基研研究会「熱場の量子論とその応用」

31 August 2015

Yukawa Institute, Kyoto University

冷却原子系による量子シミュレーション

Kyoto University

Yoshiro Takahashi

Outline

I) Preparation of Quantum Gas

Laser cooling and trapping, evaporative cooling, Bose-Einstein condensate,
Fermi Degenerate Gas

II) Ultracold Atoms in a Harmonic Trap

Feshbach resonance, Cooper paring, BEC-BCS crossover, unitary gas,
spin-orbit interaction

III) Ultracold Atoms in an Optical Lattice

Superfluid-Mott insulator transition, quantum-gas-microscope, Higgs mode,
Non-standard lattices(frustrated magnetism, flat band), Fermi-Hubbard model,
Bose-Fermi mixture

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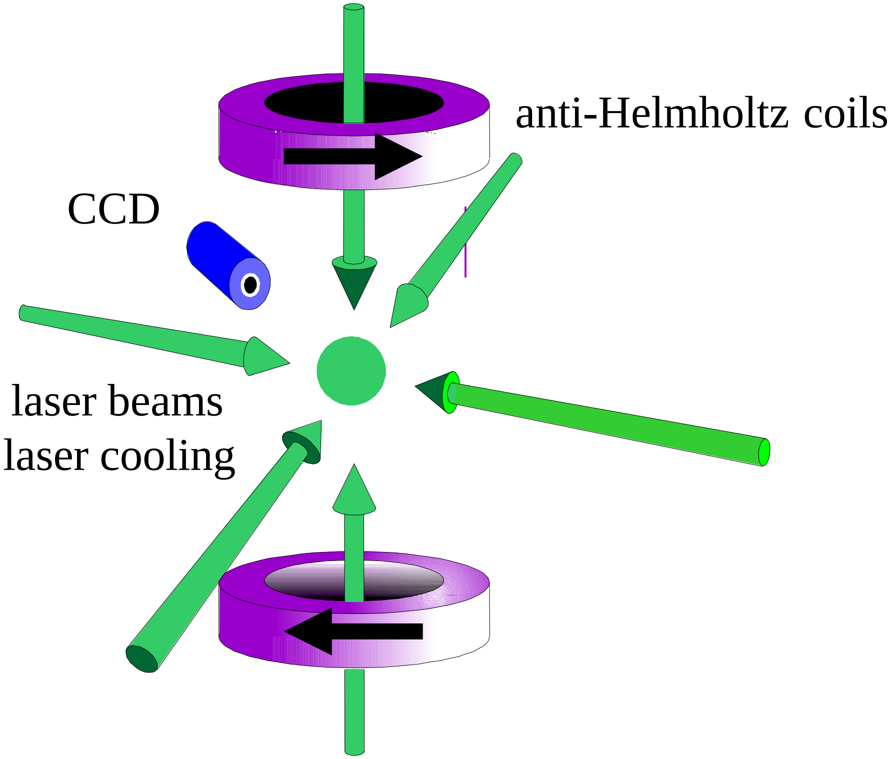
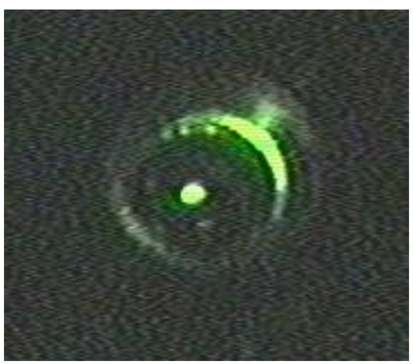
Laser Cooling and Trapping



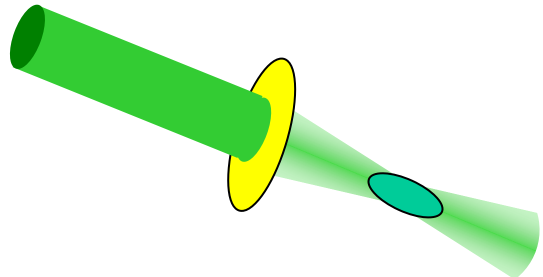


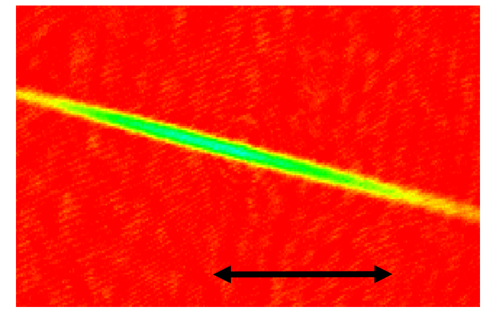
- Number: 10^7
- Density: $10^{11}/\text{cm}^3$
- Temperature: 10μK

"Magneto-optical Trap"

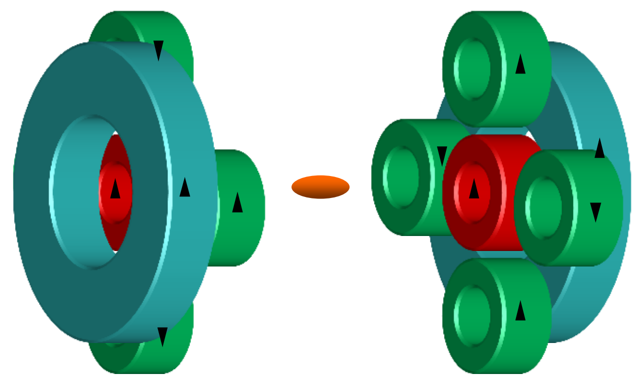
"optical trap"

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





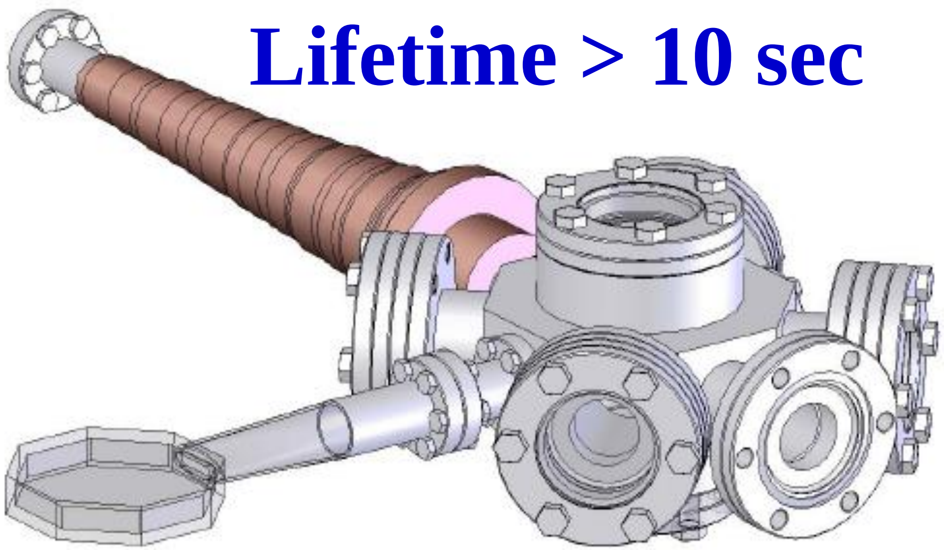
"magnetic trap" $V_{\text{int}} = -\mu \cdot B$



