「ＧＣＯＥ普遍性と創発性から紡ぐ次世代物理学　オープニングシンポジウム　」

18 February 2009

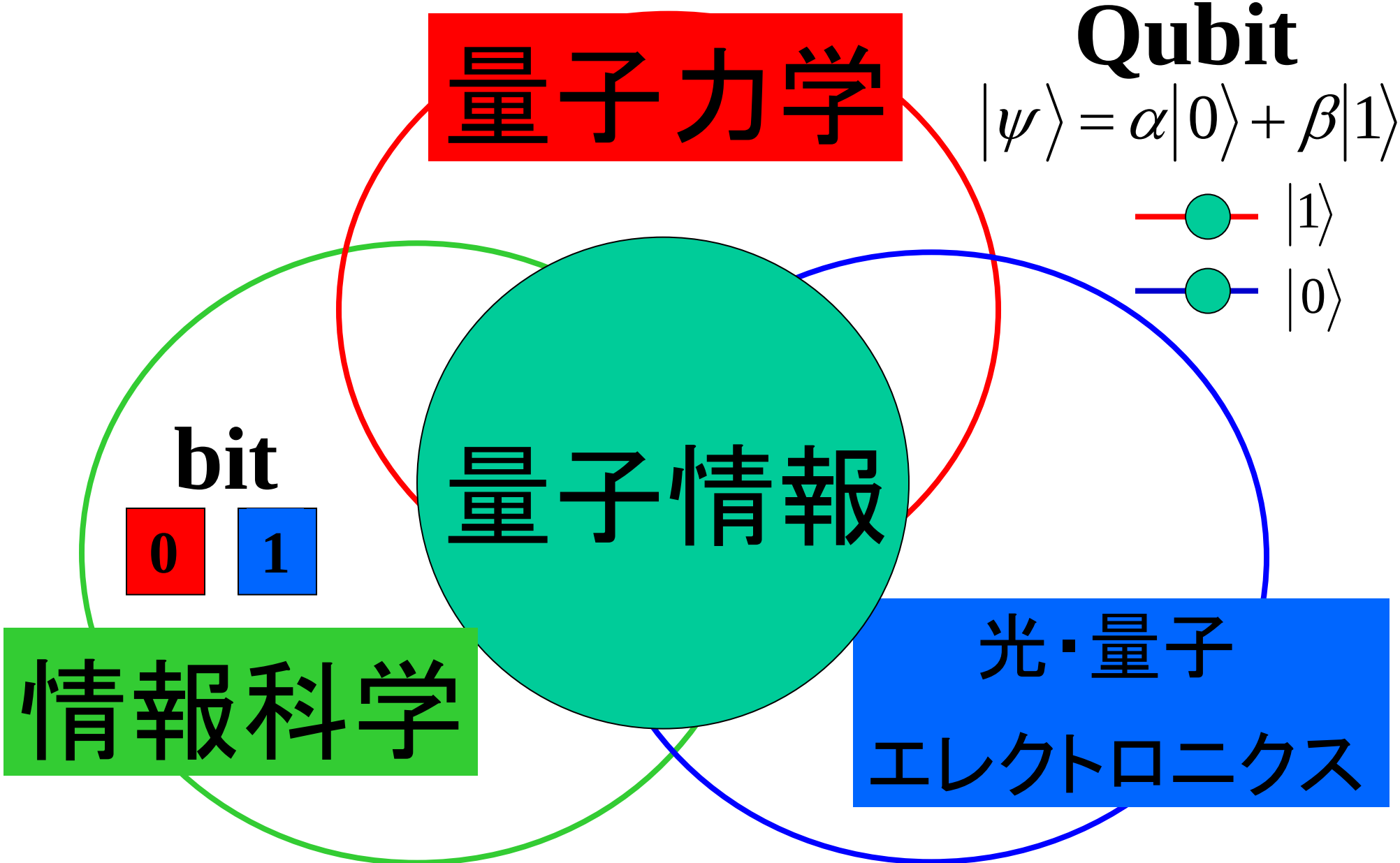
融合ｇ　原子を用いた量子情報

光格子を用いた量子情報研究

京都大学大学院　理学研究科
物理学・宇宙物理学専攻
物理学第一分野

高橋義朗

Introduction



Outline

光格子中の超低温冷却原子を用いた量子情報研究

1.量子計算(Quantum Computation)

2.量子シミュレーション（Quantum Simulation)

3.量子計測(Quantum Metrology)

Quantum Computer

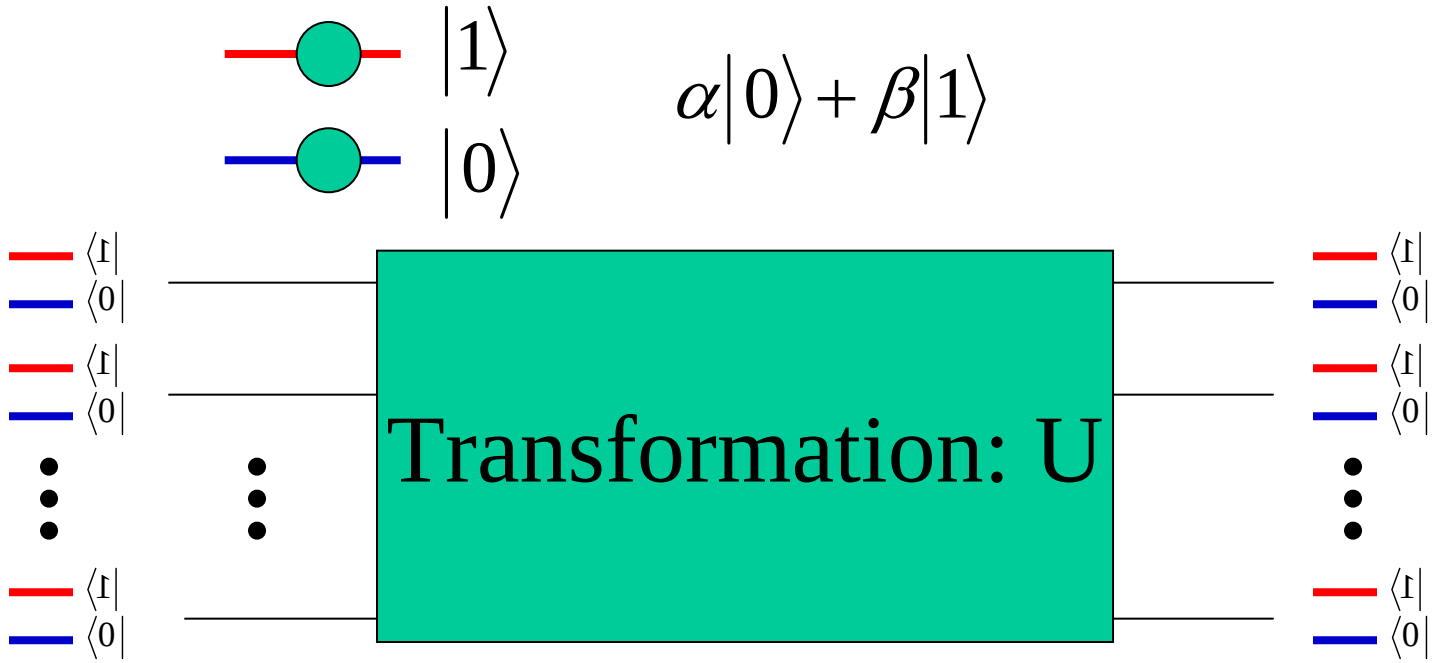
“ある種の問題を,古典 計算機と比べて非常に速く計算することができる”

