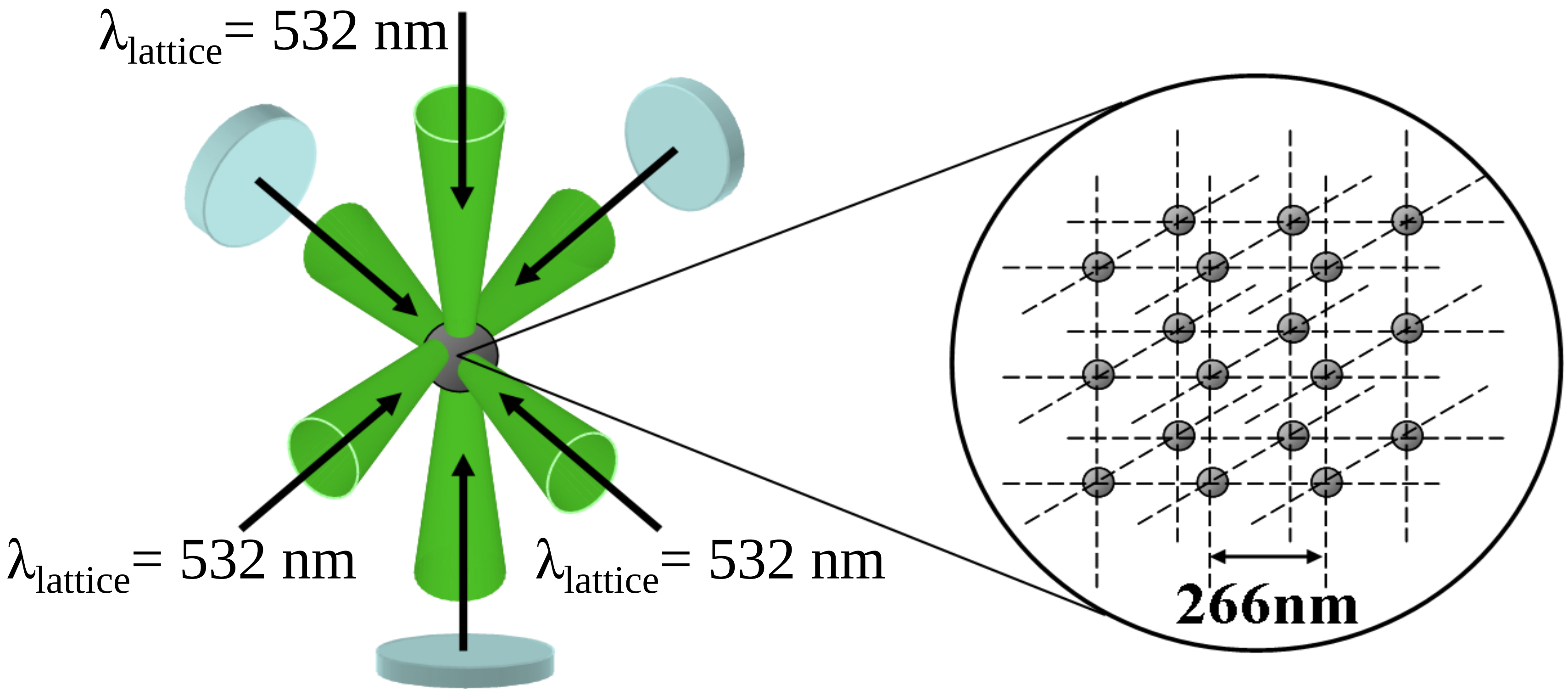
Fermion (^{173}Yb) in a 3D optical lattice

^{173}Yb(I=5/2)

a_s=10.5 nm

$$H = -t_F \sum_{<i,j>} c_i^{+} c_j + U_{FF} \sum_{i, m_F \neq m_F'} n_{m_F, i} n_{m_F', i}$$

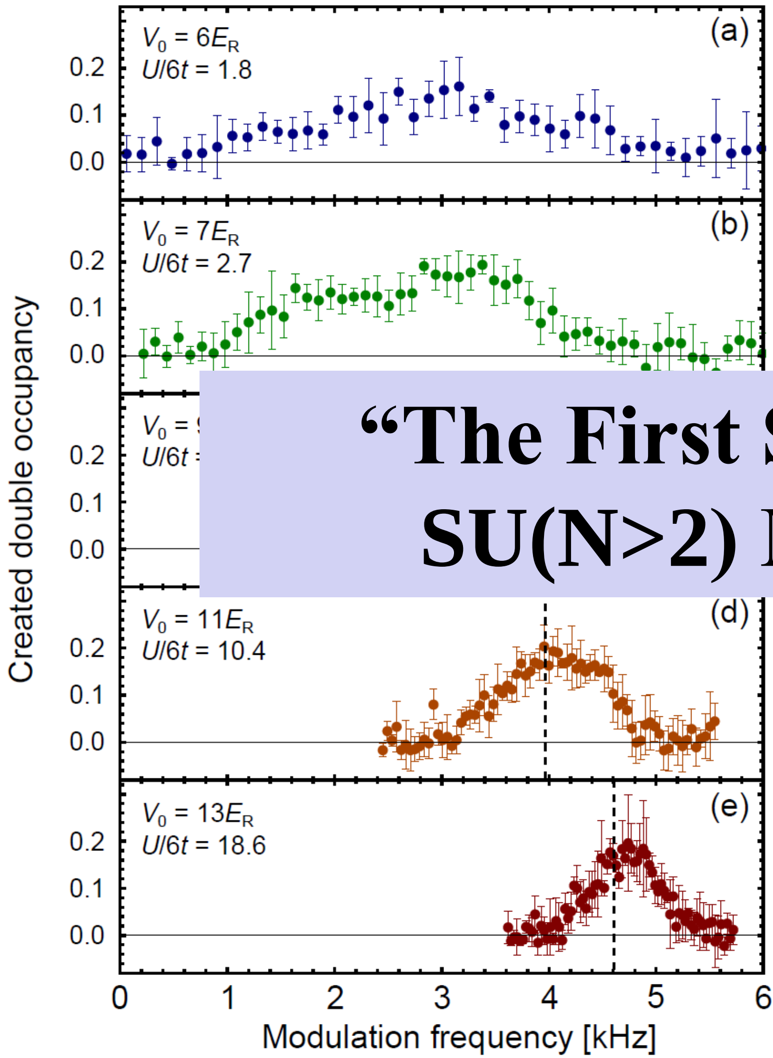
SU(6)Mott-state



"Formation of SU(6) Mott insulator"

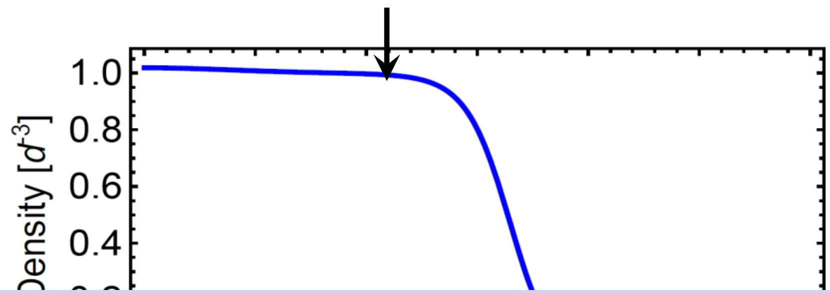
[S. Taie *et al*,]

Excitation (Mott) Gap



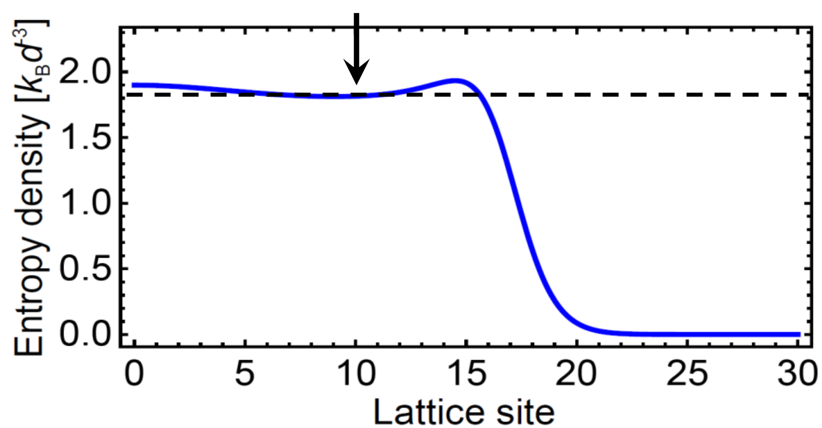
$T_{lattice}$=5.1t= 16 nK U/t=62.4

Mott Plateau (n=1)



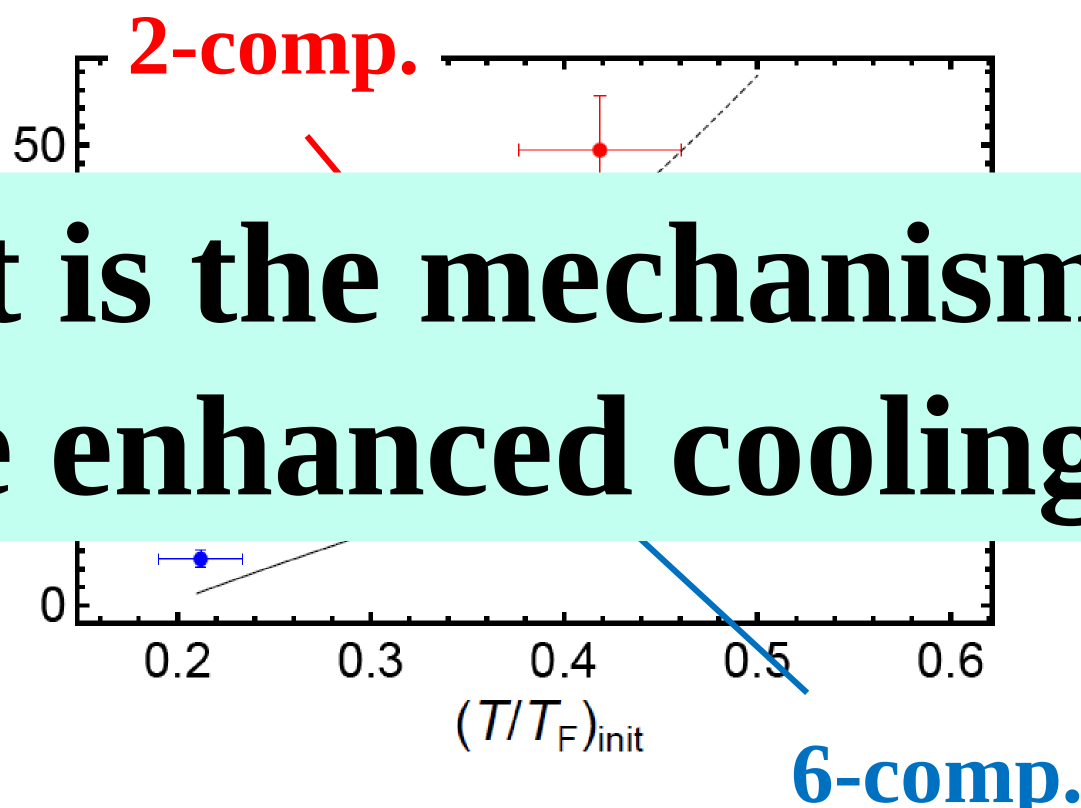
"The First Successful Formation of SU(N>2) Mott Insulating State"

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



Atomic Pomeranchuk Cooling

[^{173}Yb atoms in optical lattice; Taie *et al*,]



What is the mechanism of the enhanced cooling ?