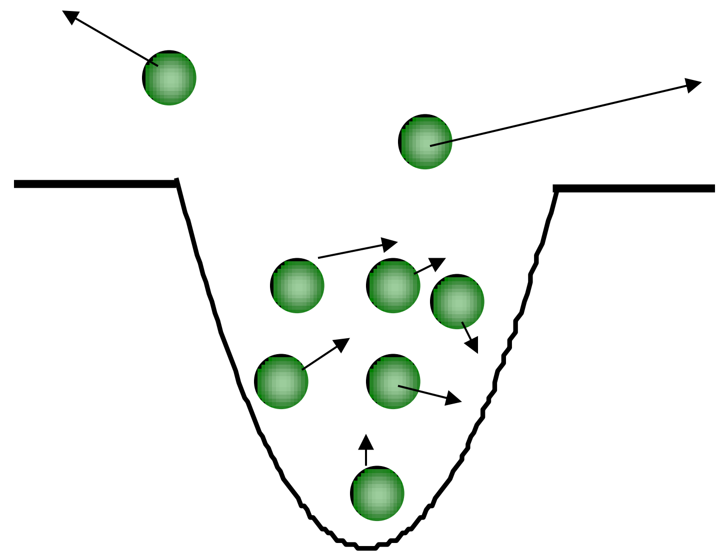
Cooling to Quantum Degeneracy

Pressure ~10^{-12} torr

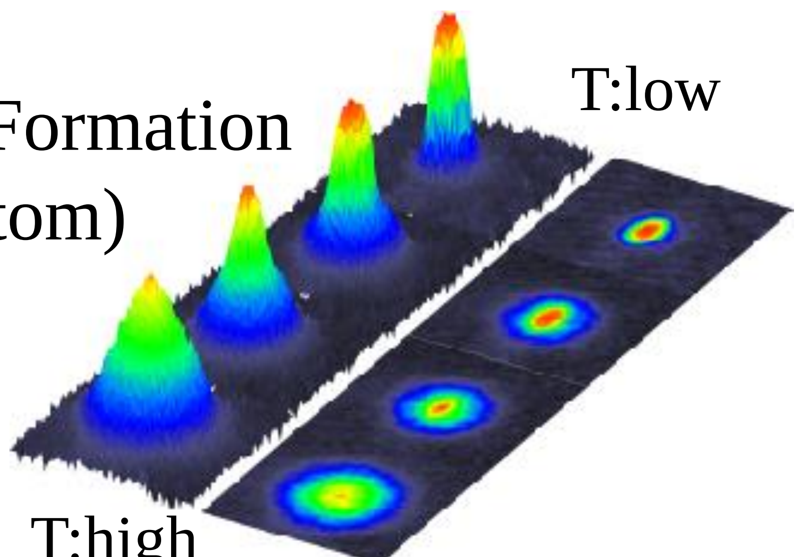
Lifetime > 10 sec

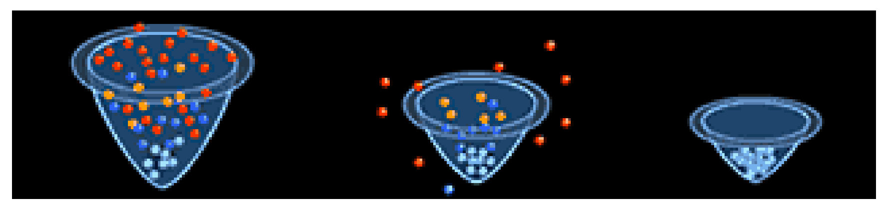


"Evaporative cooling"



BEC Formation
(Yb atom)

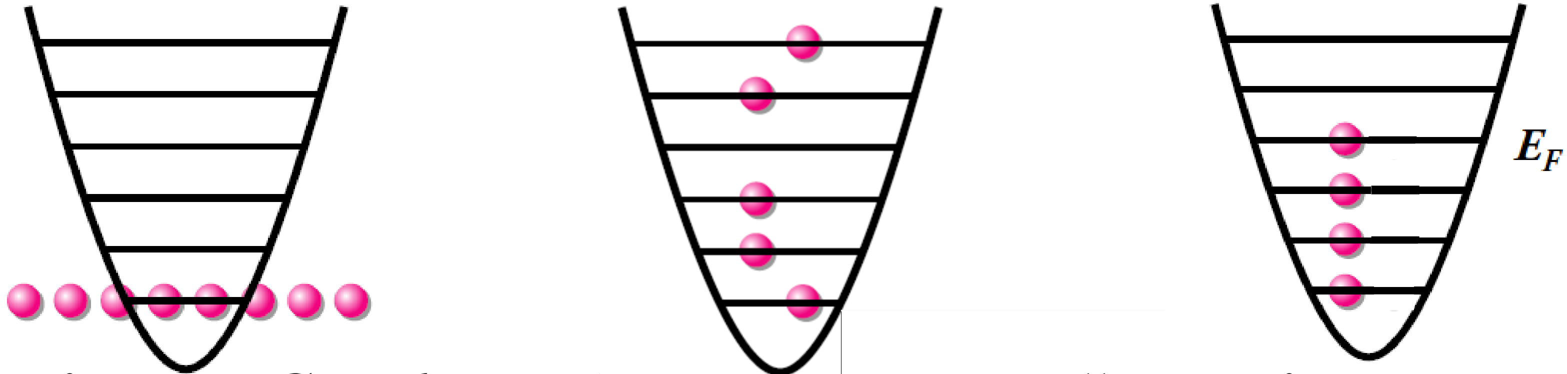




T~100 nK N~ 10^5

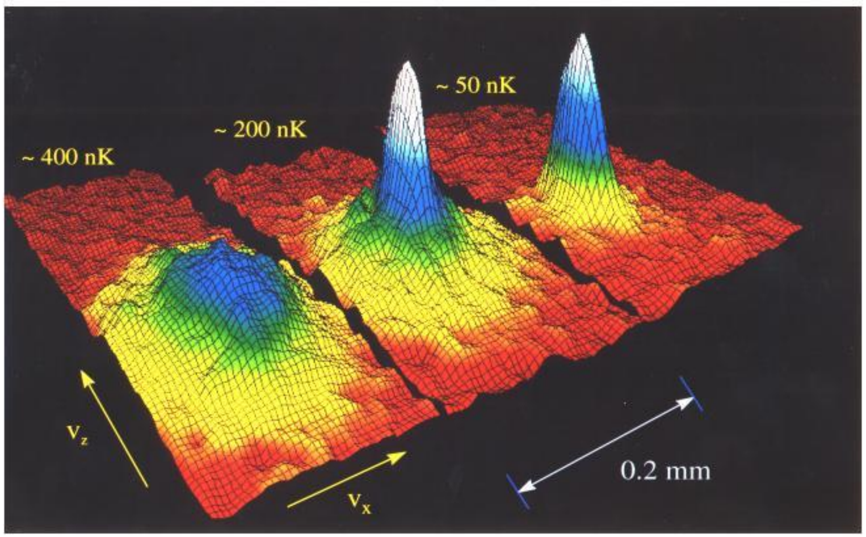
Cooling to Quantum Degeneracy

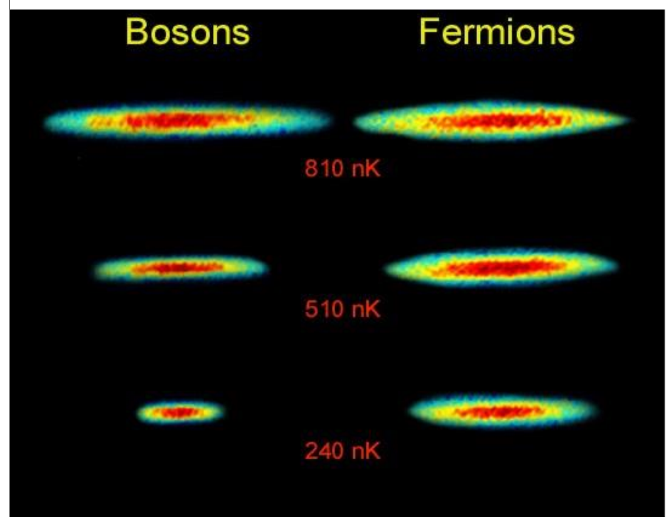
"Boson versus Fermion"