大きい数の素因数分解

Example)　3125123787 × 1654239211 ⟶⟵ 5169702307684212057

「難しい」: 現代 RSA方式公開鍵暗号の安全性を保障

- Quantum Computer では **Qubit** を使う

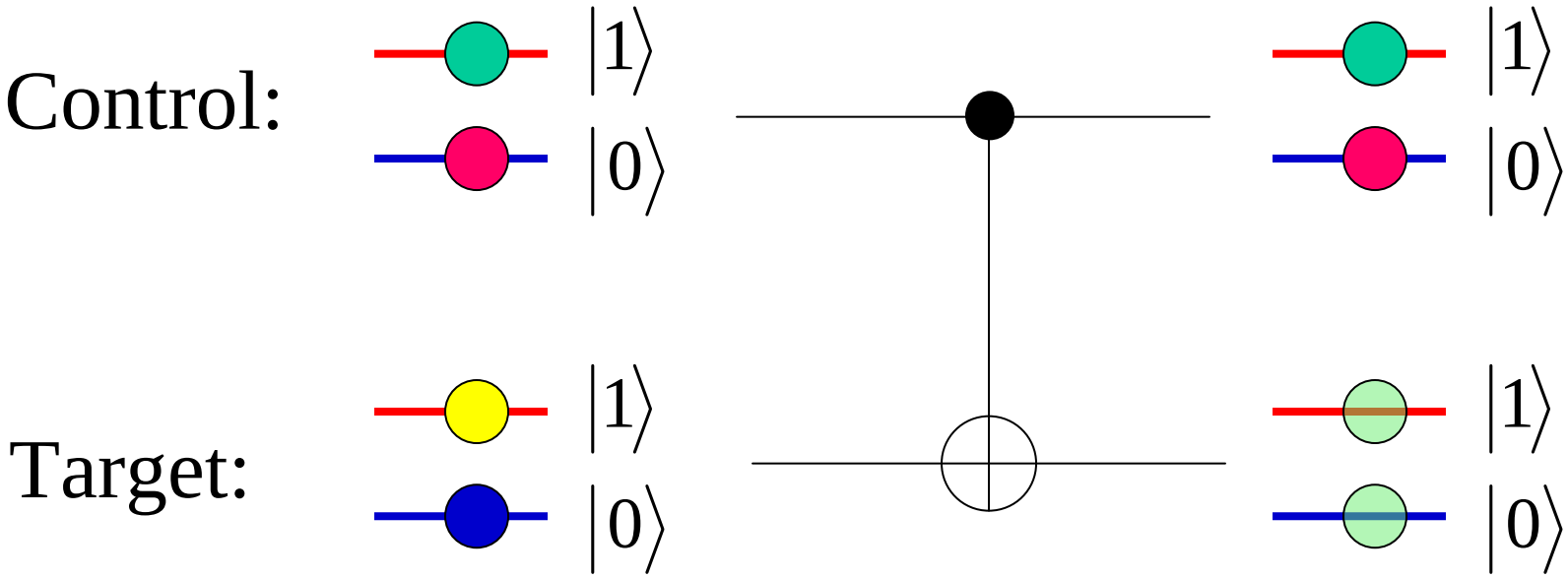


Criteria for Quantum Computation

DiVincenzo(2000)

1. よく定義された Qubitと、多数個への拡張性
2. Qubitの初期化
3. 長い寿命（decoherence 時間）
4. 任意のゲート演算が可能
   (単一Qubitの回転 と C-NOT Operation)
5. 単一原子アドレッシングと測定

C-NOT Operation



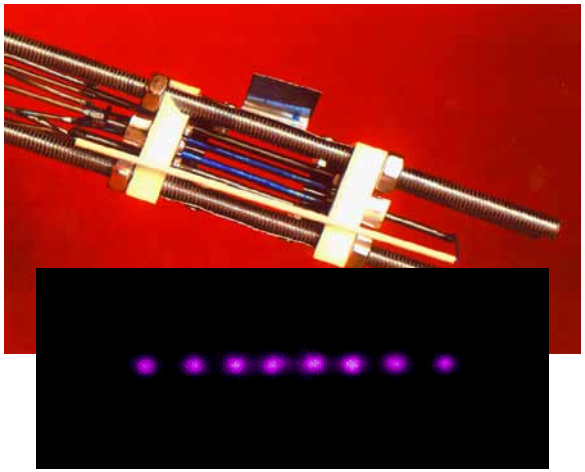
"Input"	Control	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$ $\|0\rangle$
	Target	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$ $\|0\rangle$
"Output"	Control	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$ $\|0\rangle$
	Target	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$ $\|0\rangle$

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes |0\rangle$$

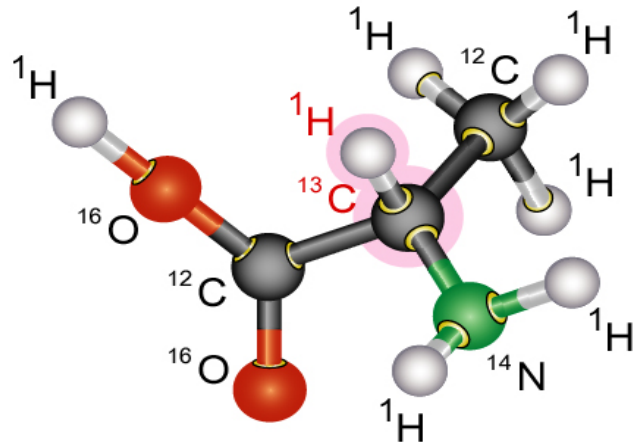
$$\Rightarrow \frac{|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle}{\sqrt{2}}$$