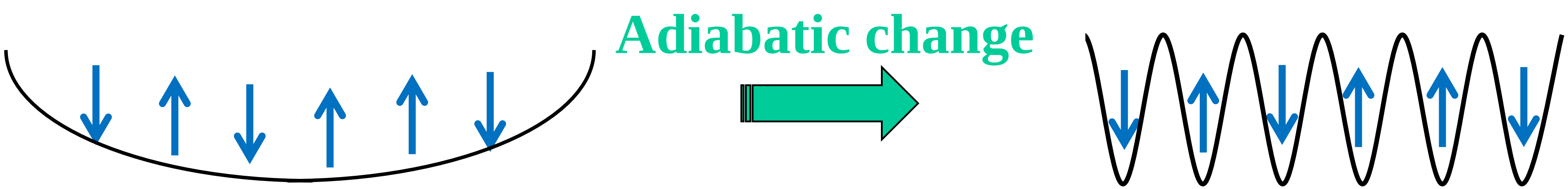
Pomeranchuk Cooling

Pomeranchuk Cooling [Pomeranchuk, (1950)]

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

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”

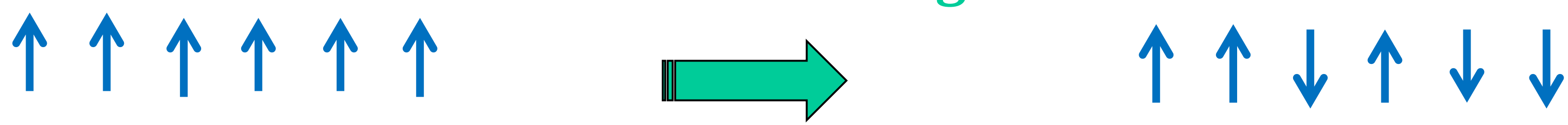
⟶ “Pomeranchuk Cooling of an Atomic Gas”

Spin Degrees of Freedom *is Cool*

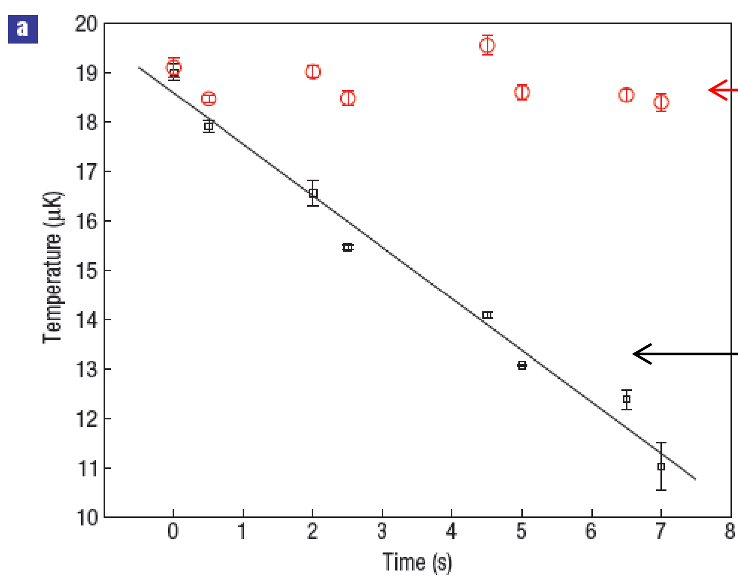
<u>Demagnetization Cooling</u> [W. J. De Haas, *et al.*, (1934)]

Initial state: Spin-polarized: **Final state: Spin-depolarized:**

Adiabatic change



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



kept at high filed(1G)

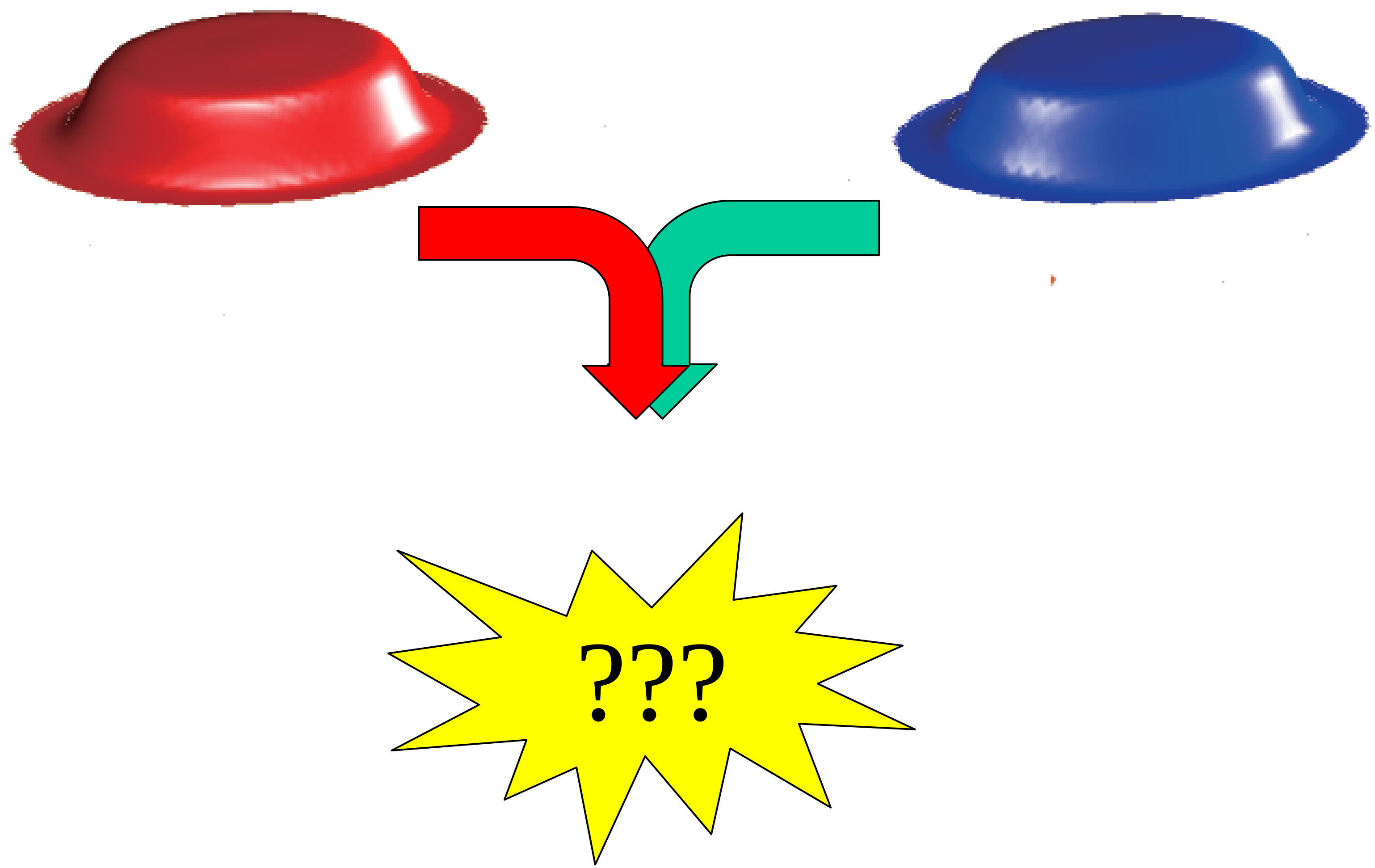
kept at low filed(50mG) and Optical Pumping

[M. Fattori, *et al* .,Nat. Physics**2**, 765(2006)]

Strongly Interacting Two Different Mott Insulators

[S. Sugawa, K. Inaba, *et al.*, arXiv:1011.4503v2]

Bosonic Mott insulator | Fermionic Mott Insulator



Mixture of Spinless Boson and SU(6) Fermion in a 3D optical lattice

^{174}Yb(Boson) + ^{173}Yb(Fermion)

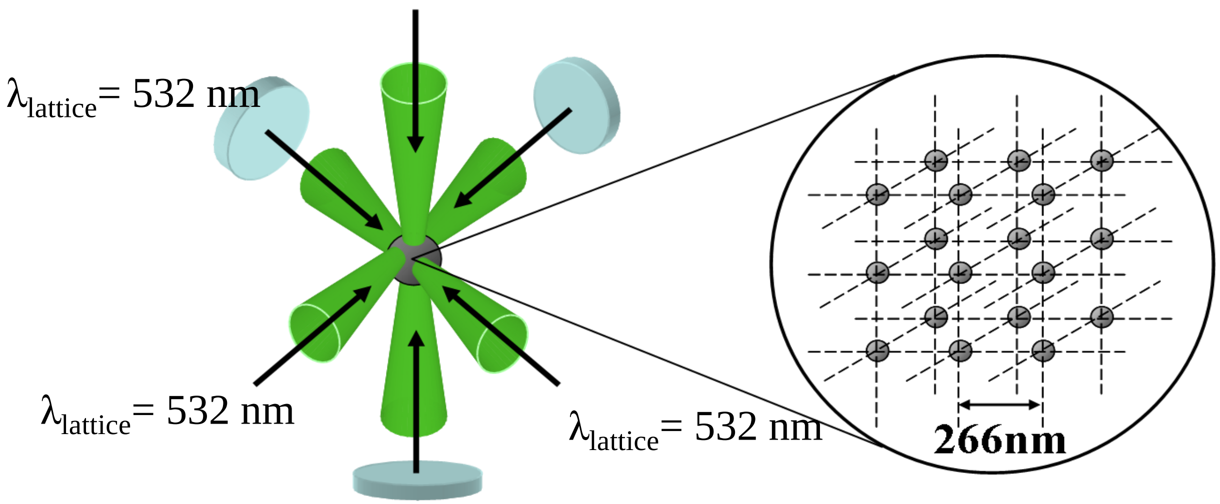
a_{BB} = +5.6 nm a_{FF} = +10.6 nm

^{173}Yb:
6-spin components

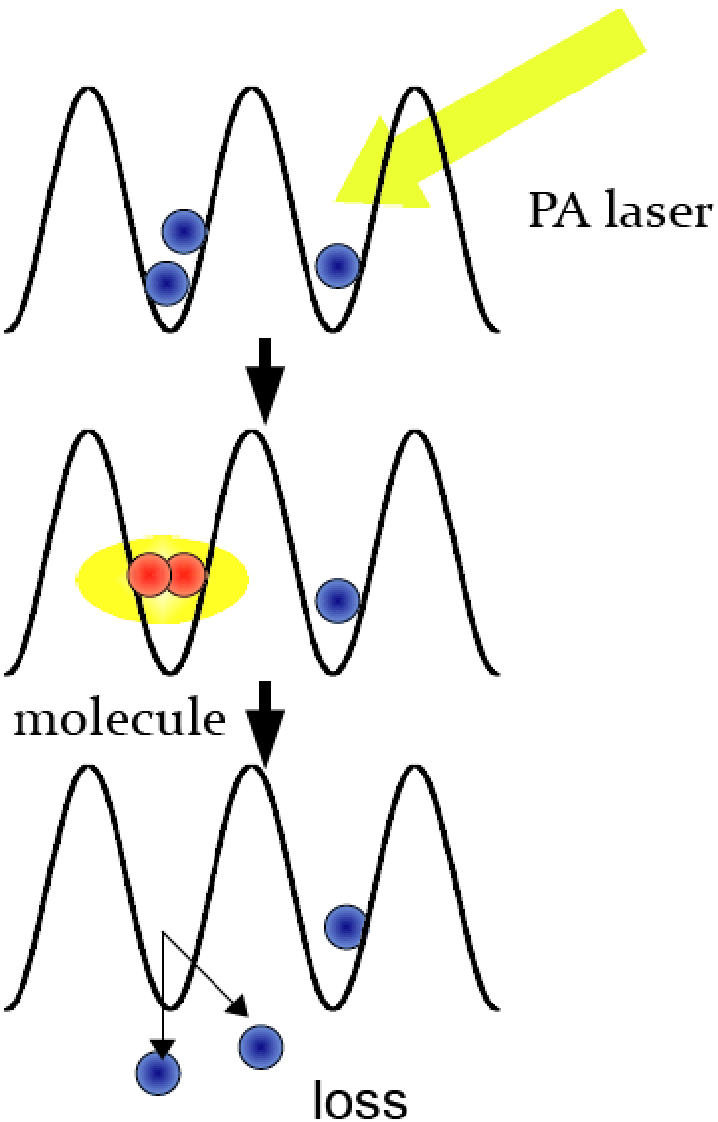
a_{BF} = +7.3 nm
(Repulsive Interaction)