"Bose-Einsten Condensation" ***"Fermi Degeneracy"***

^{87}Rb





^{6}Li and ^{7}Li

Fermi Pressure

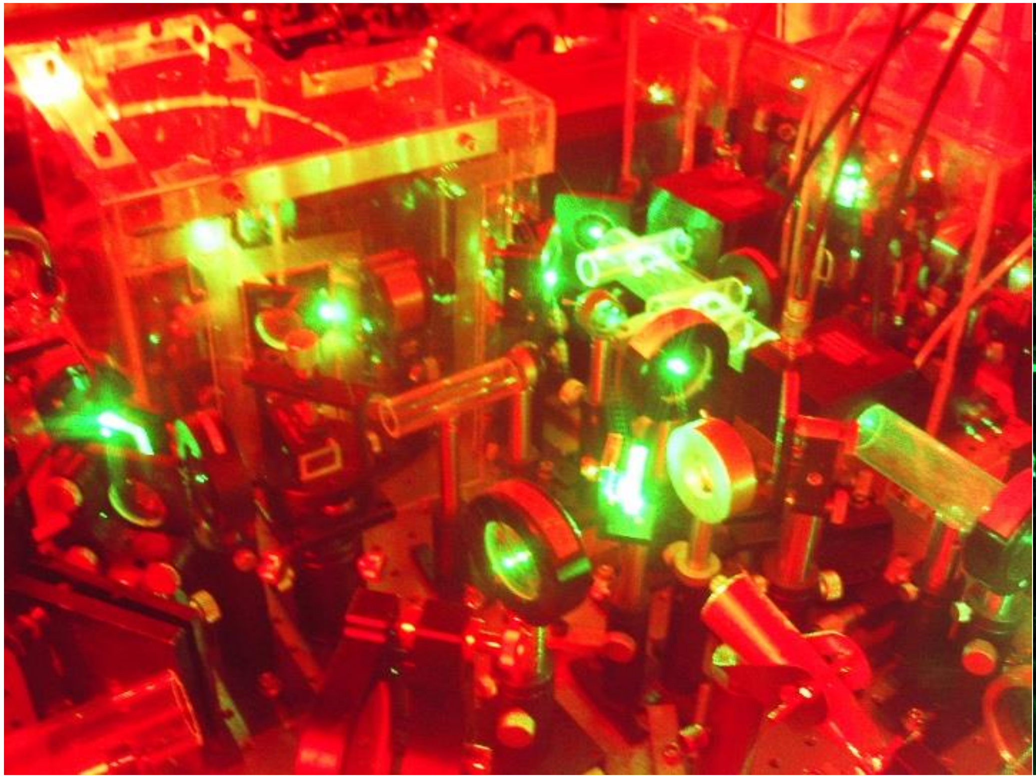
Momentum Distribution

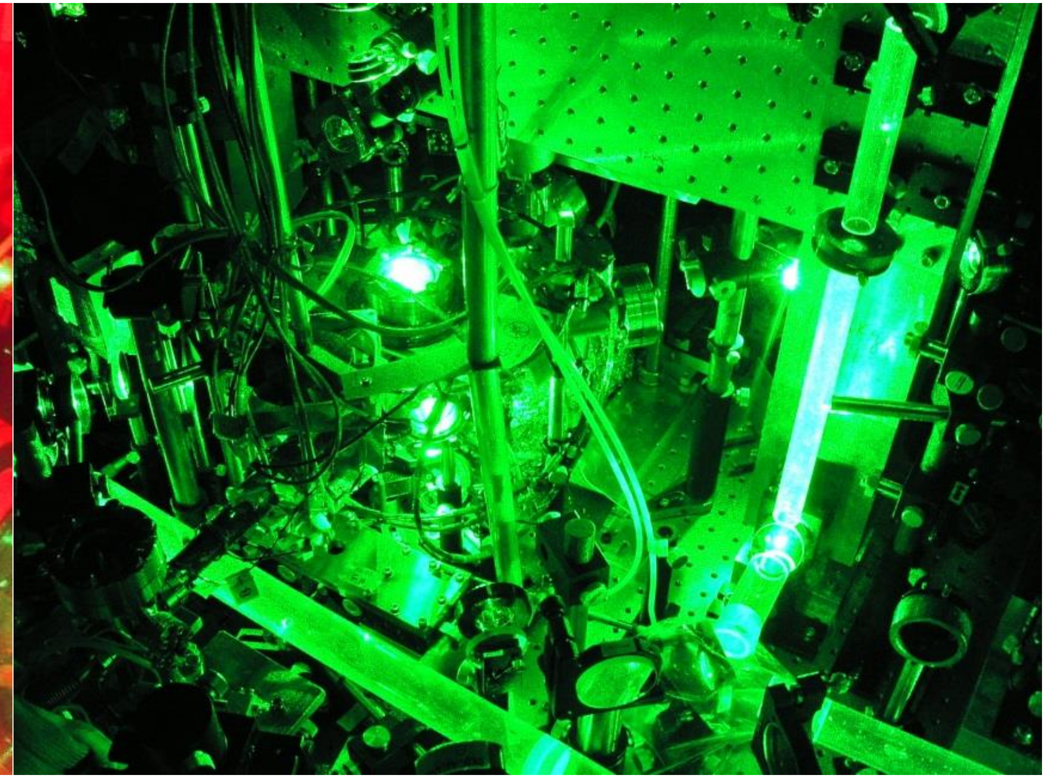
[E. Cornell et al, (1995)]

Spatial Distribution

[R. Hulet et al, (2000)]

Experimental Setup for Cold Atom





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Feshbach Resonance:

ability to tune an inter-atomic interaction

Collision is in Quantum Regime

It is described by s-wave scattering length a_s

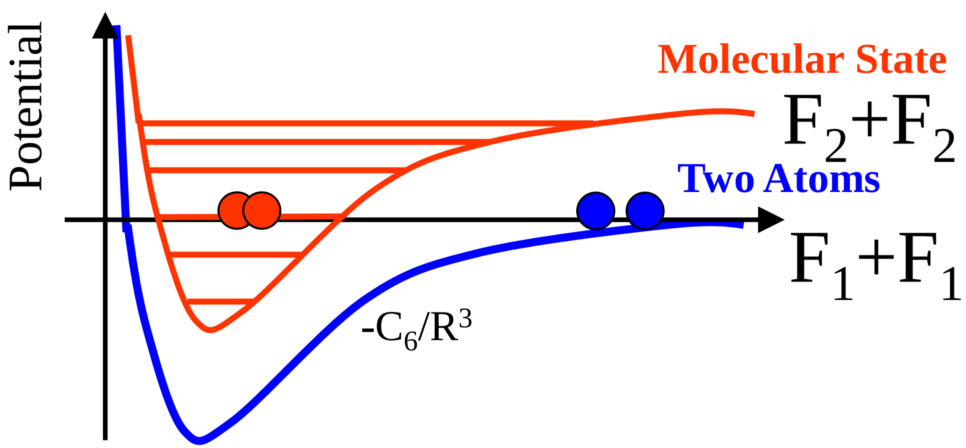
$$a_s = -\delta_l / k$$

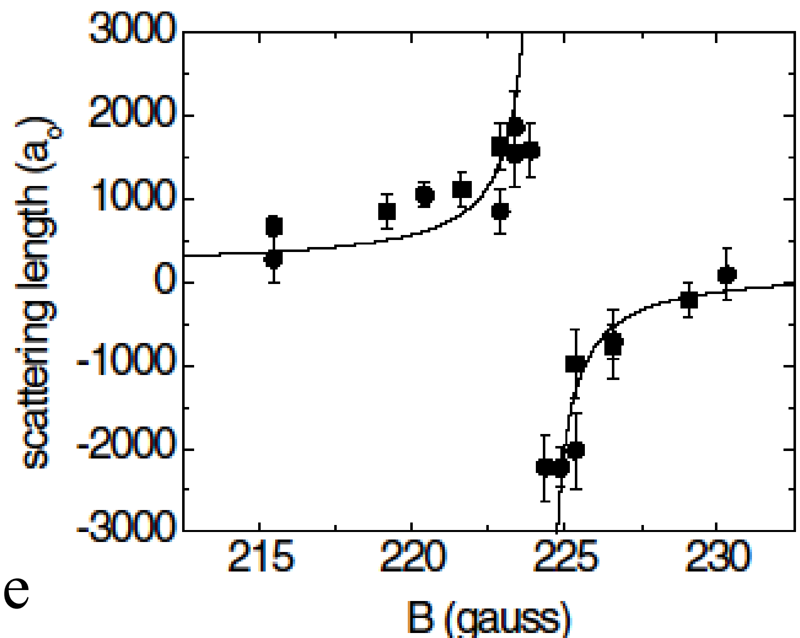
$$\sigma_0 = 4\pi |f_0|^2 = 4\pi |a_s|^2$$