Candidates of Quantum Computers

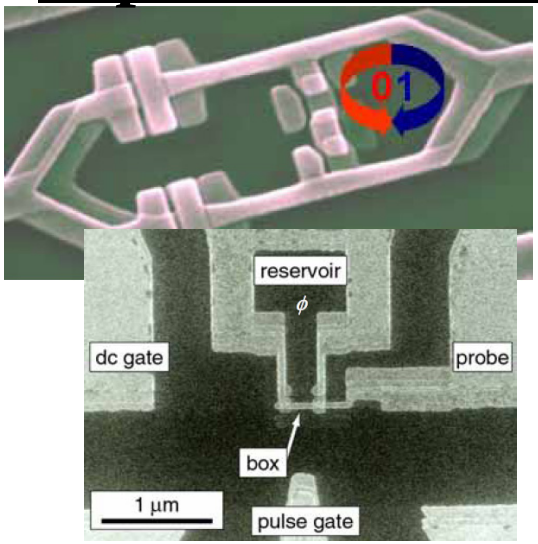
Ion Trap



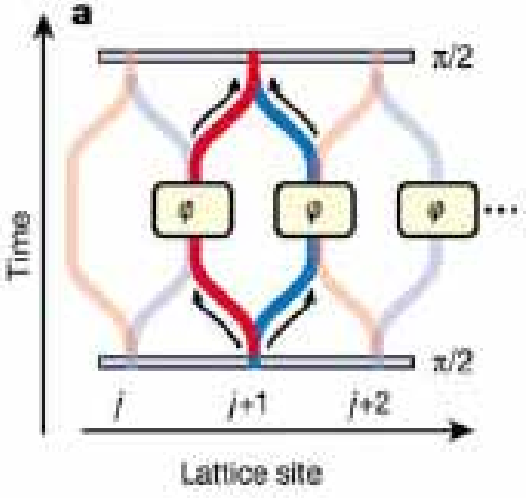
Nuclear Magnetic Resonance

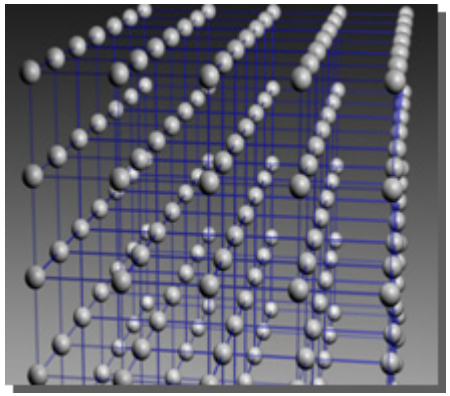


Superconductors

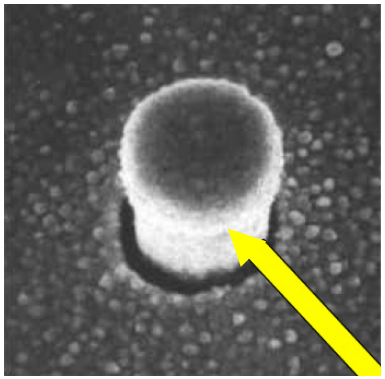


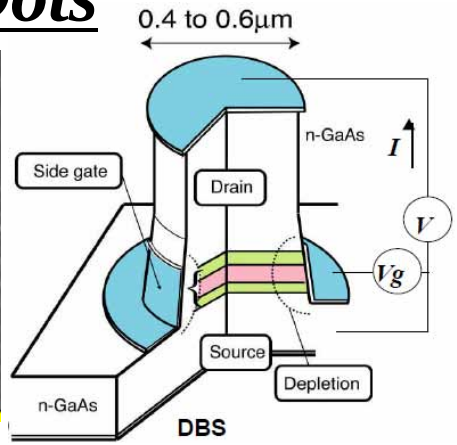
Cold Atoms in Optical Lattice



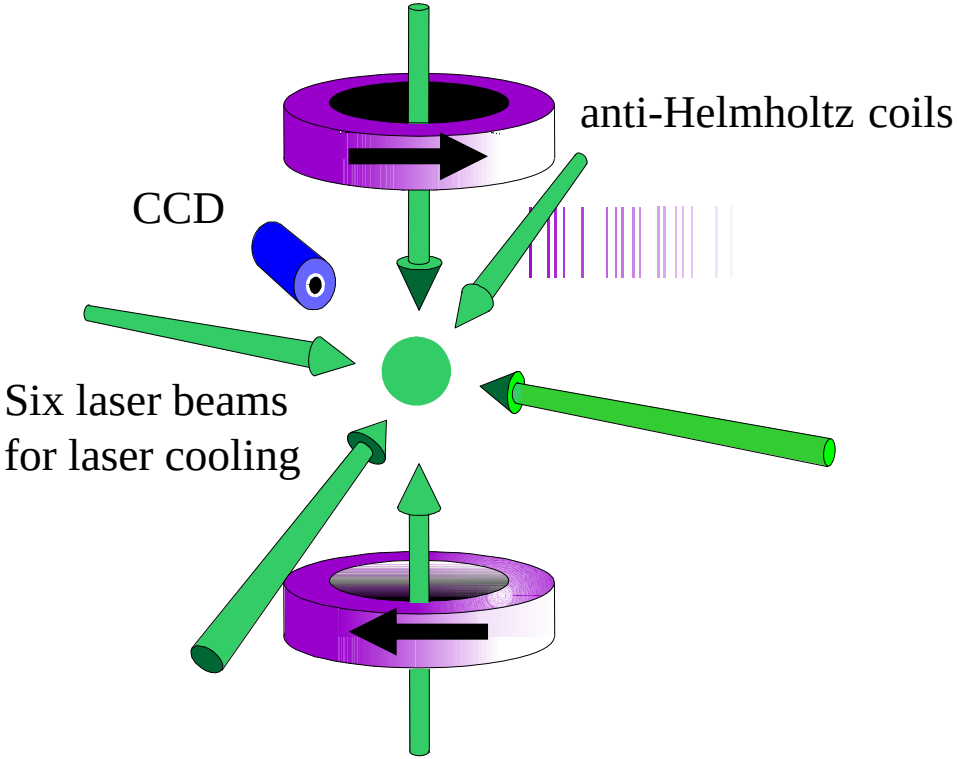


Quantum Dots

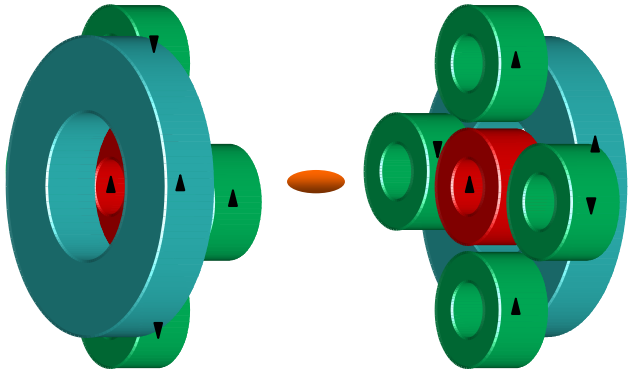




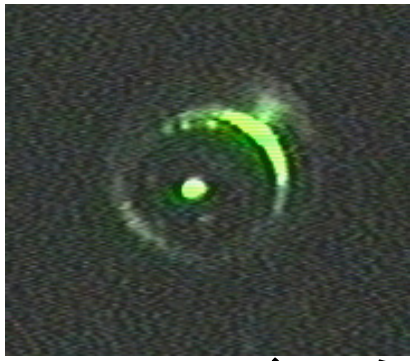
中性原子のレーザー冷却とトラップ



“磁気トラップ”



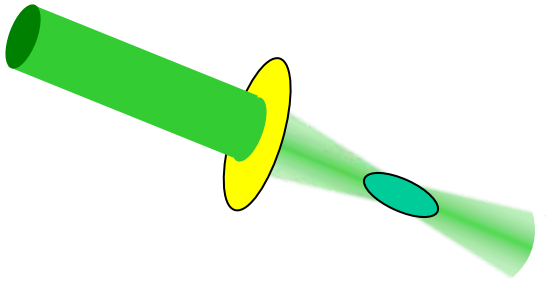
“光トラップ”