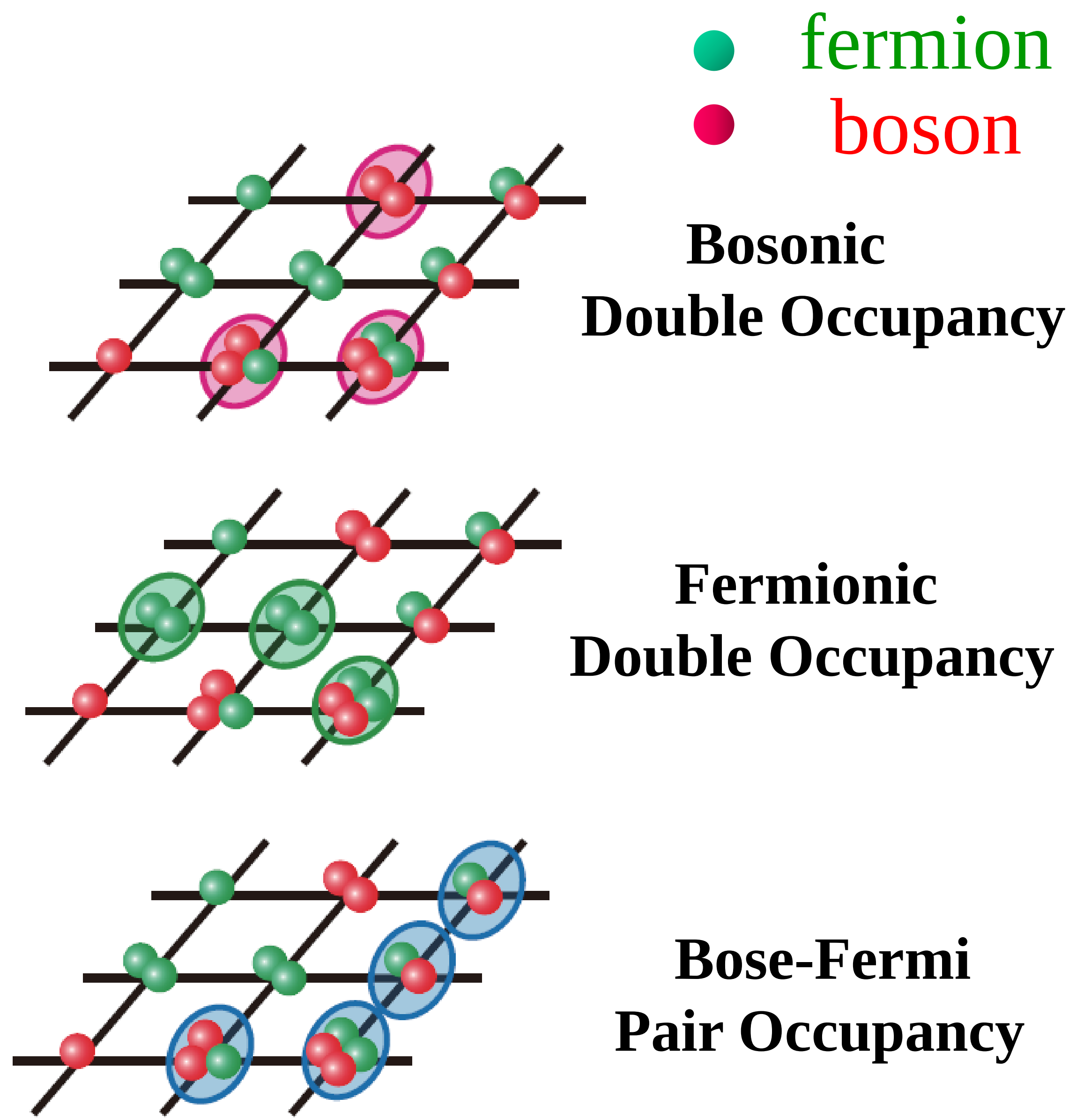
Dual Mott Insulators of Boson and Fermion:

$$J \ll k_B T < U_{BB} < U_{BF} < U_{FF}$$



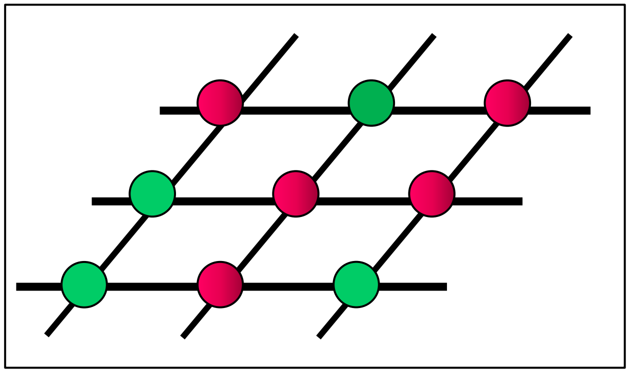
Measurement of Site Occupancy by Photoassociation



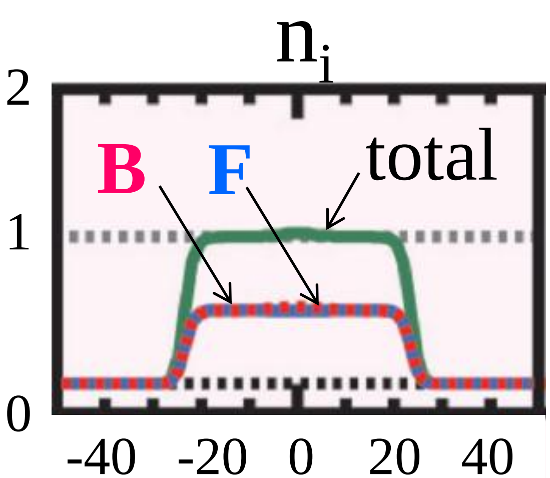


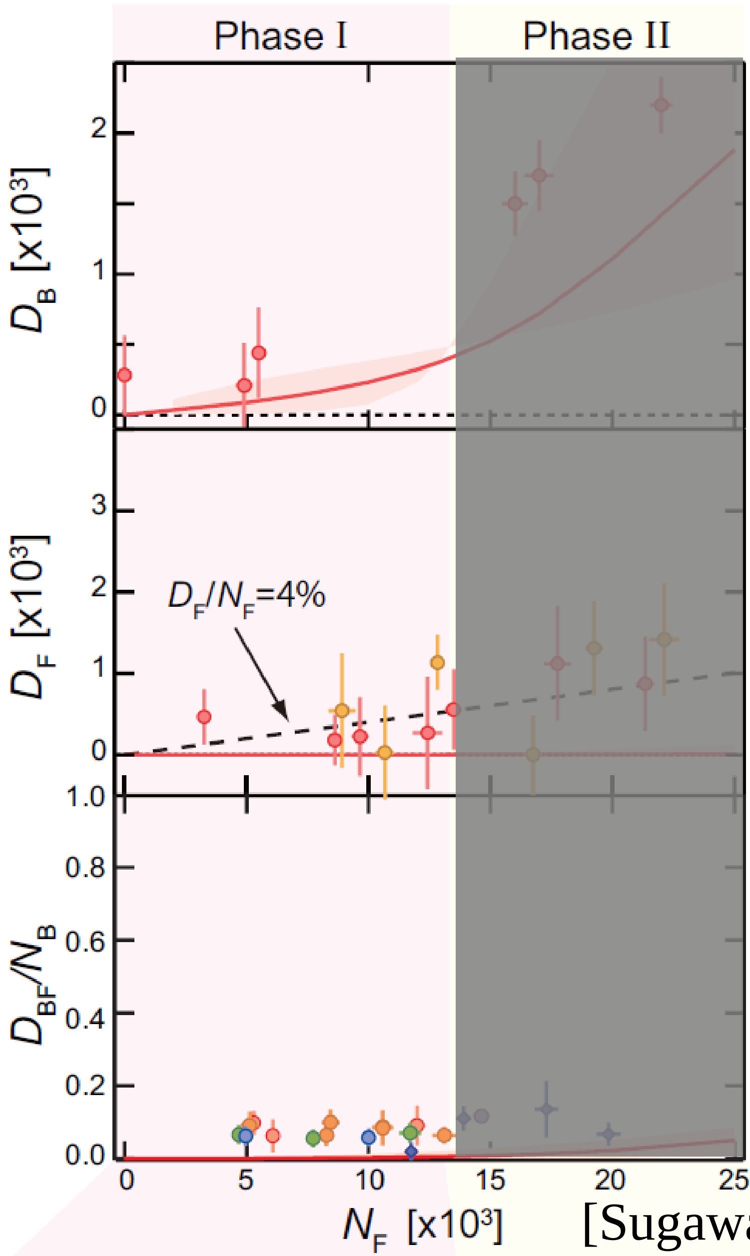
Repulsively Interacting Bose-Fermi Mott Insulators

- fermion
- boson



“Mixed Mott Insulator”

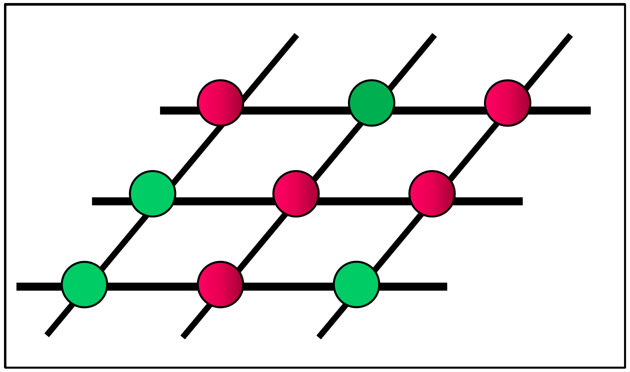




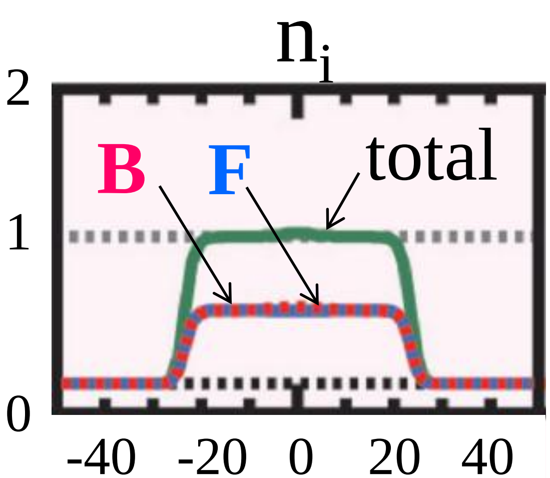
[Sugawa *et al*. *NP*. **7**, 642–648 (2011)]