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

→ Control of Interaction(a_s)

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



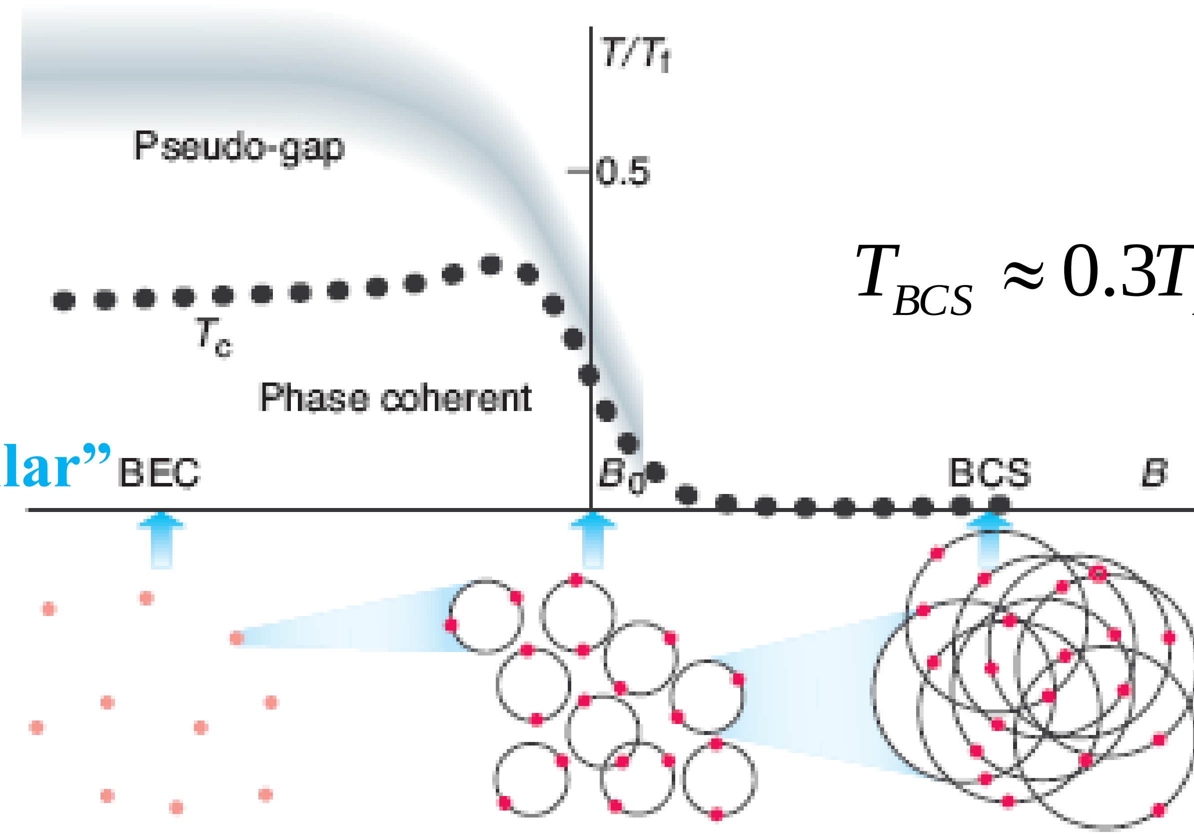


"Magnetic field tunes the energy difference between closed channel and open channel"

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

BEC – BCS Crossover

Leggett, ...



"molecular"

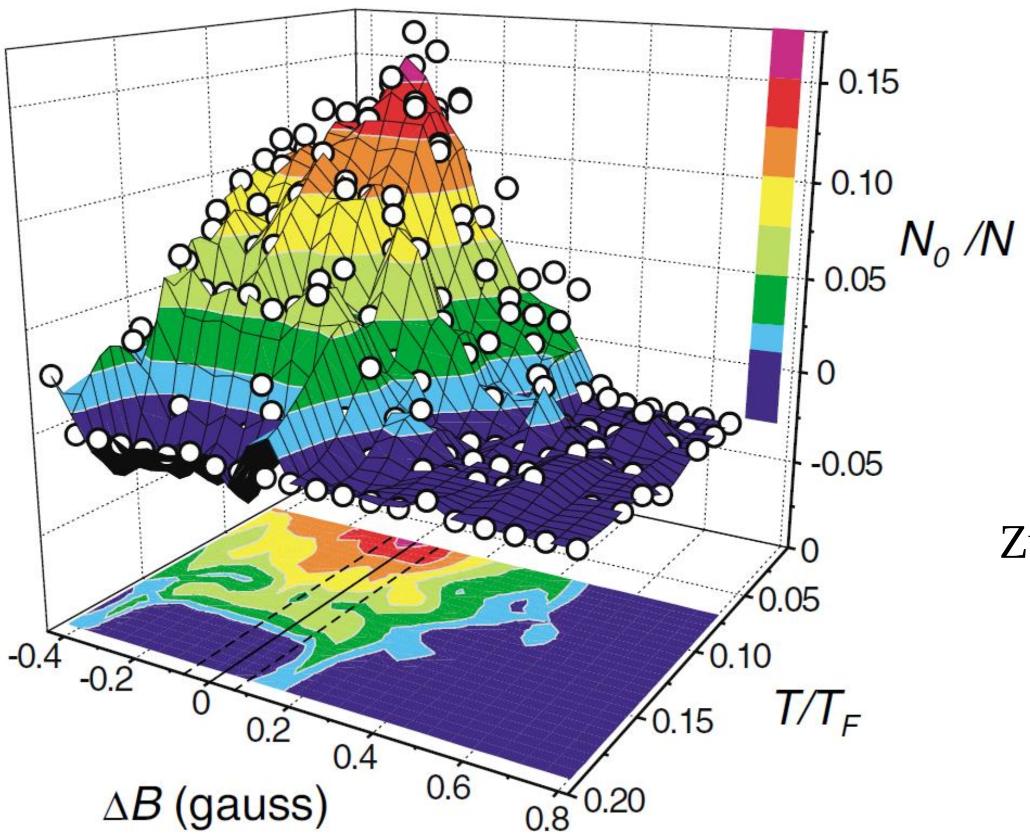
$$T_{BCS} \approx 0.3 T_F \exp\left(-\frac{\pi}{2k_F|a_s|}\right)$$