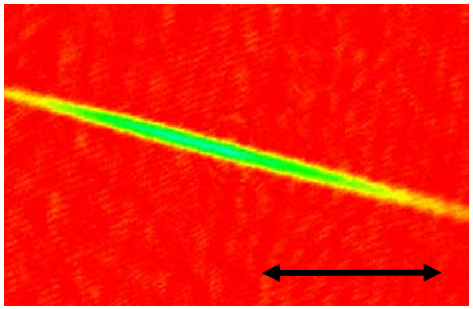


10mm

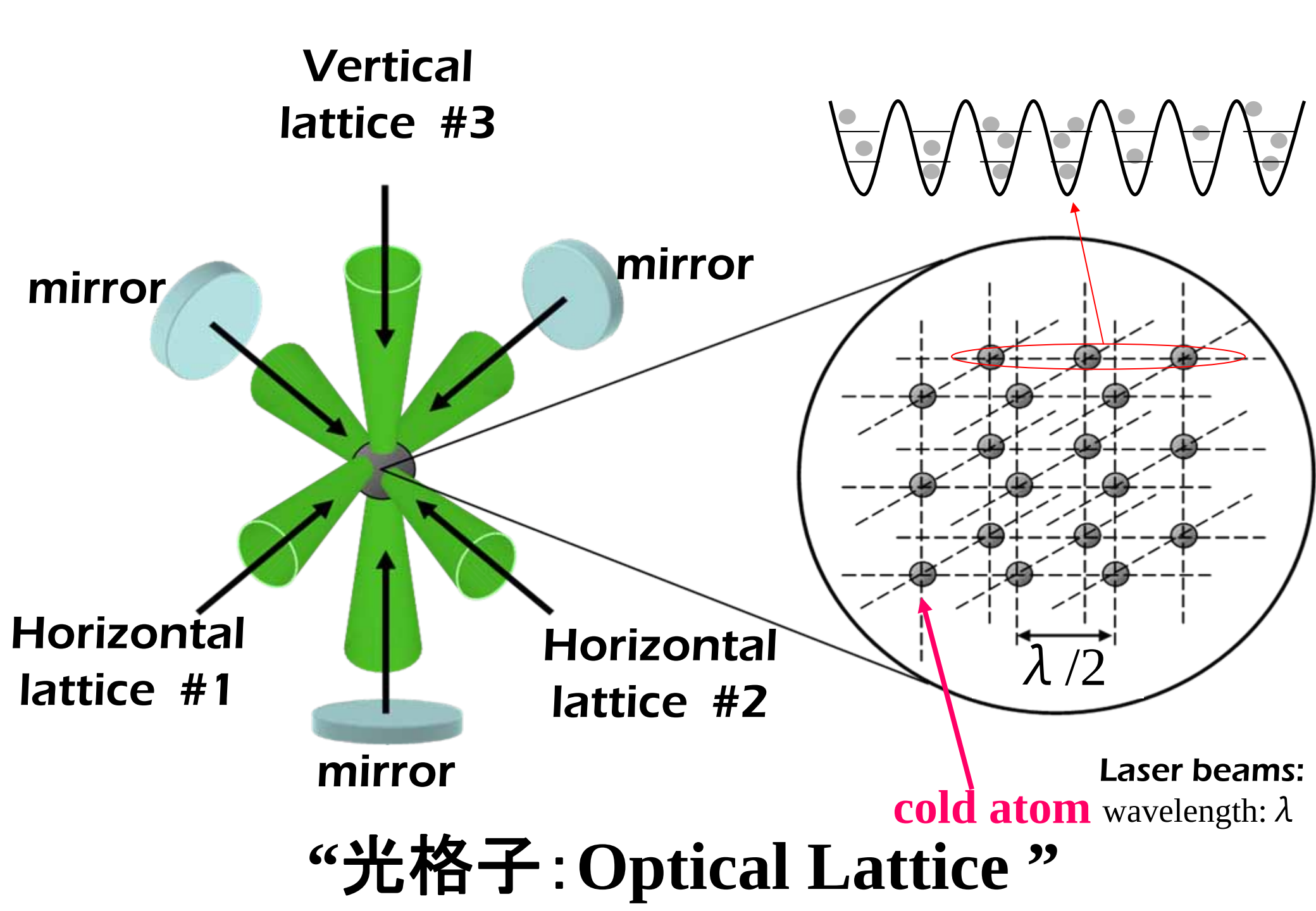
“レーザー冷却”

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





500 μm



“光格子：Optical Lattice ”

光格子Quantum Computation

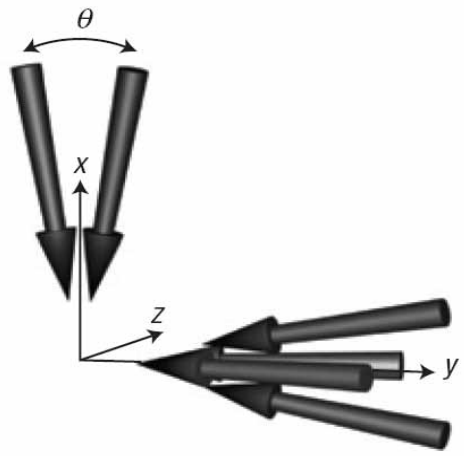
DiVincenzo(2000)

1. よく定義された Qubitと、多数個への拡張性 ○
2. Qubitの初期化 ○
3. 長い寿命（decoherence 時間） ○
4. 任意のゲート演算が可能
   (単一Qubitの回転 と C-NOT Operation) ○
5. 単一原子アドレッシングと測定 ×

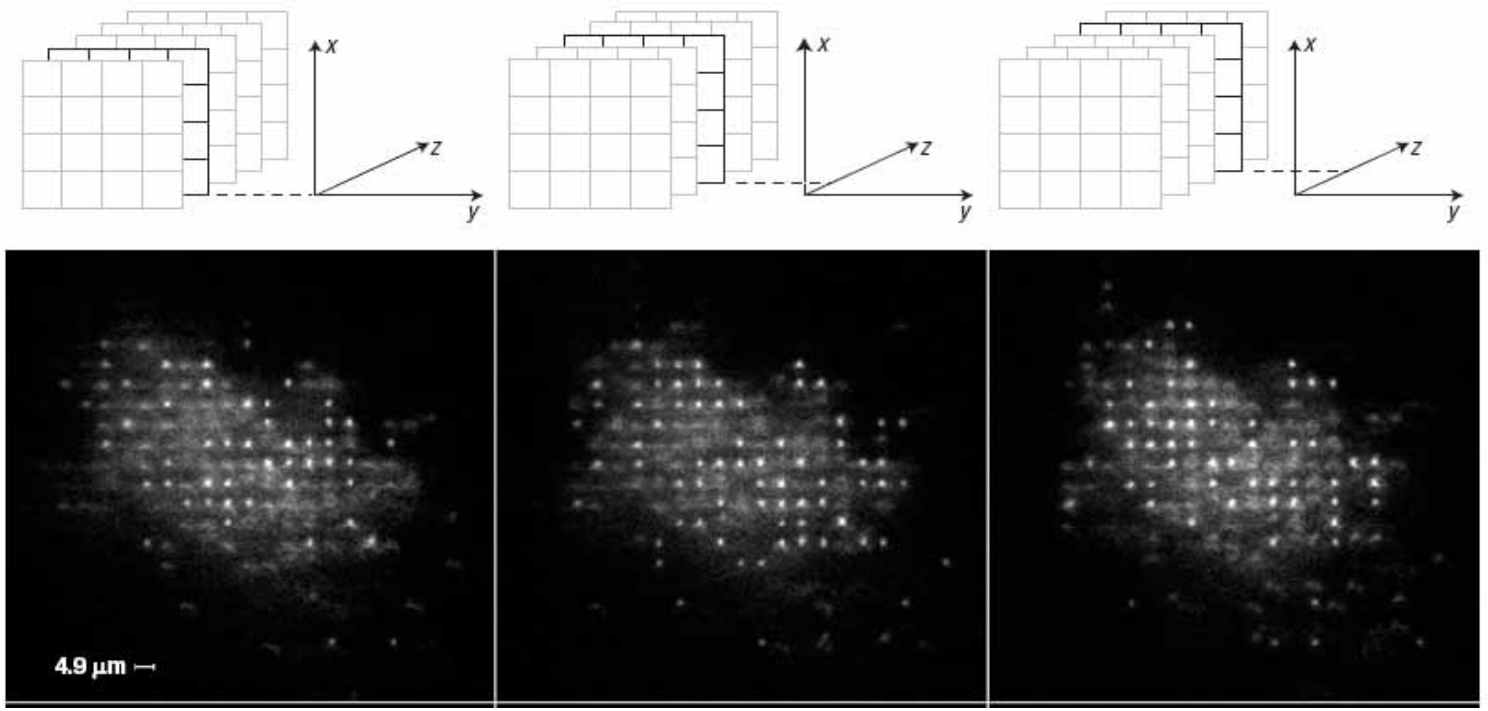
3D optical lattice中の単一原子の観測

[K. D. Nelson, X. Li, and D. S. Weiss, Nature physics **3**, 556(2007)]