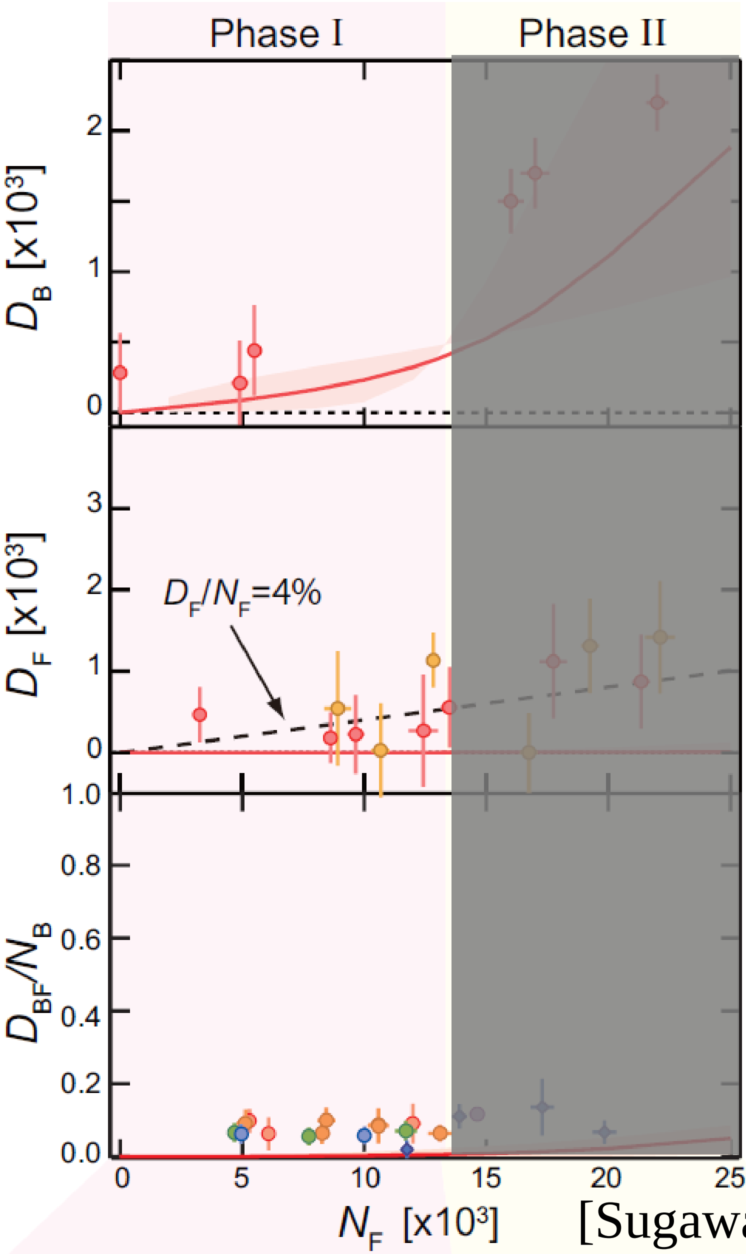
Repulsively Interacting Bose-Fermi Mott Insulators

- fermion
- boson



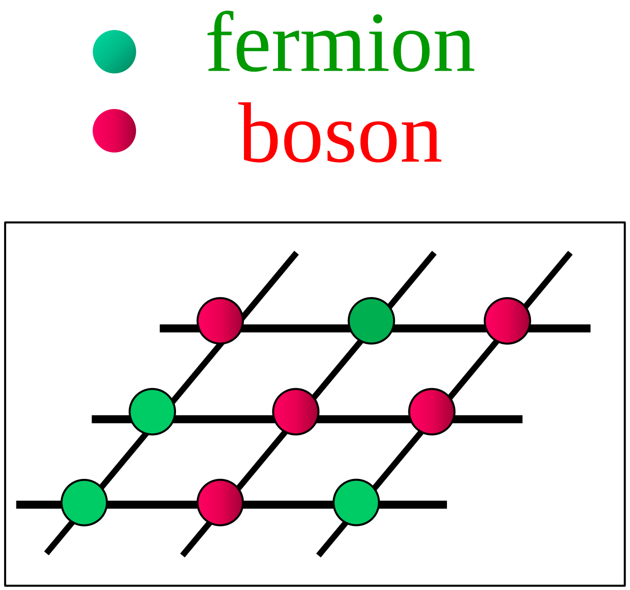
“Mixed Mott Insulator”



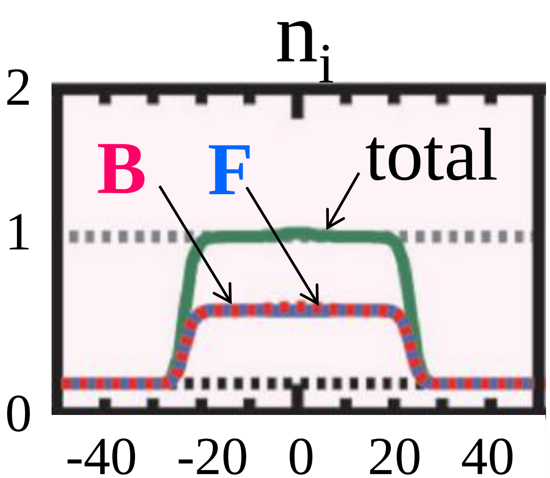


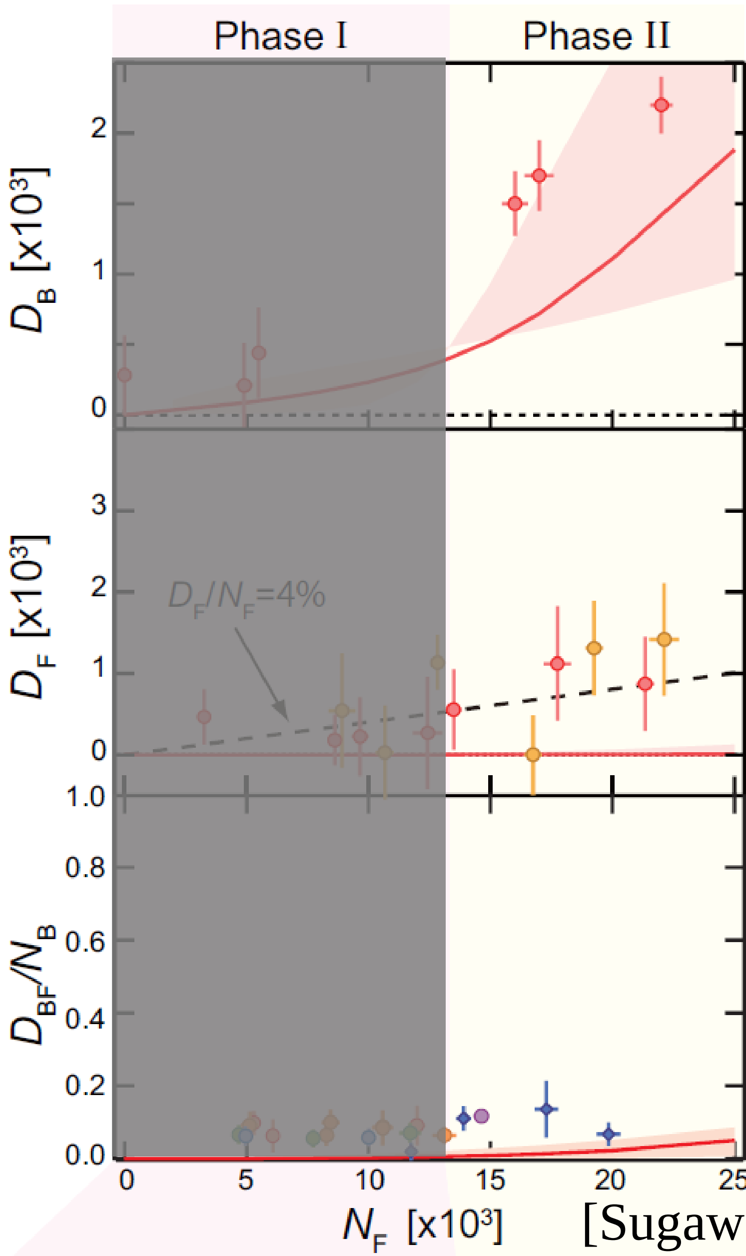
[Sugawa *et al*. *NP*. **7**, 642–648 (2011)]

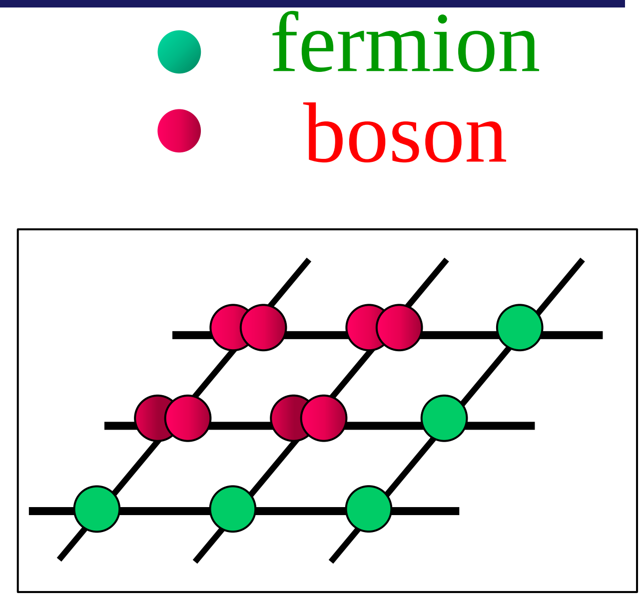
Repulsively Interacting Bose-Fermi Mott Insulators



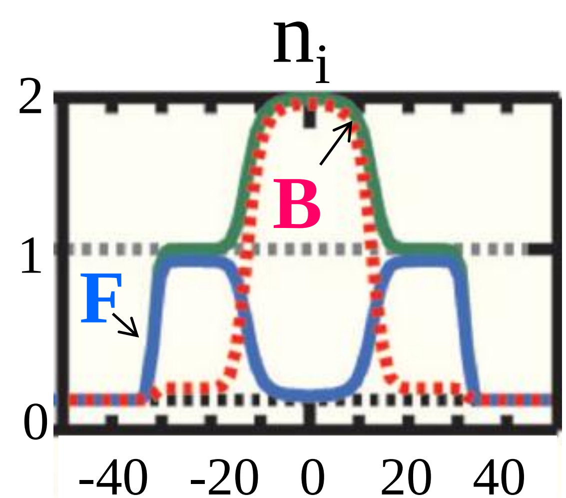
“Mixed Mott Insulator”