"Unitary Gas"

$$+\infty \xrightarrow{\quad 0 \quad} -\infty$$

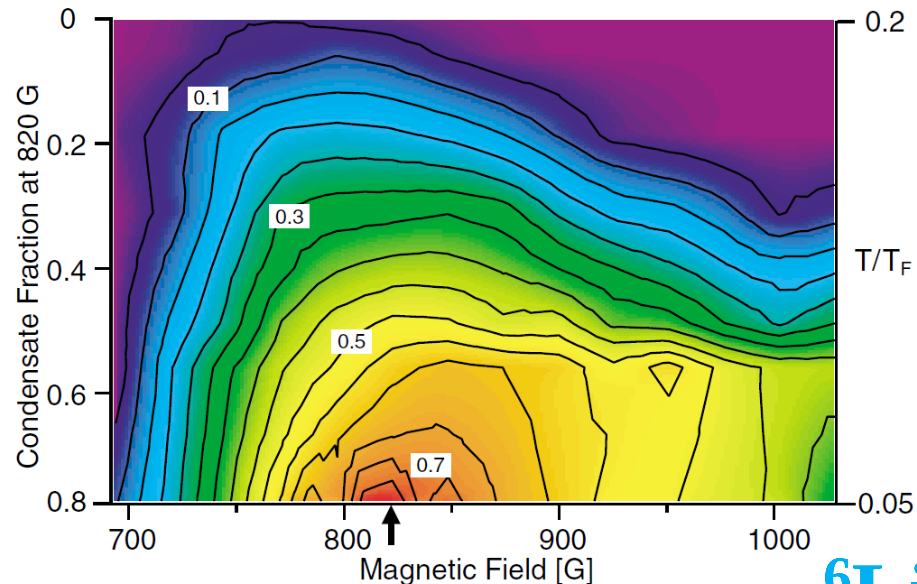
$1/(k_F a)$

BEC – BCS Crossover: experiments



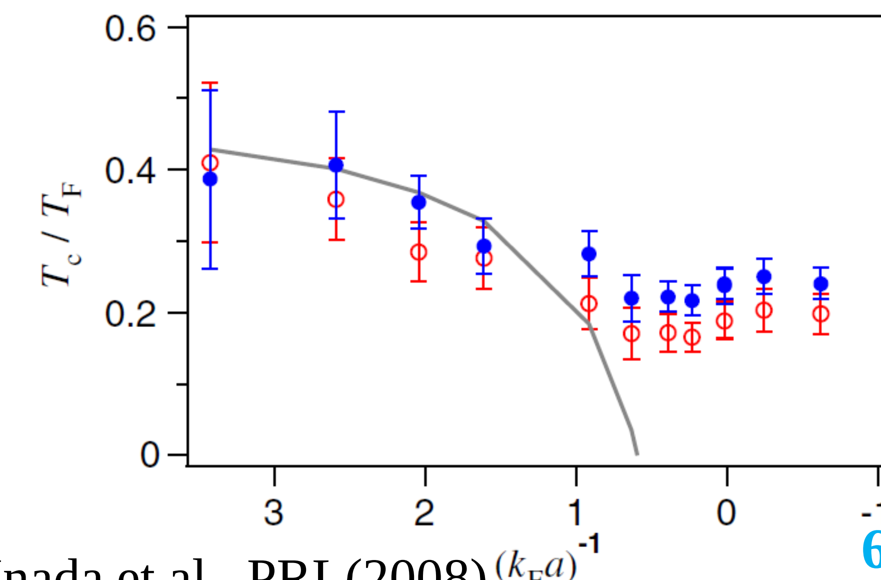
Regal et al., PRL(2004)

^{40}K



^{6}Li

Zwierlein et al., PRL(2004)



Inada et al., PRL(2008)

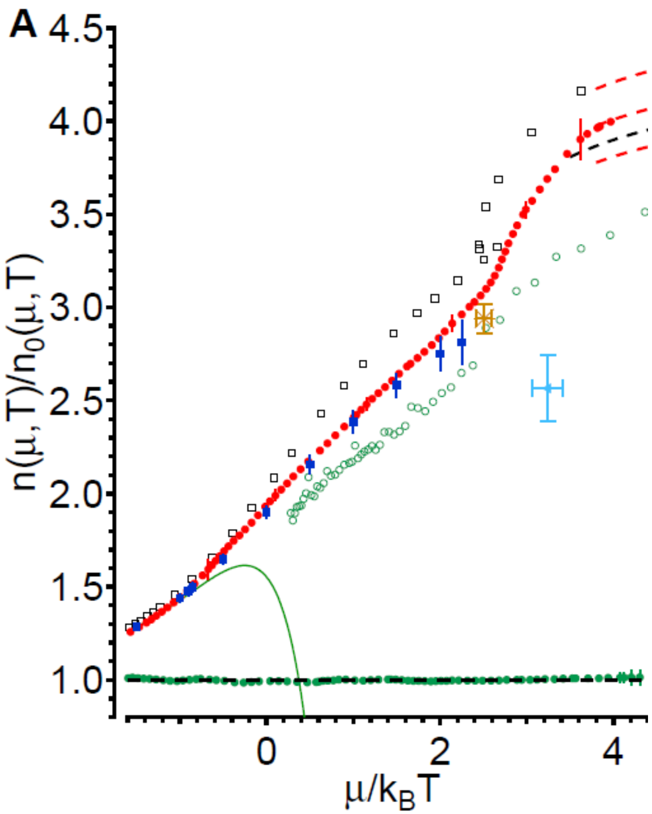
^{6}Li

Equation of State for Unitary Gas

M. J. H. Ku *et al*, (2011): MIT Zwierlein Group

$$\text{EoS} \qquad n(\mu, T) \equiv \frac{1}{\lambda^3} f_n(\beta\mu)$$

Density



- : experimental EoS
- : Monte Carlo
- : 3rd order Virial expansion
- : self-consistent T-matrix
- : ENS experiment
- : Tokyo experiment

^{6}Li

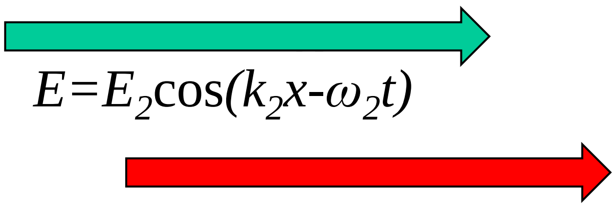
Spin-Orbit Interaction in Cold Atoms:

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

$\alpha=\beta$: $SOI \propto \sigma_y k_x$

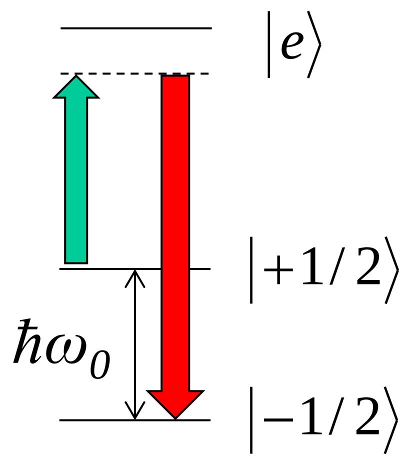
Y. –J. Lin, et al., Nature 471, 83(2011)

"lasers for Raman Transition"



$E=E_2\cos(k_2x-\omega_2t)$

$E=E_1\cos(k_1x-\omega_1t)$



"pseudo-spin +1/2":

$$\frac{\hbar\omega_0}{2}\hat{\sigma}_z = \frac{\hbar\omega_0}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

$\delta = \omega_0 - (\omega_1 - \omega_2)$: detuning

$Q = k_1 - k_2$: momentum transfer

$\longrightarrow$ *after the local pseudo-spin rotation with $\theta=Qx$ about z-axis* $\hat{U} = \exp(i\frac{Qx}{2}\hat{\sigma}_z)$

$$\hat{H} = \frac{\hbar^2k^2}{2m}\hat{1} + \frac{\hbar\delta}{2}\hat{\sigma}_y + \underbrace{\frac{\hbar\Omega}{2}\hat{\sigma}_z}_{B_z} + \underbrace{\hbar Q\frac{\hbar k_x}{2m}\hat{\sigma}_y}_{SOI} + \frac{E_R}{4}\hat{1}$$