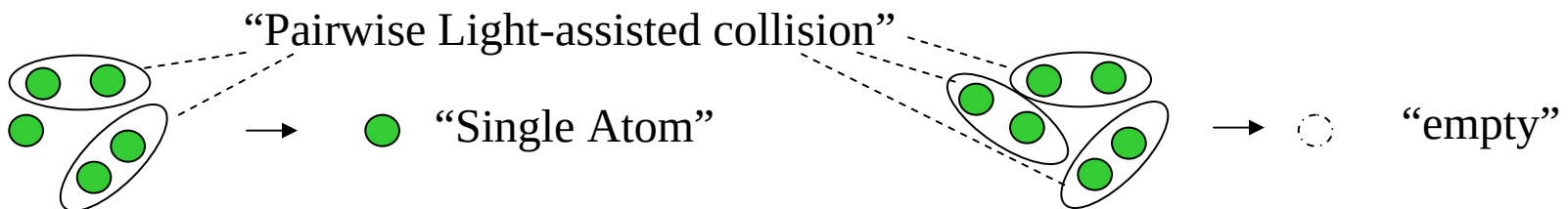
2.8 μm field of depth → imaging only one lattice plane



λ =845.5 nm
(blue-detuned)



Cs atoms: MOT+3D lattice:initially 6 atoms per lattice site



イッテルビウム(^{171}Yb)原子を用いた光格子量子計算機

“ electron spin qubit”

$|0\rangle' \equiv |m_F = +3/2\rangle$

$|1\rangle' \equiv |m_F = -3/2\rangle$

“ 量子演算”

大きい磁気モーメント $\mu = 3\mu_B$

磁場勾配: $10G/cm$

周波数分解能: $1kHz$

空間分解能: $250\ nm$

$^1P_1$ **~ 5 ns**

$^3P_2$

$^3P_1$

$^3P_0$

“光磁気共鳴イメージング“

“単一原子検出“

~ 10 mHz

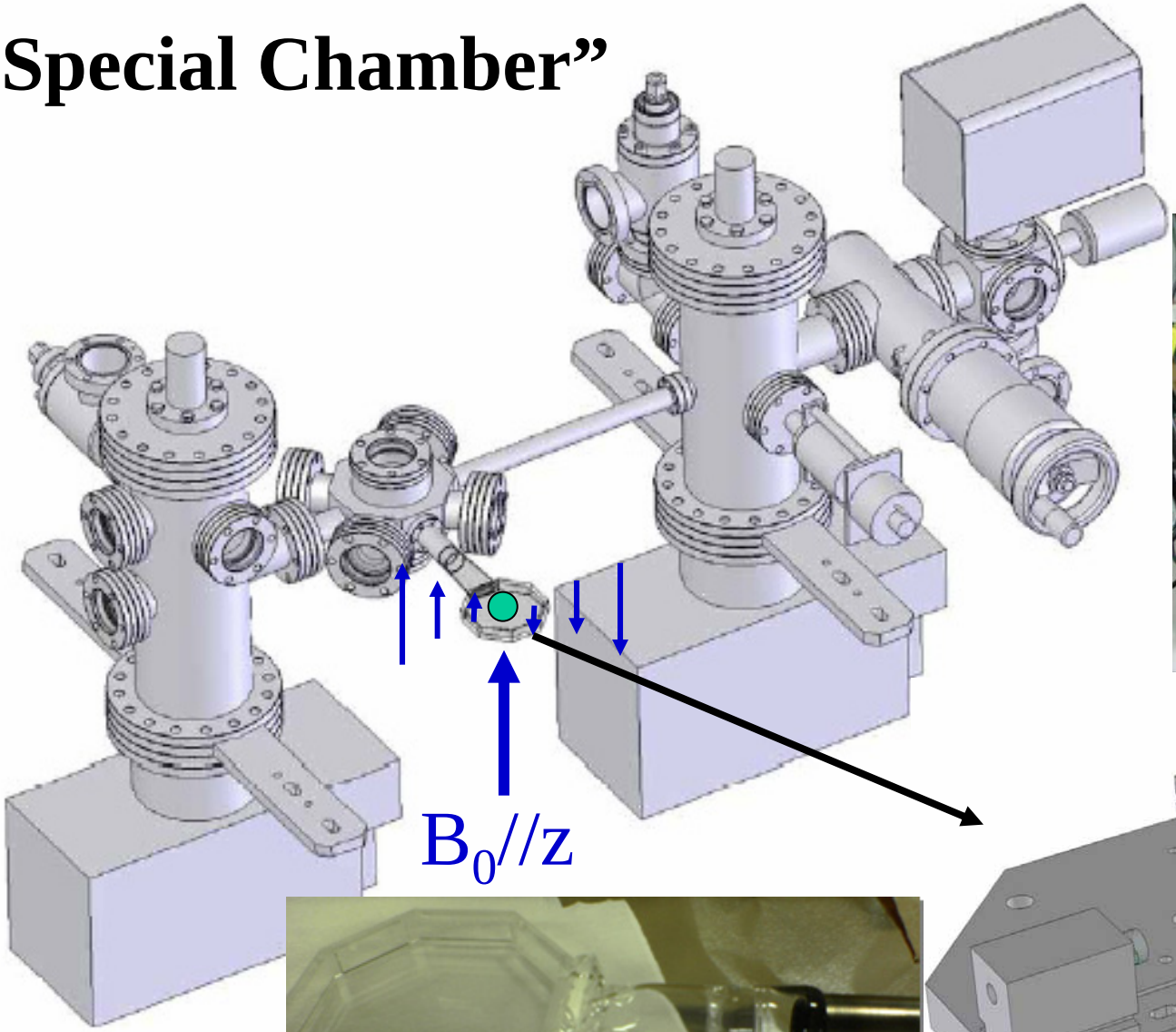
$|m_I = +1/2\rangle$

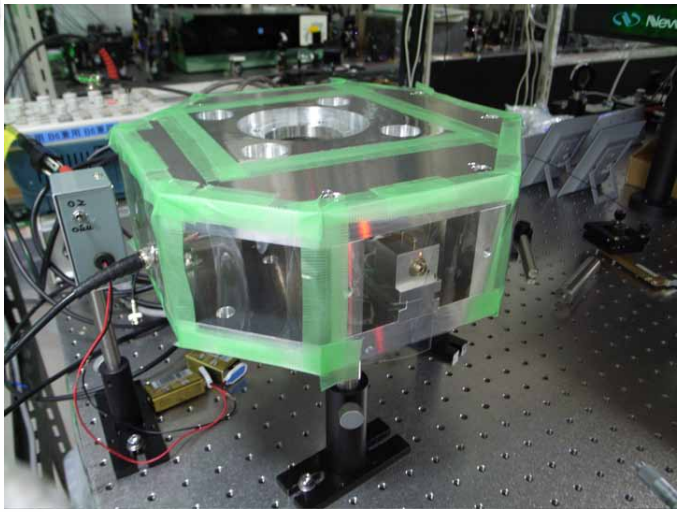
“ nuclear spin qubit”