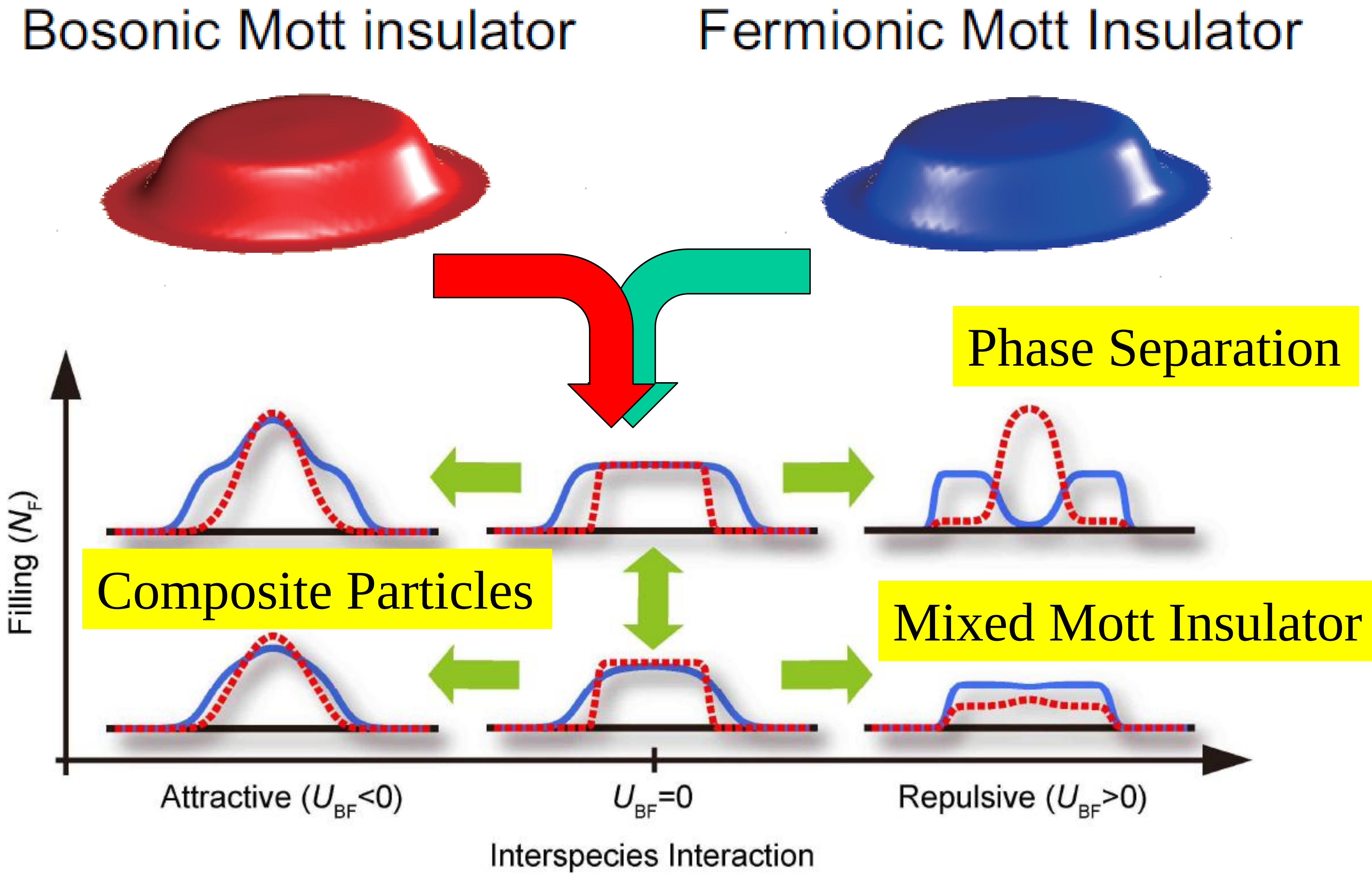
“Phase Separation”



[Sugawa *et al.* *NP.* **7**, 642–648 (2011)]

Strongly Interacting Two Different Mott Insulators

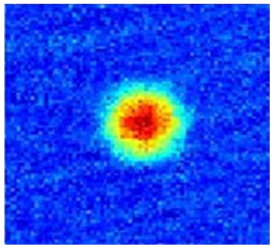
[S. Sugawa, K. Inaba, *et al.*, arXiv:1011.4503v2]



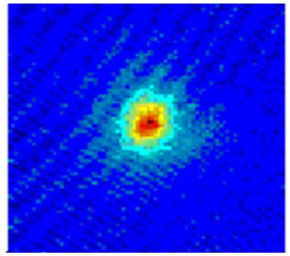
Anderson Hubbard Model with Li-Yb Mixture

Fermion(^{6}Li)-Boson(^{174}Yb)

^{6}Li



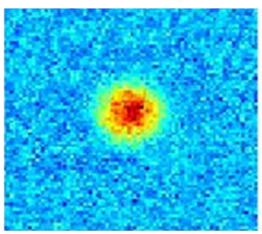
^{174}Yb



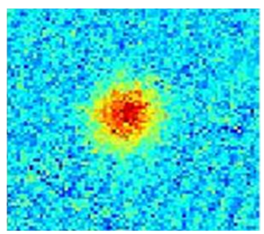
$T/T_F = 0.08 \pm 0.01$

Fermion(^{6}Li)-Fermion(^{173}Yb)

^{6}Li

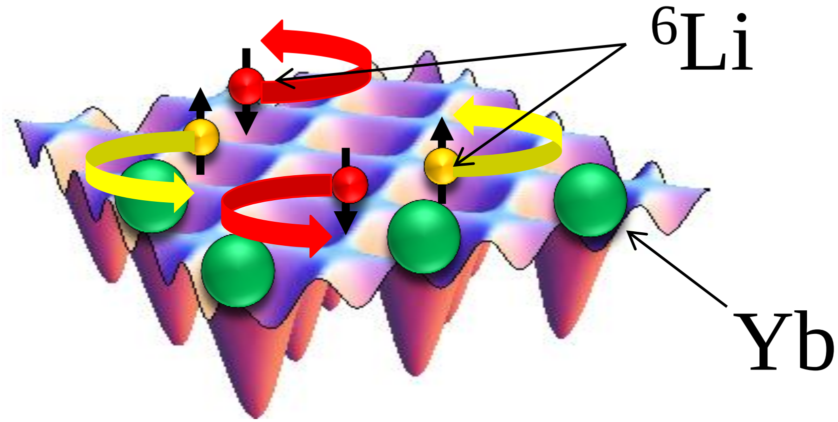


^{173}Yb



$T/T_F = 0.07 \pm 0.02$

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



[D. Semmler, K. Byczuk, and W. Hofstetter, PRB **81**, 115111(2010)]

$$M_{^{174}Yb} / M_{^{6}Li} \cong 29$$

Summary2

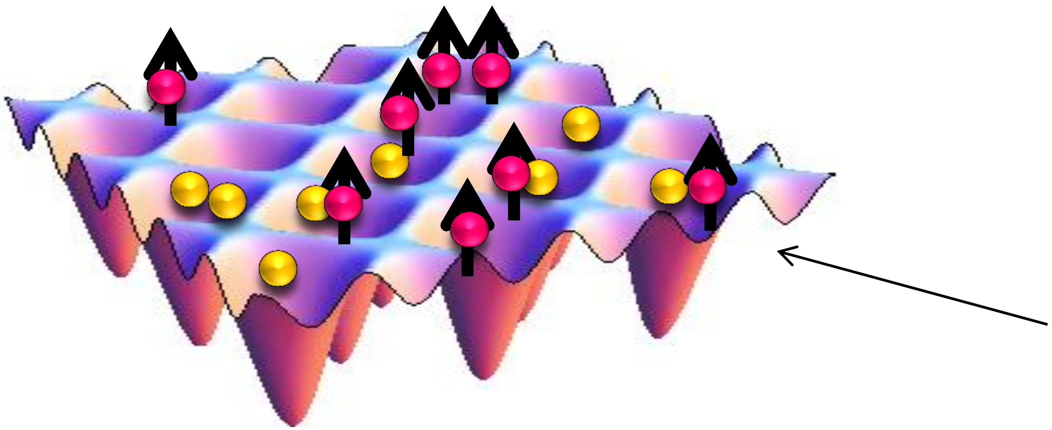
Quantum Simulation of Hubbard Model Using Yb atoms in an Optical Lattice

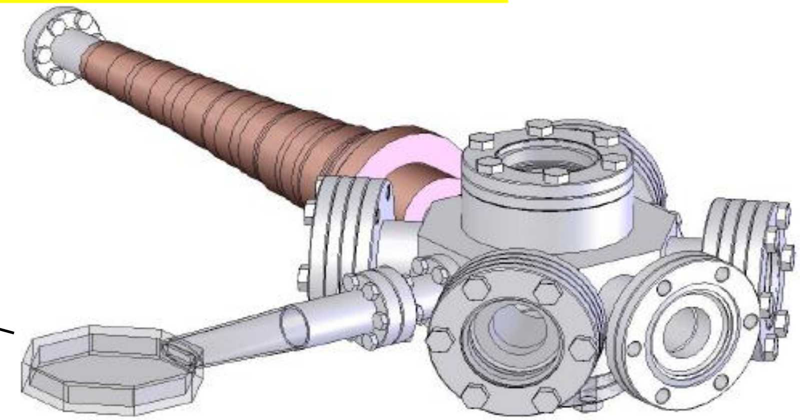
1)Bose-Hubbard Model: *Superfluid-Mott Insulator Transition*
High-Resolution Laser spectroscopy
2)Fermi-Hubbard Model: *Fermi Mott Insulator*
SU(6) Mott insulator
Pomeranchuk Cooling,
Close to quantum magnetism
3)Bose-Fermi-Hubbard Model:
Mixed Mott Insulaotr
4)Plan
Anderson Localization (Lieb Lattice, Spin-Orbit interaction)

(Optical and magnetic Feshbach resonance, Quantum Gas Microscope)

基礎物理学への応用

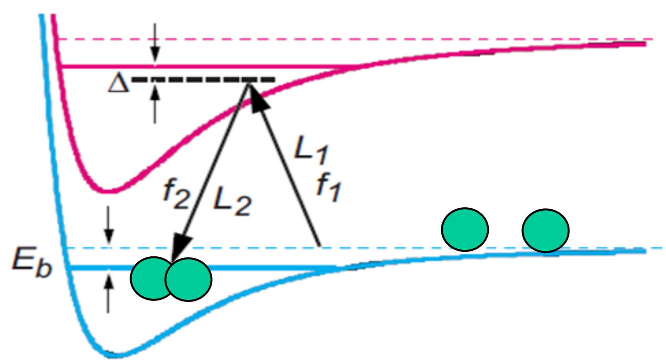
極低温極性分子を用いた時間反転対称性の検証

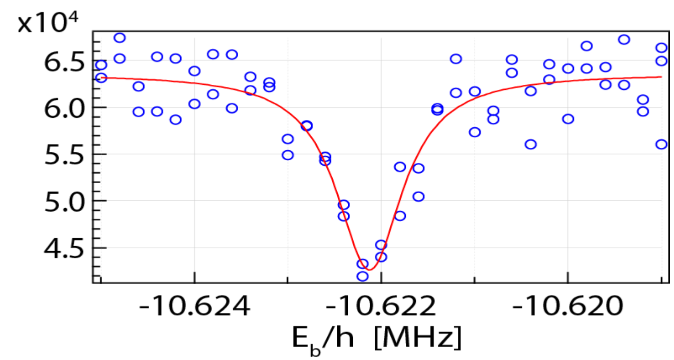




極低温原子の超精密分光による近距離重力補正の検証

$$V(r) = -\frac{GM_1M_2}{r} \times \left(1 + \alpha\, e^{-r/\lambda}\right)$$





Outline

- **Possible Test of Gravity at Short Range by Photoassociation**

- **Possible EDM Search by using Ultracold HgYb Molecules**

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- **Possible Test of Gravity at Short Range by Photoassociation**