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

:Recoil Energy

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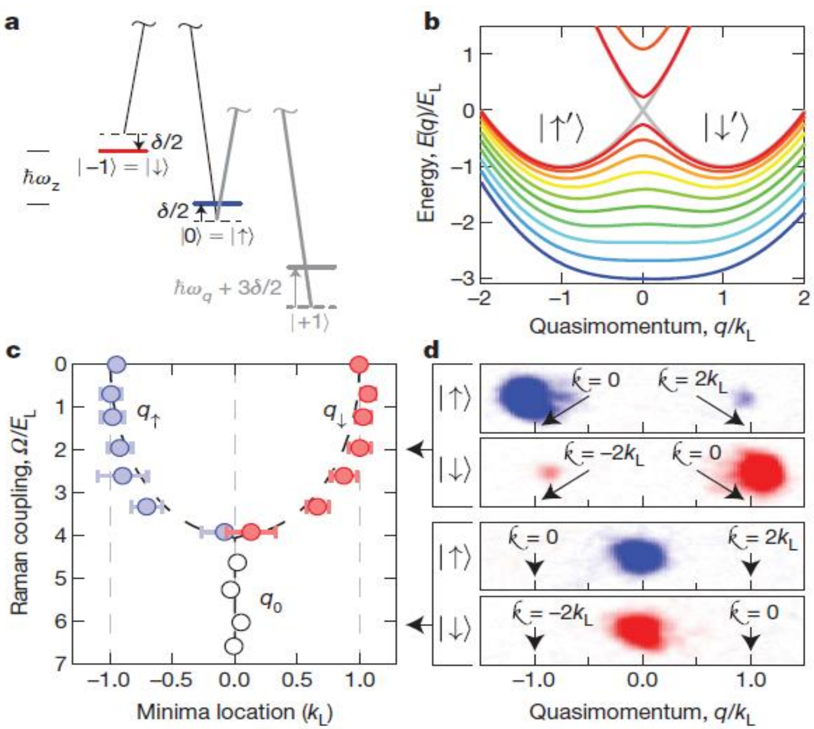
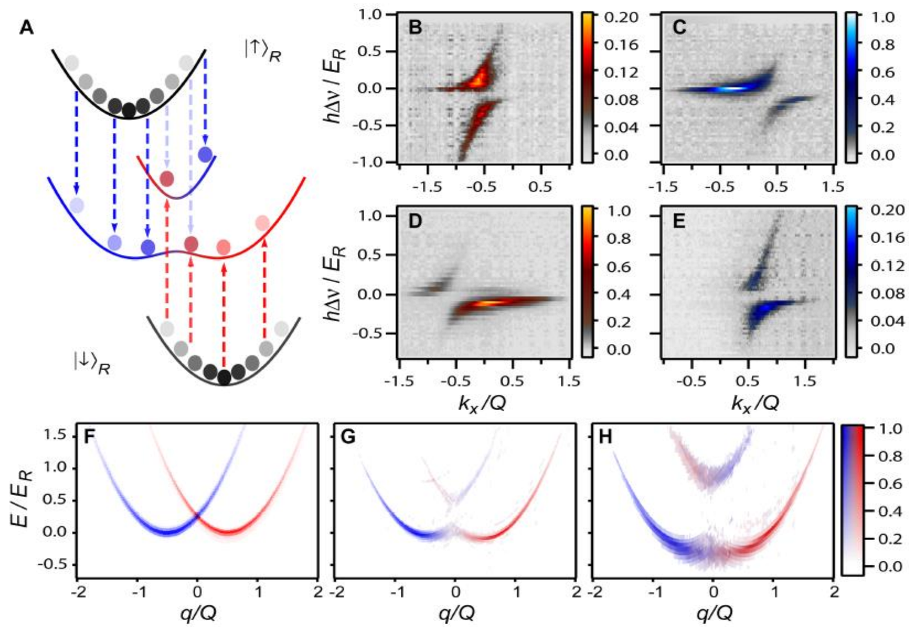


"Boson: ^{87}Rb"

P. Wang et al., (2012)

L. W. Cheuk et al., (2012)

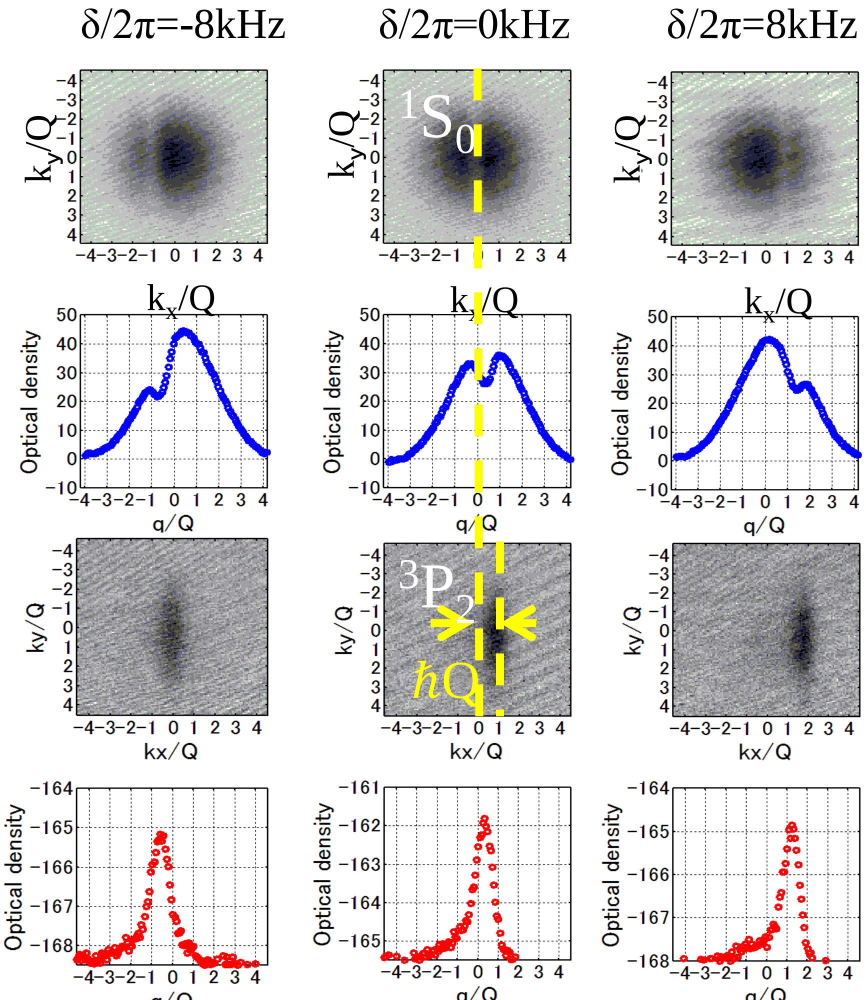


"Fermion: ^{6}Li, ^{40}K"

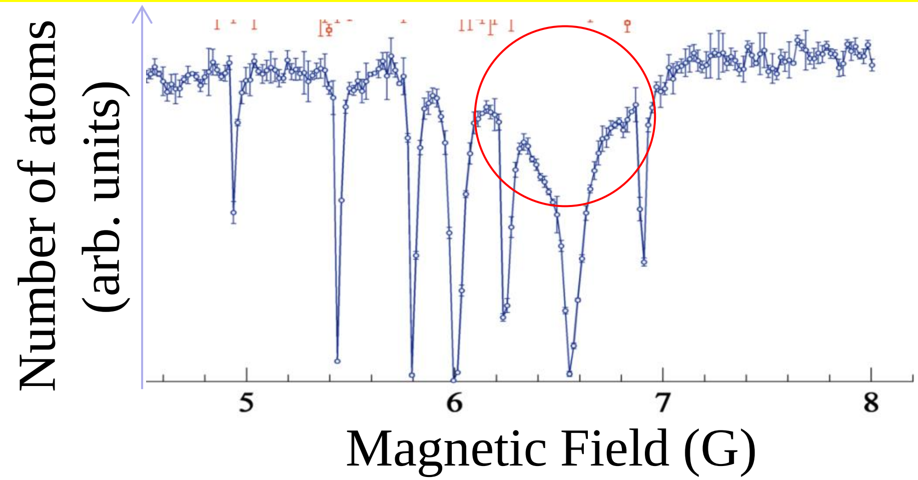
Topological Superfluids, Majorana Edge state
by **Spin-Orbit Interaction** + **Strong s-Wave Interaction**

[M. Sato et *al*., PRL**103**,020401(2009), PRB**82**, 134521(2010)]