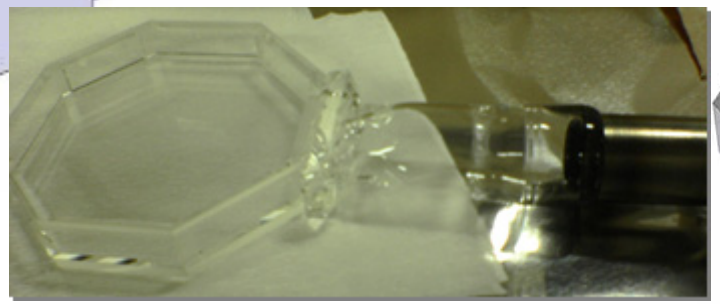
$|m_I = -1/2\rangle$

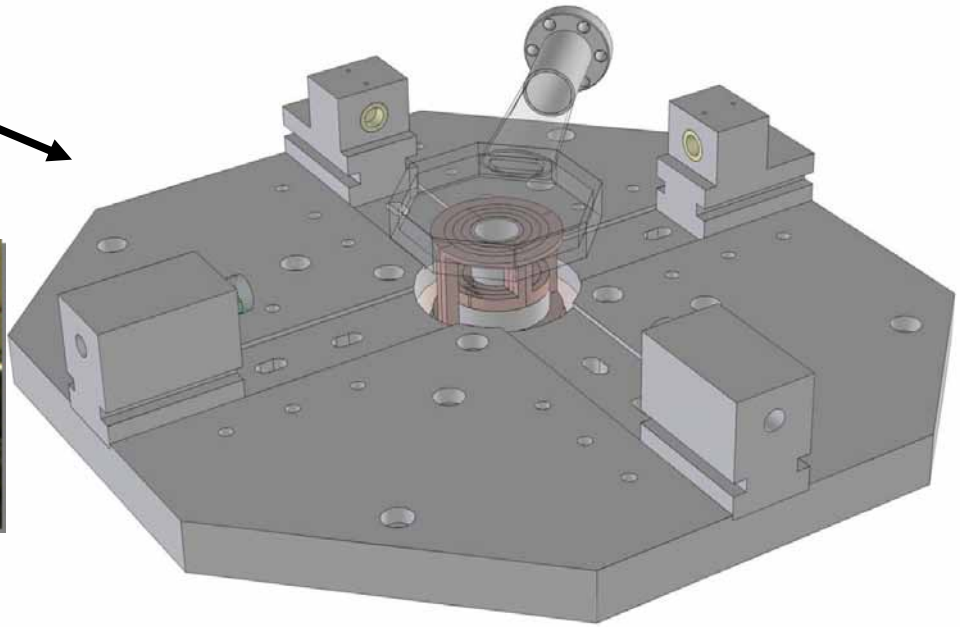
$^1S_0$ → **“ メモリー”** :長いコヒーレンス時間

“Special Chamber”









Poster 21:加藤真也

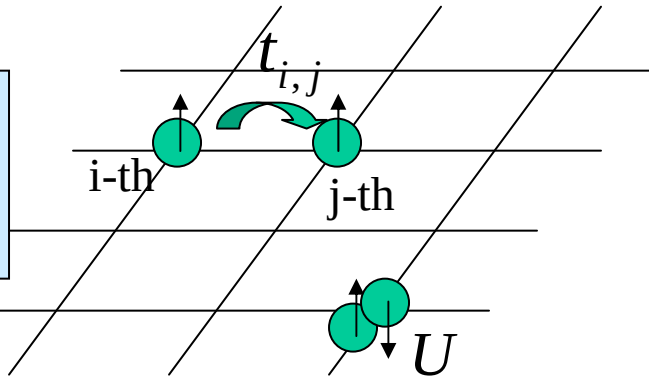
Quantum Simulation

"Interesting"

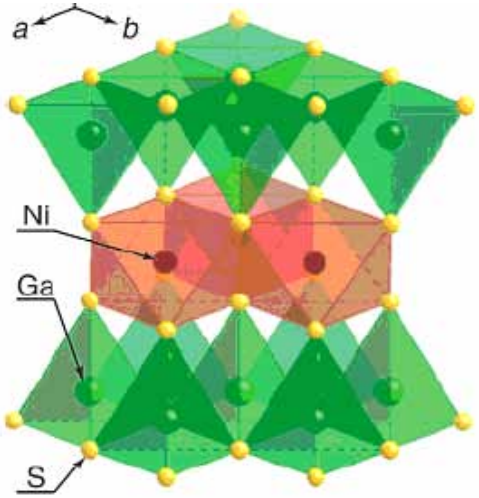
Many-body Quantum System

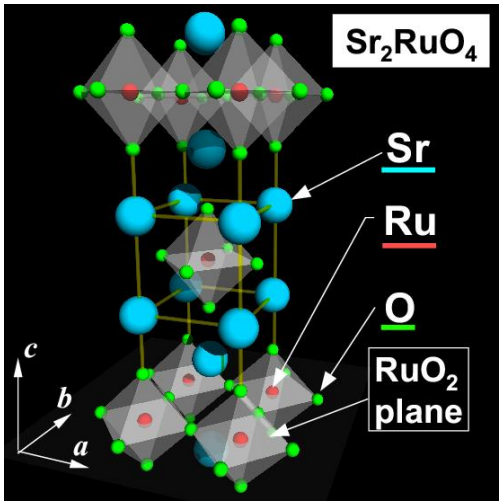
Hubbard Model:

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



→ Magnetism, Superconductivity





Quantum Simulation

"Interesting"

Many-body Quantum System

Hubbard Model:

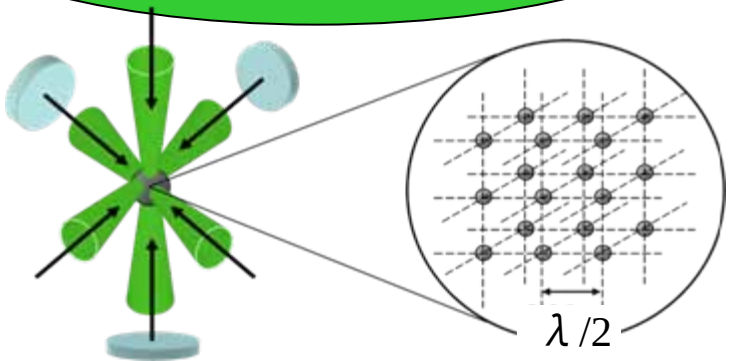
$$H = -t \sum_{<i,j>} c_i^+ c_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

"Controllable"