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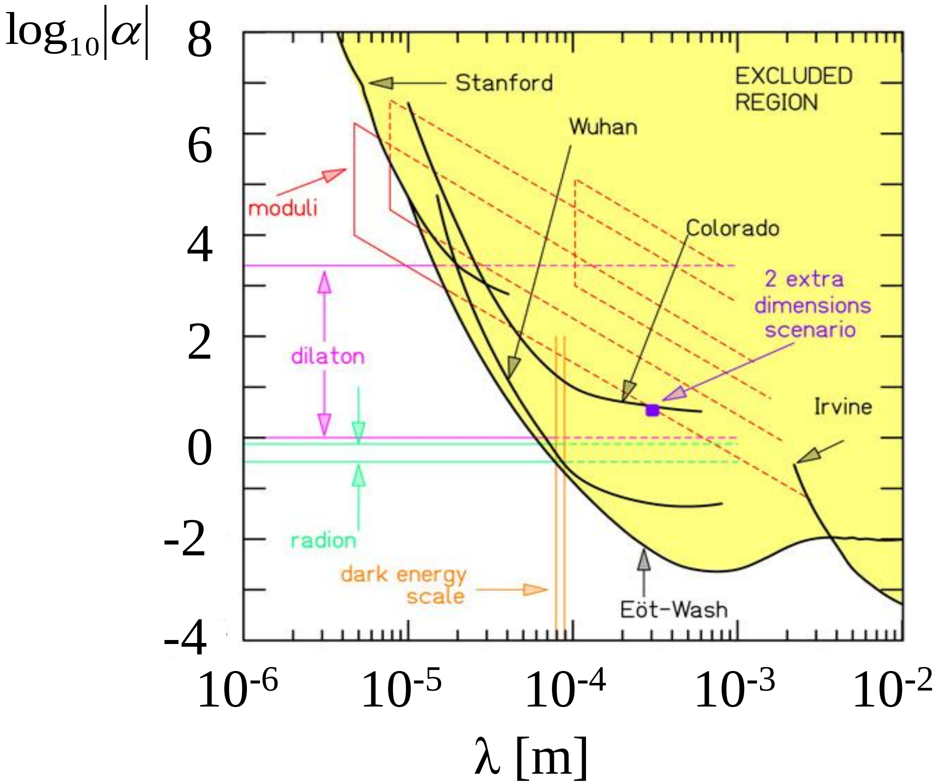
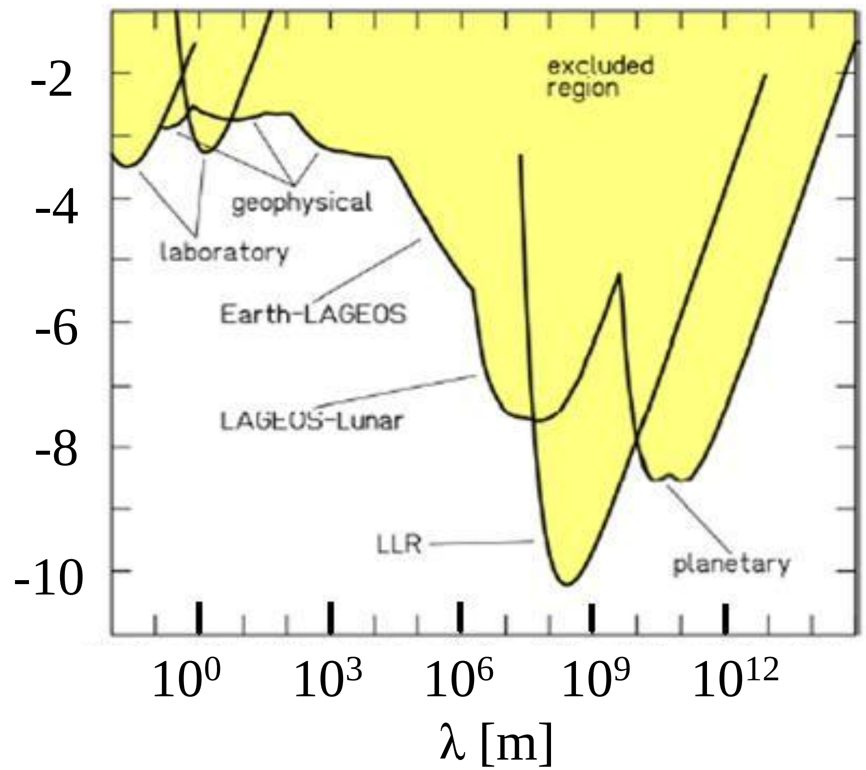
Test of the Gravitational r^{-2} Law at Short Range

$$V(r) = -\frac{GM_1M_2}{r} \quad \Rightarrow \quad V(r) = -\frac{GM_1M_2}{r}\left(1+\underline{\alpha\, e^{-r/\lambda}}\right)$$

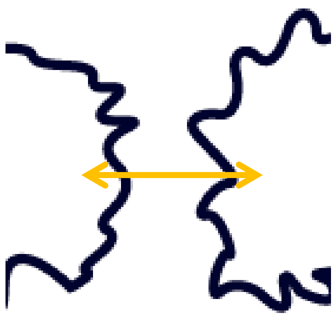


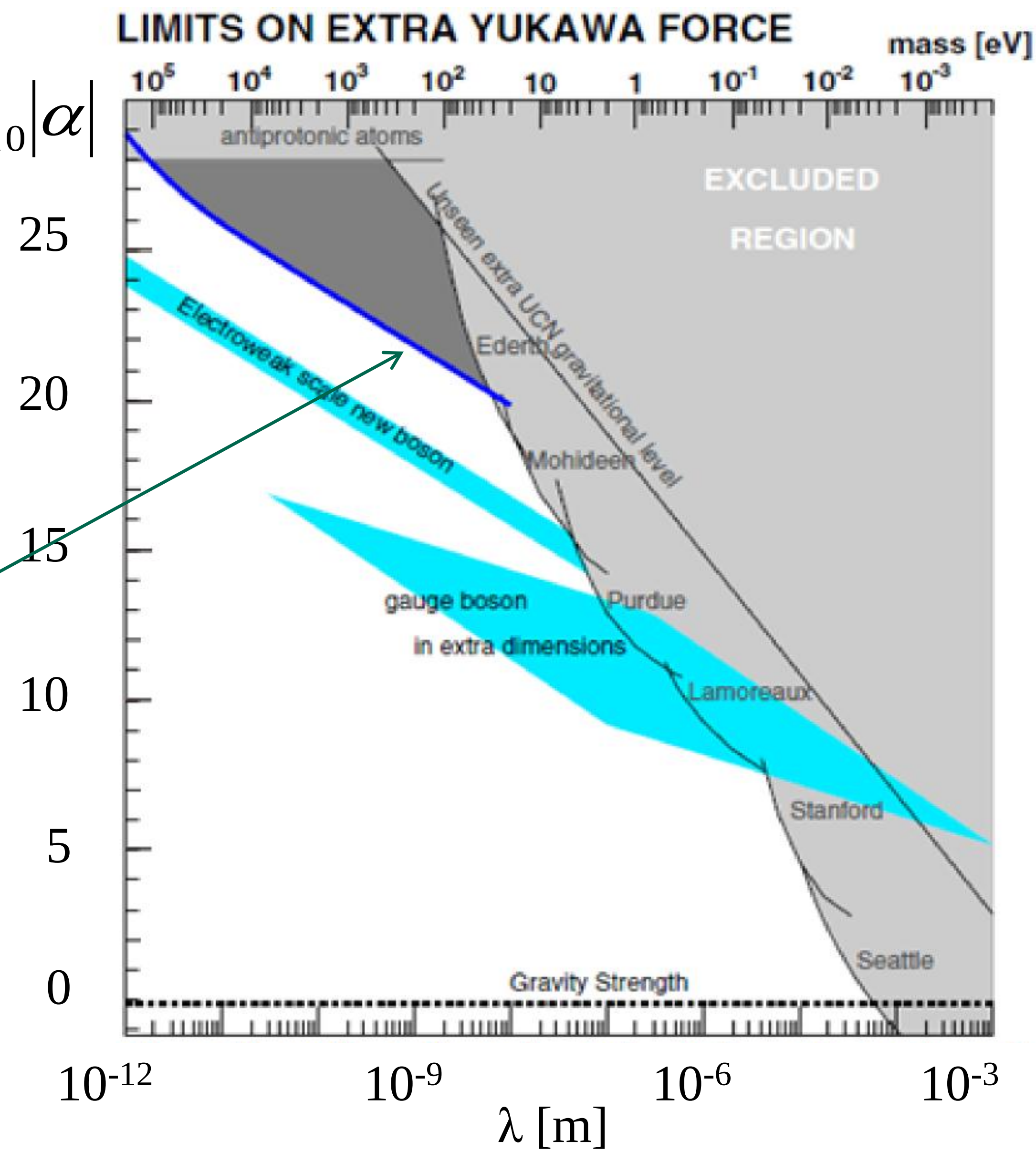


Prog.Part.Nucl.Phys., **62**, 102(2009)

Gravity at Short Range

$$V(r) = -\frac{GM_1M_2}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$





$$|\alpha| \sim 10^{22}\ @1\,\text{nm}$$

[*PRD*, **77**, 034020 (2008)]

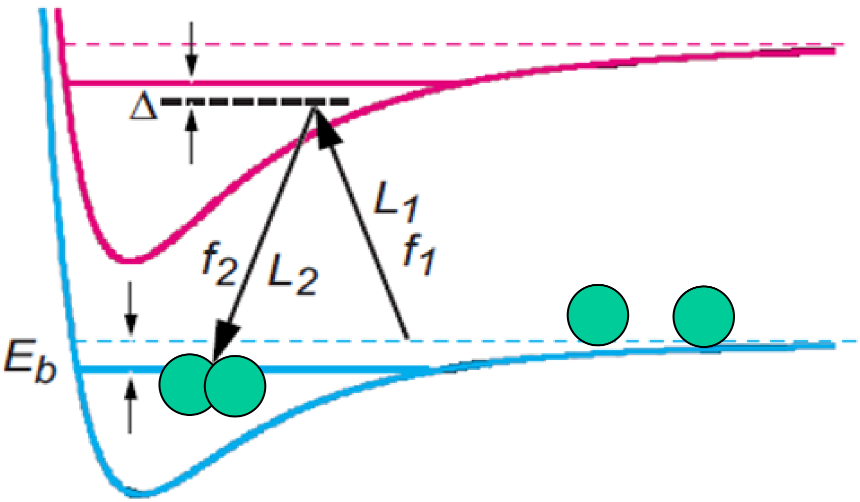
(neutron scattering data)