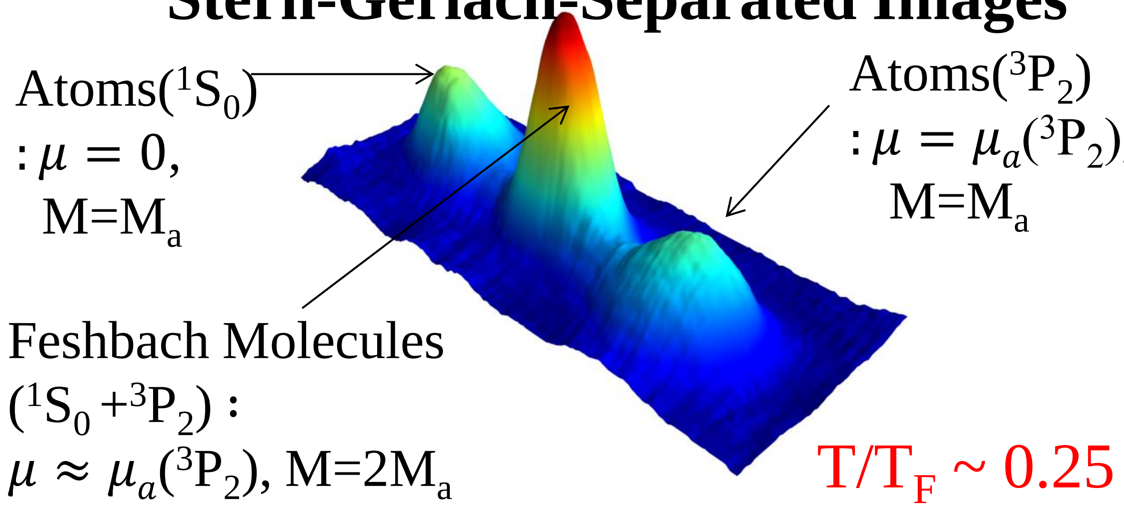
SOI between $^1S_0+^3P_2$(^{174}Yb)



Feshbach Resonance:$^1S_0+^3P_2$(^{171}Yb)



Stern-Gerlach-Separated Images



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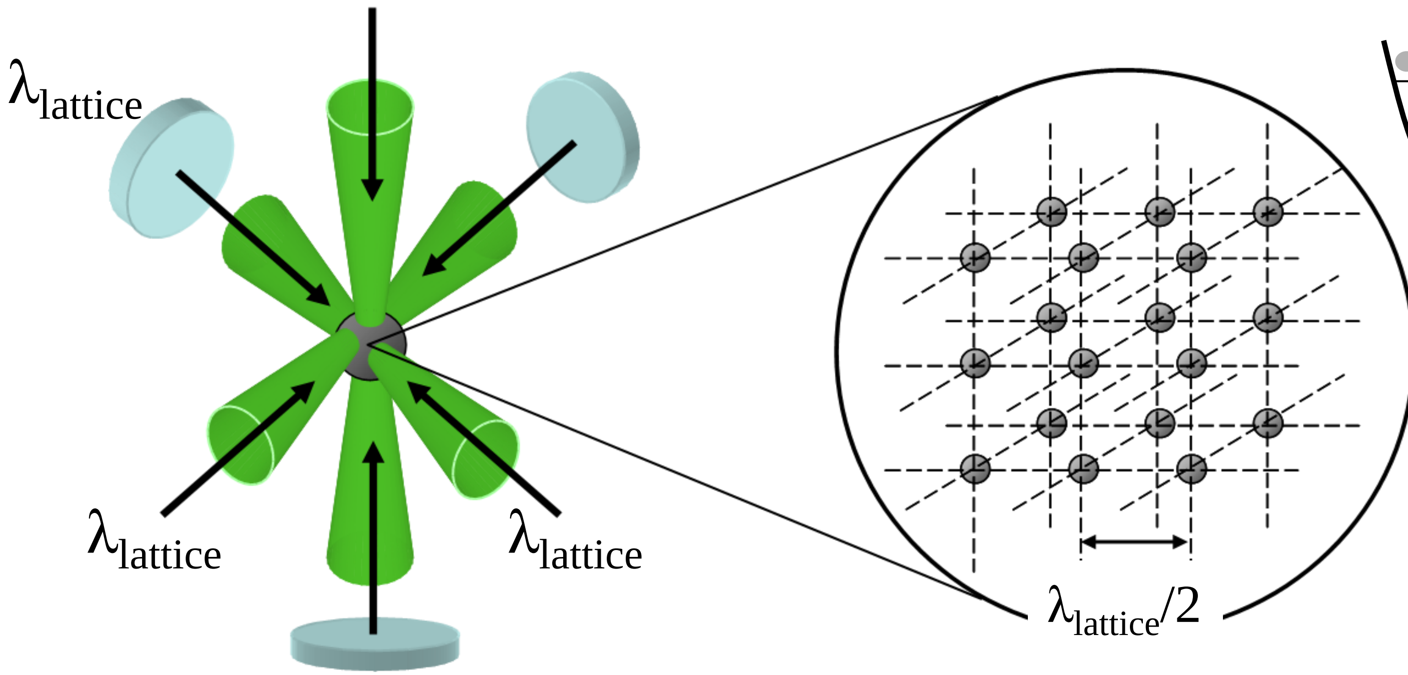
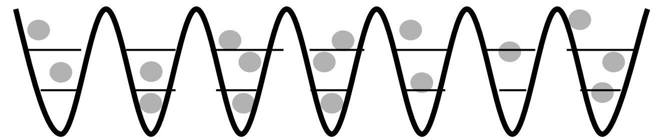
Quantum Simulation of Strongly Correlated Electron System



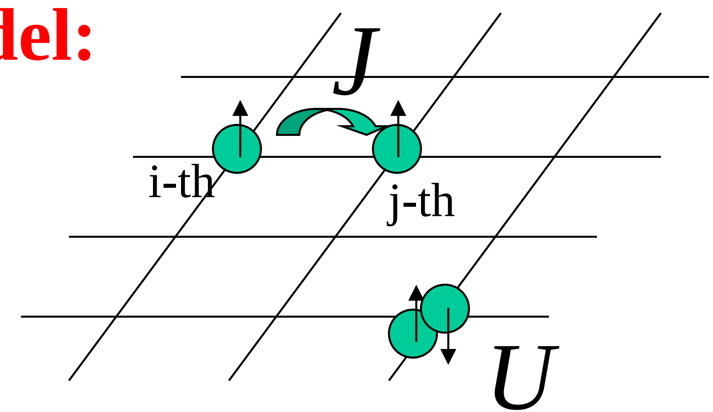


$$V_o(x) = V_o \sin^2(k_L x)$$

"ultracold atoms in an optical lattice"

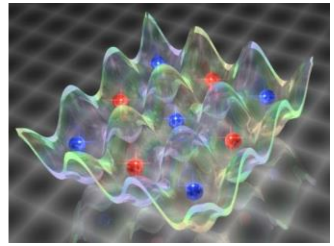
ideal Quantum Simulator of **Hubbard Model:**

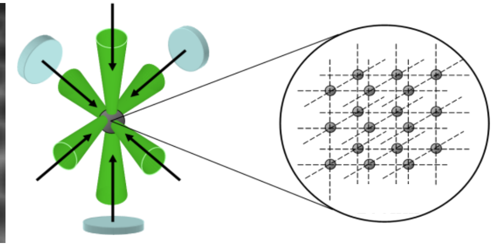
$$H = -J \sum_{<i,j>} c_i^+ c_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