Many-body Classical System

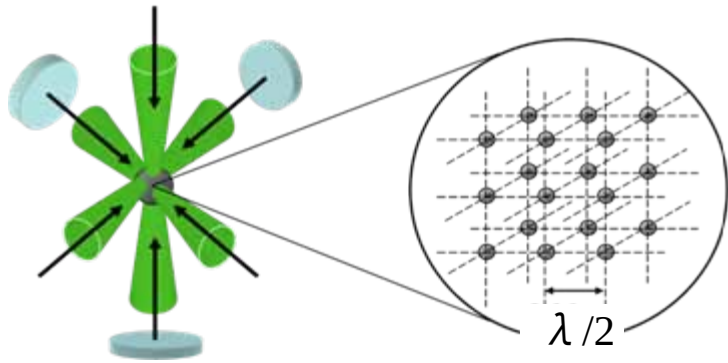
Many-body Quantum System

"HARD"



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

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



$$t = E_R(2/\sqrt{\pi})\xi^3 \exp(-2\xi^2) \qquad U = E_R a_s k\sqrt{8/\pi}\xi^3$$

$$\xi \equiv (V_o / E_R)^{1/4} \quad , E_R \equiv (\hbar k)^2 / 2m \quad , a_s : \text{scattering length}$$

Controllable Parameters

hopping between lattice sites	: t	lattice potential	: V_0
On-site interaction	: U	scattering length	: a_s
filling factor (e- or h-doping)	: n	atom density	: n

No impurity, No lattice defects, Various geometry

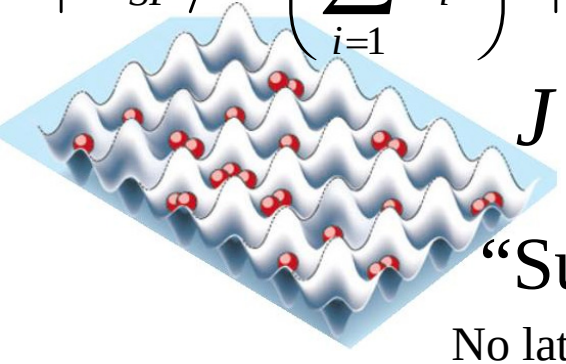
Bose-Hubbard Model:

"Superfluid - Mott-insulator Transition"

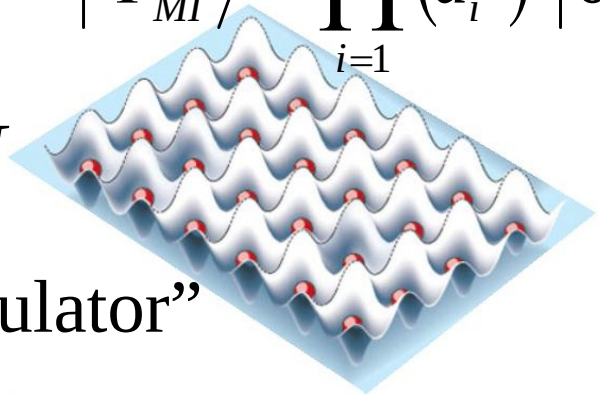
$$H = -J \sum_{<i,j>} a_i^+ a_j + \frac{U}{2} \sum_i n_i (n_i - 1)$$

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

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



$J >> U$ ⟺ $J << U$

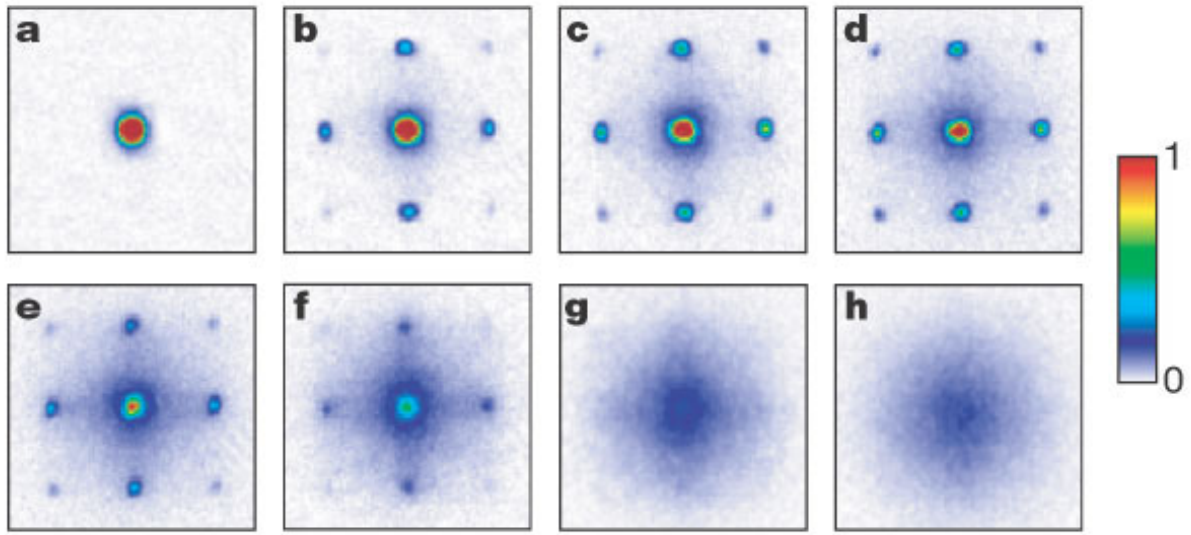


"Superfluid" "Mott Insulator"

^{87}Rb BEC

$N = 2 \times 10^5$

No lattice $V_0 / E_R =$ 3 7 10

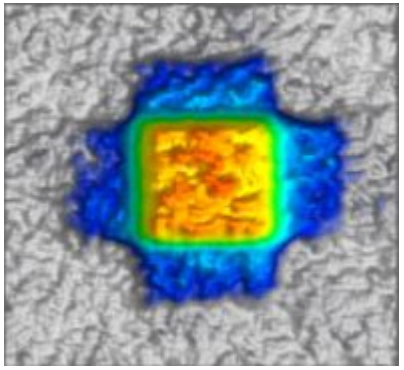


$U / t \approx 6 \times 5.8$ →

13 14 16 20

[M. Greiner, *et al.*, Nature 415,39 (2002)]

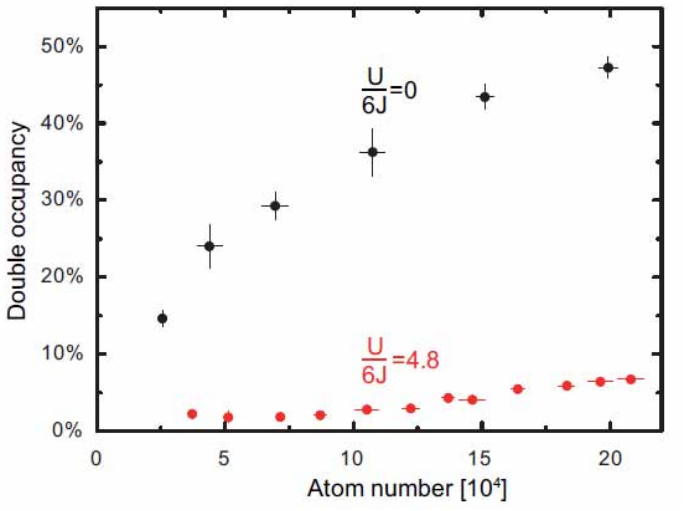
Fermions in Optical Lattice



“Fermi-Surfaceの観測”

[M. Köhl, et al, PRL**9**4, 080403 (2005)]

“A Mott insulator of ^{40}K atoms in an optical lattice”