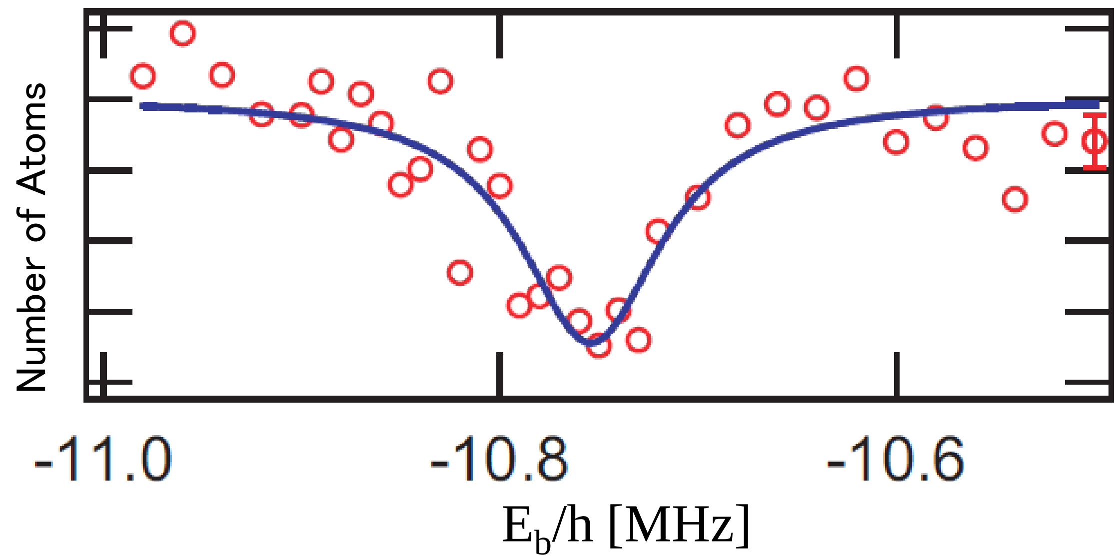
Our Approach : Photoassociation

[M. Kitagawa, et al., PRA **77**, 012719(2008)]

thermal gas :~100kHz

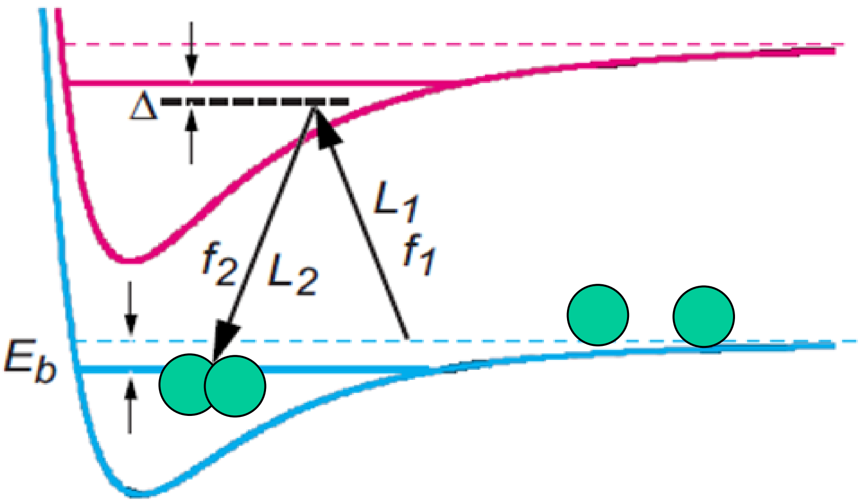
^{174}Yb:v=1, J=0

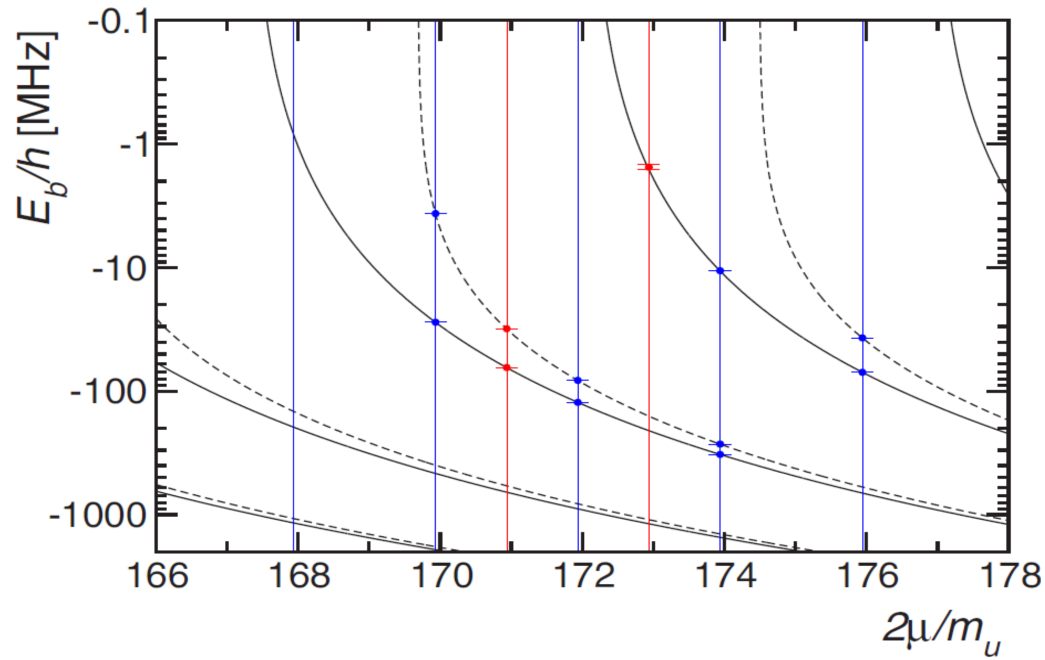




Our Approach : Photoassociation

[M. Kitagawa, et al., PRA **77**, 012719(2008)]





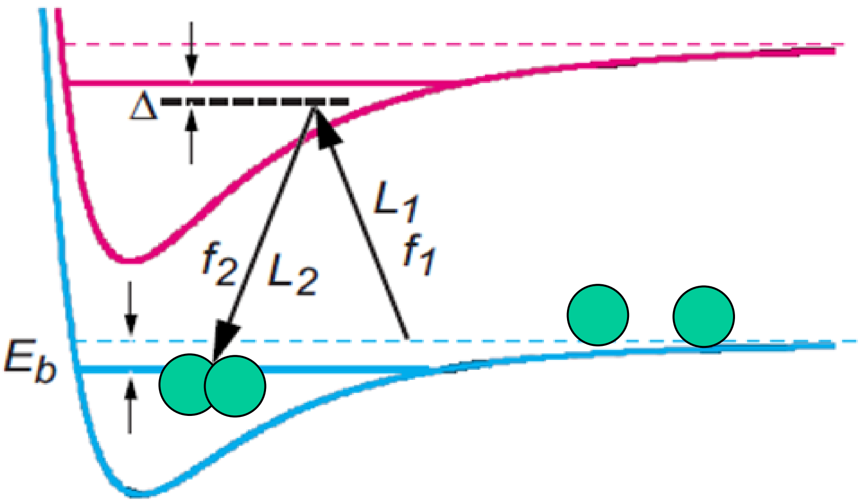
Lenard-Jones-type Potential

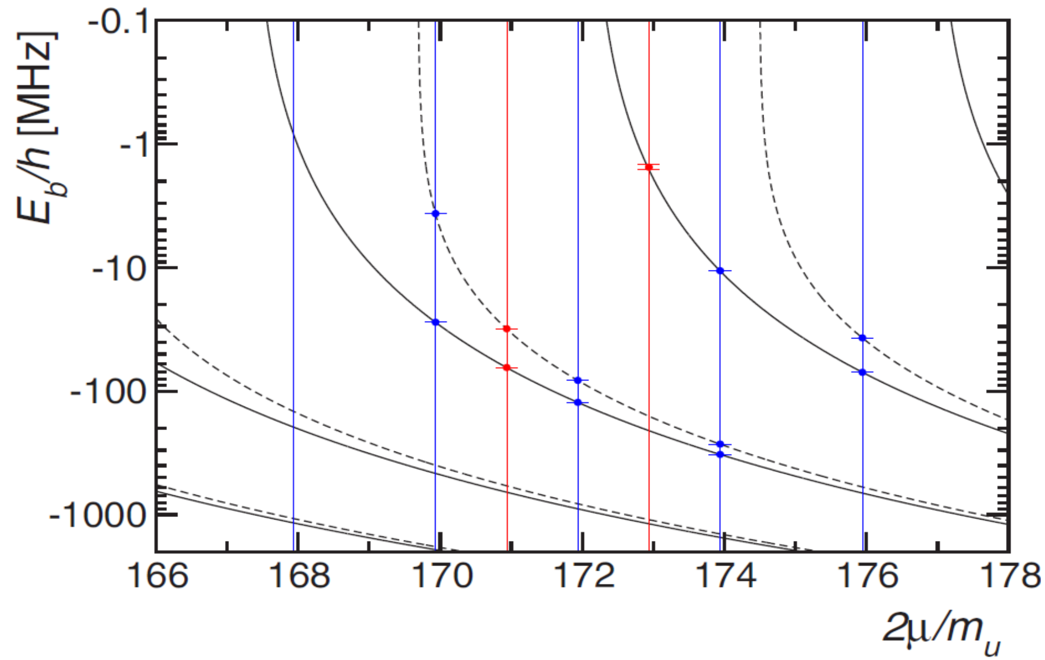
$$V(r) = \frac{C_{12}}{r^{12}} - \frac{C_6}{r^6} - \frac{C_8}{r^8}$$

C_6=1931.7 $E_h\ a_0^6$, C_8=1.93×10^6 $E_h a_0^8$, C_{12}=1.3041 $E_h a_0^{12}$

Our Approach : Photoassociation

[M. Kitagawa, et al., PRA **77**, 012719(2008)]





Lenard-Jones-type Potential

$$\Rightarrow V(r) = \frac{C_{12}}{r^{12}} - \frac{C_6}{r^6} - \frac{C_8}{r^8} - \frac{GM_1M_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

Δf=1kHz ⇓ $|\alpha| <\sim 10^{20}$ @1 nm

C_6=1931.7 $E_h a_0^6$, C_8=1.93×10^6 $E_h a_0^8$, C_{12}=1.3041 $E_h a_0^{12}$

Many Advantages of Ytterbium

Nice Atomic Species for this experiment !