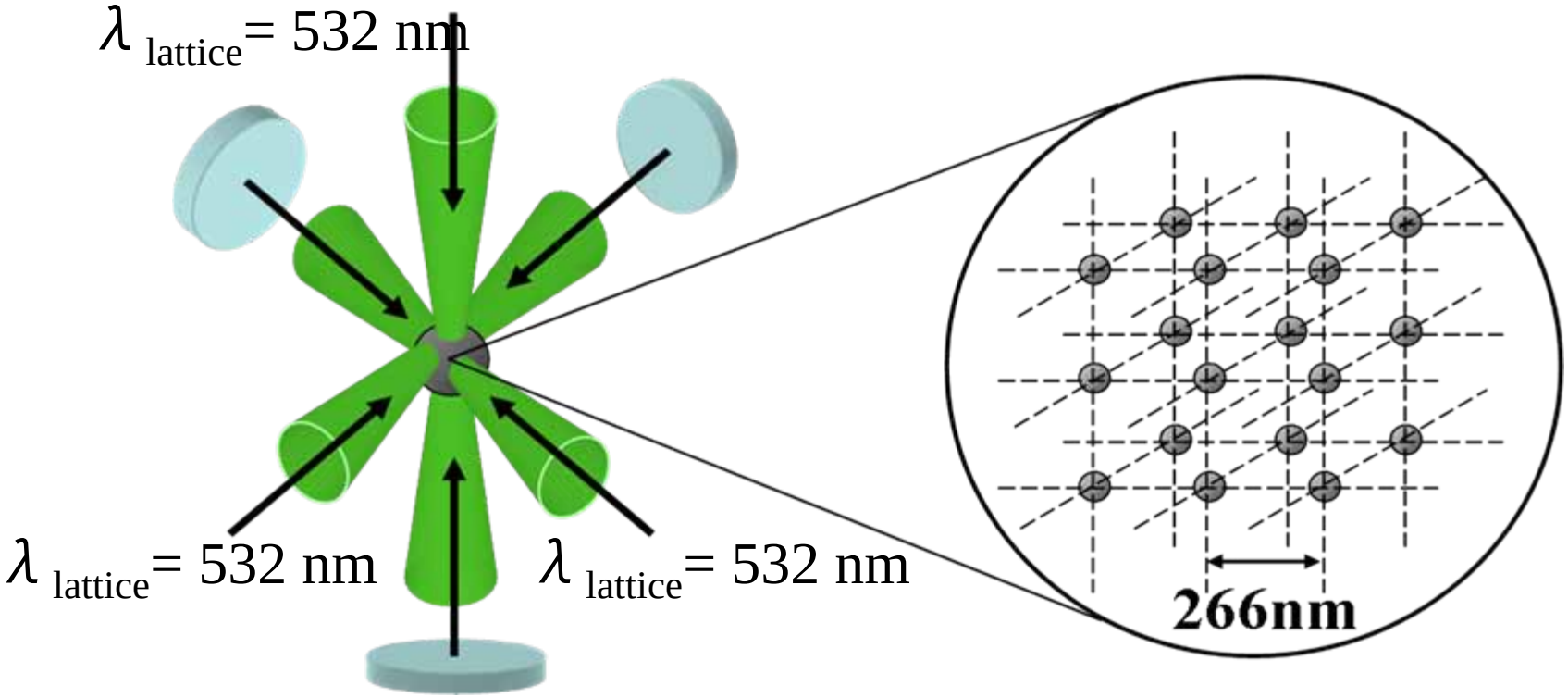
[R. Jördens *et al.*, Nature **455**, 204 (2008)]

[U. Schneider, *et al.*, arXiv:0809.1464]

Bose-Fermi-Hubbard Model for a 3D optical lattice

$$H = -t_B \sum_{<i,j>} a_i^+ a_j + \frac{U_{BB}}{2} \sum_i n_{Bi}(n_{Bi} - 1) - t_F \sum_{<i,j>} c_i^+ c_j + U_{BF} \sum_i n_{Bi} n_{Fi}$$

^{174}Yb(Boson) +^{173}Yb(Fermion): a_{BF} = 7.3 nm



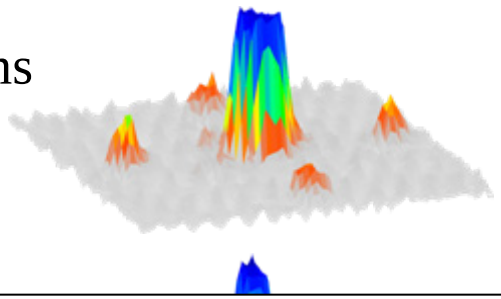
^{174}Yb(Boson)

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

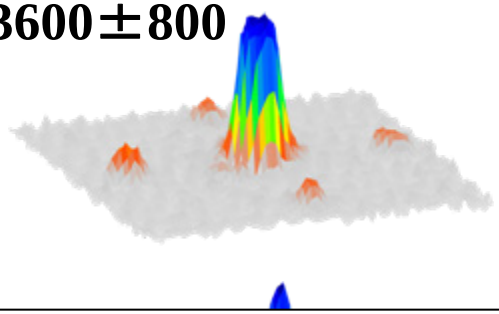
BEC, N_B~12000±2000

BEC, N_B~9000±1000
Fermion, T/T_F ~0.6,
N_F~3600±800

TOF10 ms

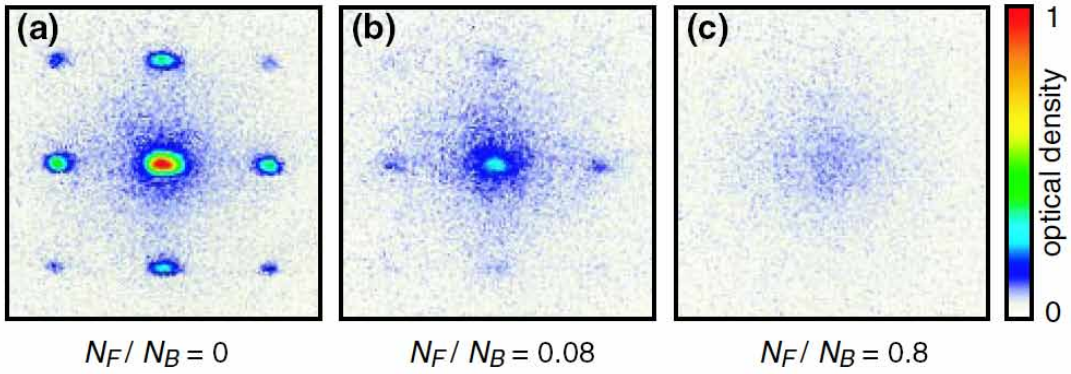


$V = 5E_R$



[K. Gűnter, et al, PRL96, 180402 (2006)] [S. Ospelkaus, et al, PRL96, 180403 (2006)]

" ^{40}K(Fermion)-^{87}Rb(Boson)" **a_{BF} = -10.9 nm**



Poster 36:素川靖司 41:田家慎太郎

Summary

Various Quantum Information Systems:
classification by system size and complexity

Optical Lattice Quantum Computer
proposal of Yb-based optical lattice quantum computer

Quantum Simulation of Hubbard Model
alkali and Yb atoms quantum simulator

Quantum Metrology
improvement of optical lattice clock by spin-squeezing

Quantum Optics Group Members

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R. Namiki Y.T. M. Muramatsu H. Shimizu T. Takano S. Taie