- Heavy (N~174)
- Single Molecular Potential :No Hyperfine Structure

  Contrary to Alkali Dimers

  Insensitivity to magnetic field

- Many Isotopes:

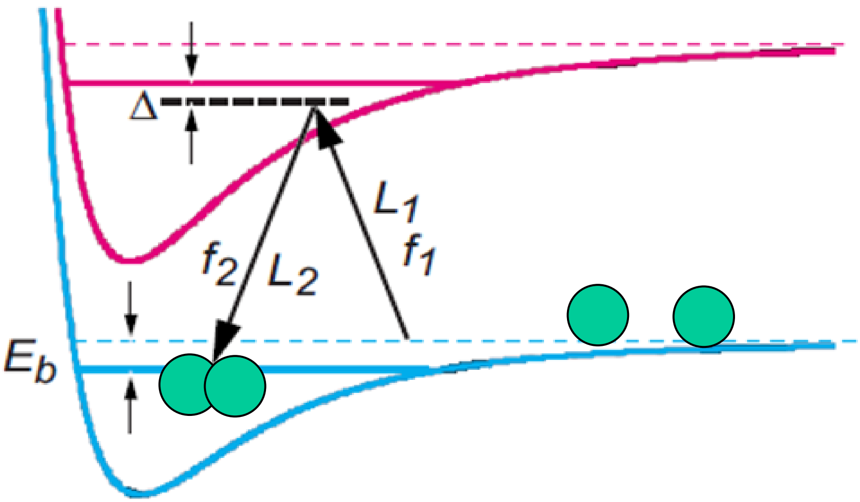
  ^{168}Yb, ^{170}Yb, ^{171}Yb, ^{172}Yb, ^{173}Yb, ^{174}Yb, ^{176}Yb

  Check the mass dependence

- Ultracold Quantum Gases :

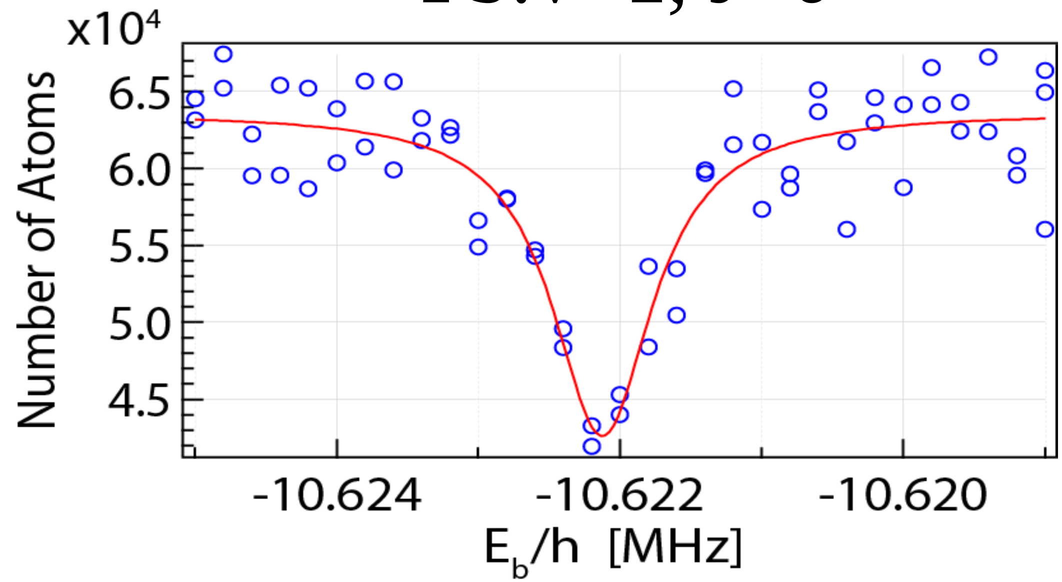
  Free from thermal shift and broadening

Our Approach : Photoassociation



BEC :~1kHz

^{174}Yb:v=1, J=0



Lenard-Jones-type Potential

$$V(r)=\frac{C_{12}}{r^{12}}-\frac{C_6}{r^6}-\frac{C_8}{r^8}-\frac{GM_1M_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

Δf=1kHz

$|\alpha| <\sim 10^{20}$

@1 nm

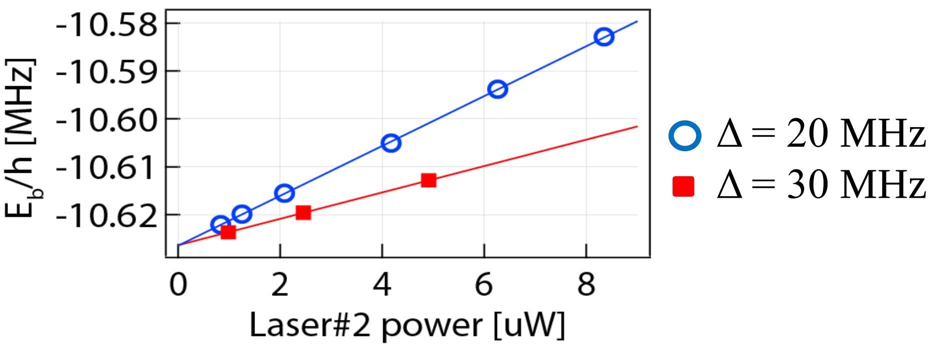
$C_6=1931.7\ E_h\, a_0^6$, $C_8=1.93\times 10^6\ E_h a_0^8$, $C_{12}=1.3041\ E_h a_0^{12}$

Evaluation of Systematic Shifts

Light Shift due to Photoassociation Laser

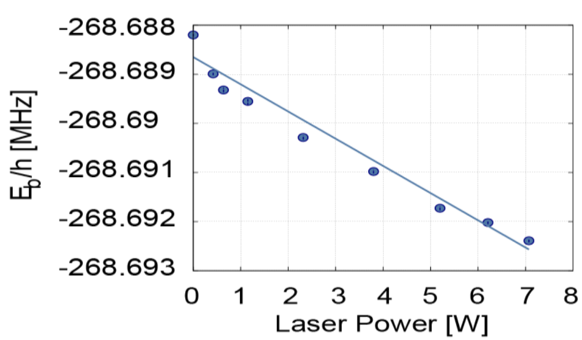
$$\delta_{LS} = \beta\left(\frac{I_1}{\Delta + f_1 - f_2} + \frac{I_2}{\Delta}\right)$$

$$= \alpha_1(\Delta) I_1 + \alpha_2(\Delta) I_2$$



Light Shift due to Optical Trapping Laser

Atoms and Molecules have slightly different polarizabilities

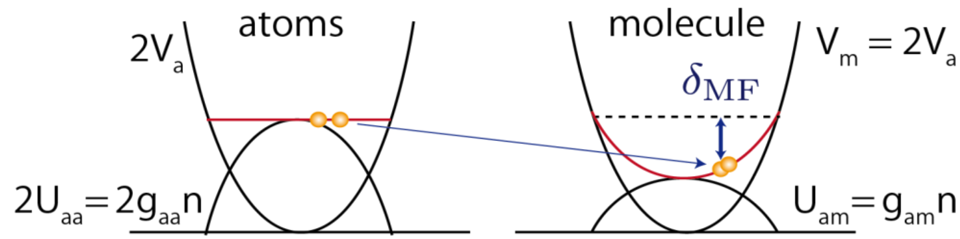


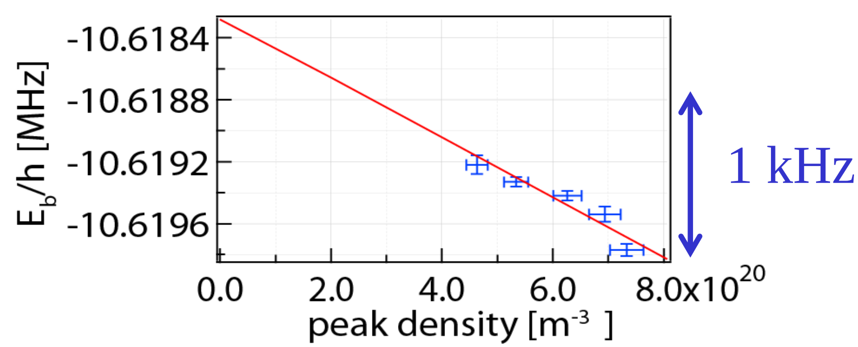
Collision Shift due to Atom-Dimer Collision

$$\delta_{\mathrm{MF}} = 2\pi\hbar^2\left(\frac{2a_{\mathrm{aa}}}{\mu_{\mathrm{aa}}} - \frac{a_{\mathrm{am}}}{\mu_{\mathrm{am}}}\right) n_{\mathrm{atom}}(r)$$

a_{am} : scattering length between atom and molecule

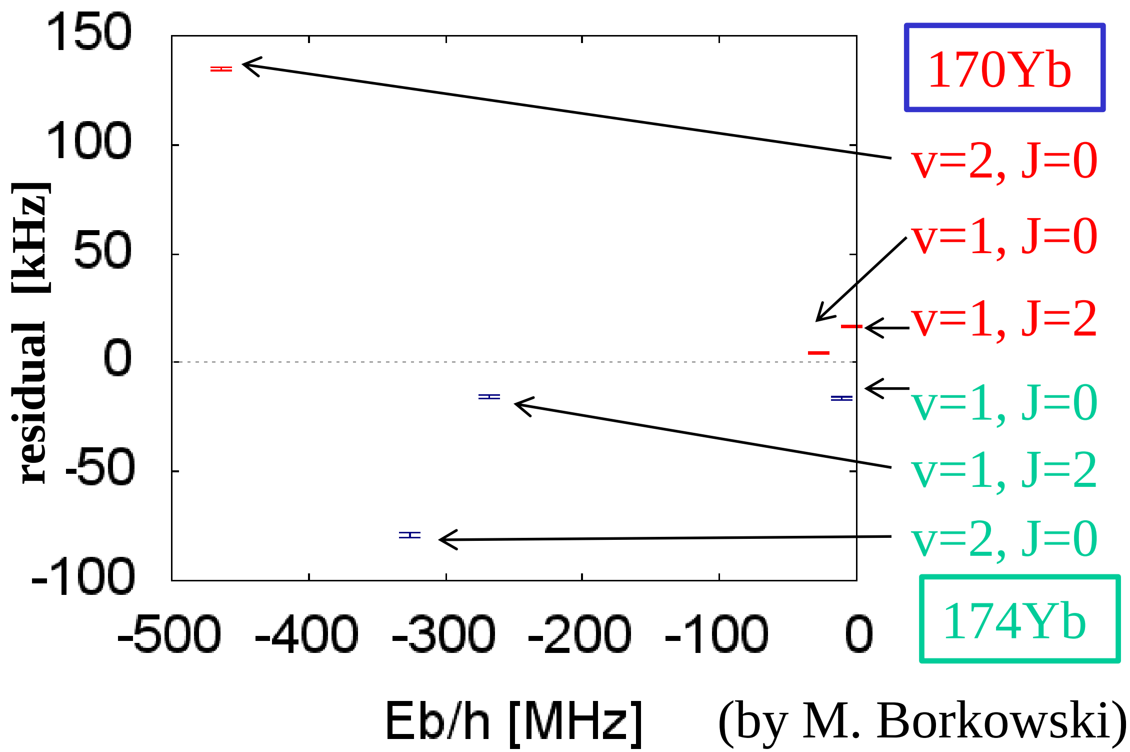
$$\{V(r) + g|\psi(r)|^2\}\psi(r) = \mu\psi(r)$$





Results (Preliminary)

Level	Binding energy[MHz]	
^{168}Yb(v=2, J=0)	-195.18141(46)	
^{168}Yb(v=1, J=2)	-145.53196(48)	
^{170}Yb(v=1, J=0)	-27.70024(44)	#
^{170}Yb(v=2, J=0)	-463.72552(80)	#
^{170}Yb(v=1, J=2)	-3.66831(32)	#
^{174}Yb(v=1, J=0)	-10.62513(53)	#
^{174}Yb(v=2, J=0)	-325.66378(98)	#
^{174}Yb(v=3, J=0)	-1527.88542(40)	
^{174}Yb(v=1, J=2)	-268.63656(56)	#
^{174}Yb(v=2, J=2)	-1432.82493(64)	



(by M. Borkowski)

C_6=1933.4 $E_h a_0^6$, C_8=2.086×$10^65E_h a_0^8$

This does NOT immediately mean the existence of Yukawa force

→ Correction on Born-Oppenheimer Approximation:

$$C_{n,n} = -\frac{\hbar^2}{2\mu}\int \psi_e^n(\vec{r}_i, R)\nabla_R^2 \psi_e^n(\vec{r}_i, R)\, d\vec{r}_i \propto \frac{1}{\mu}$$