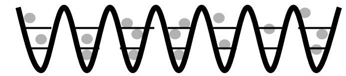


Nice Features of ultracold Atoms in an Optical lattice

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







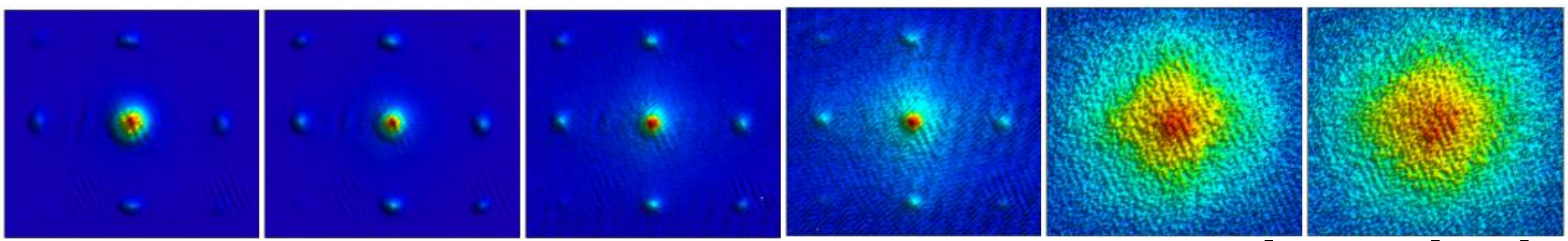
$$V = V_o \sin^2(kx)$$

1)Macroscopic Quantum System：typically ～10^5

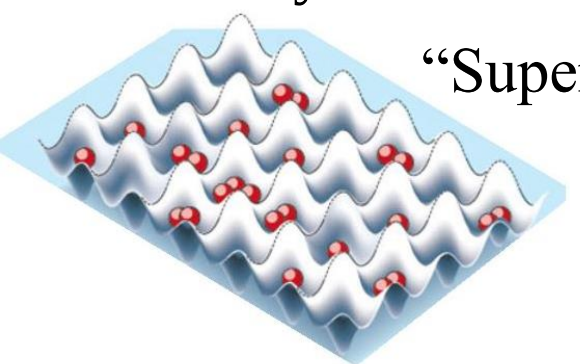
2)Clean (no impurity, no lattice defects)

3)High controllability of Hubbard parameters

Small ⟵ U/J ⟶ Large

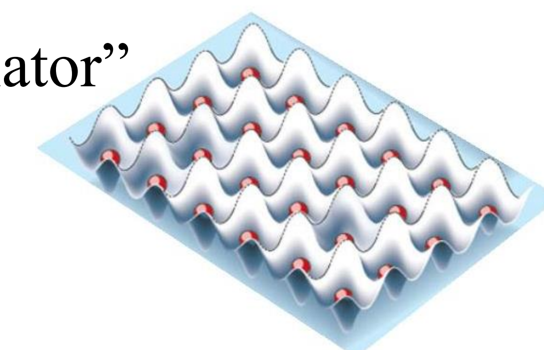


Weakly-interacting Strongly-correlated

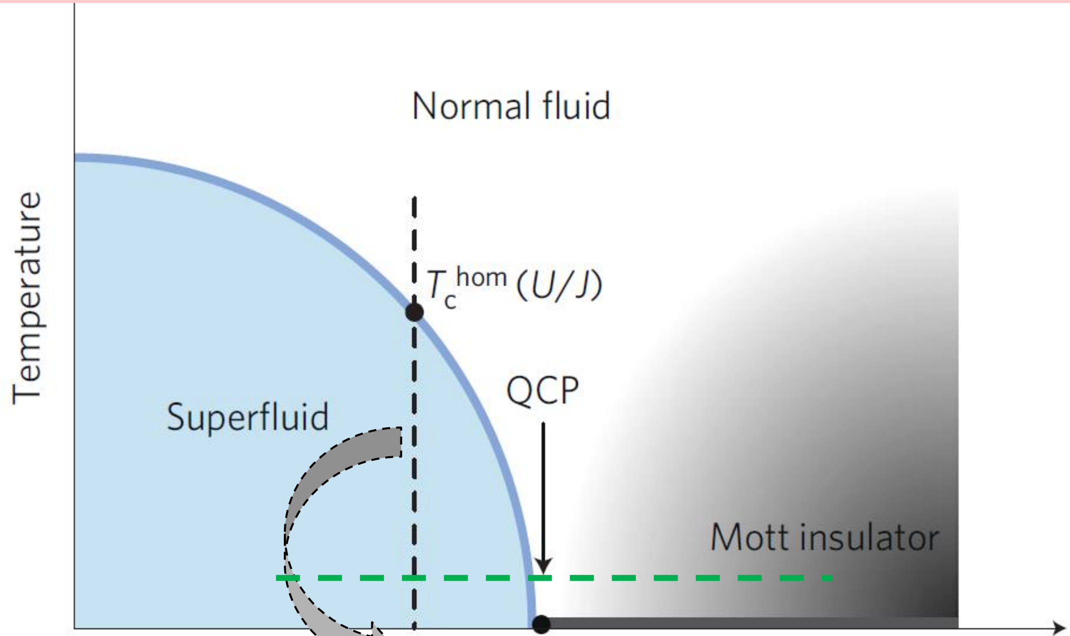


“Superfluid”

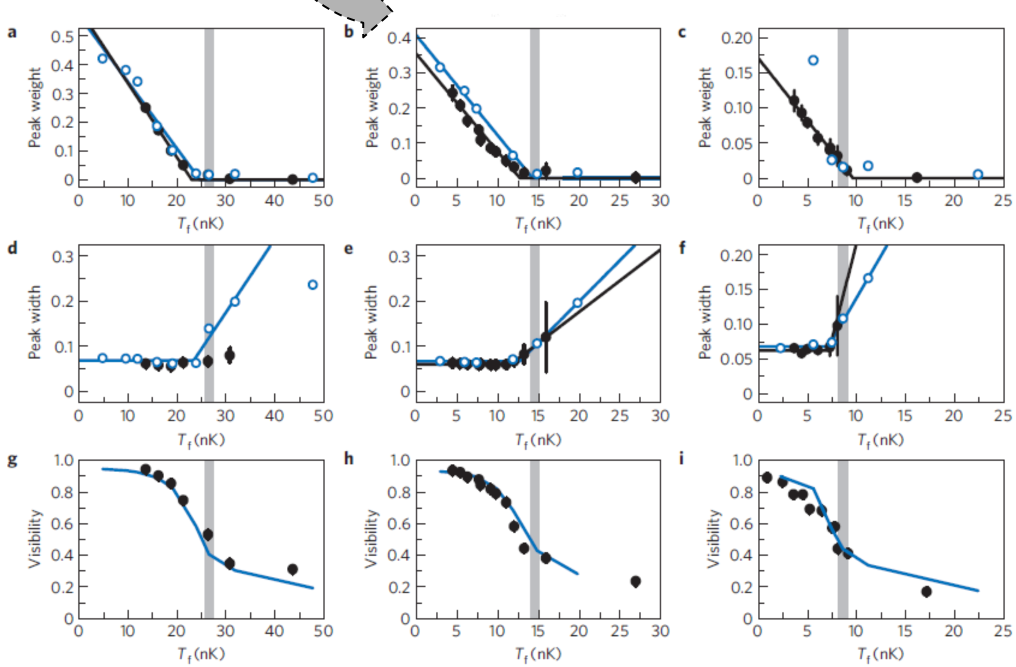
“Mott Insulator”



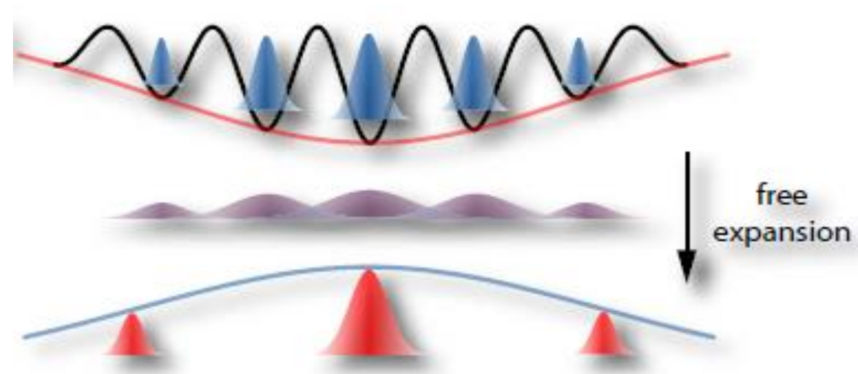
Phase Diagram of Bose-Hubbard Model (T>0)



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

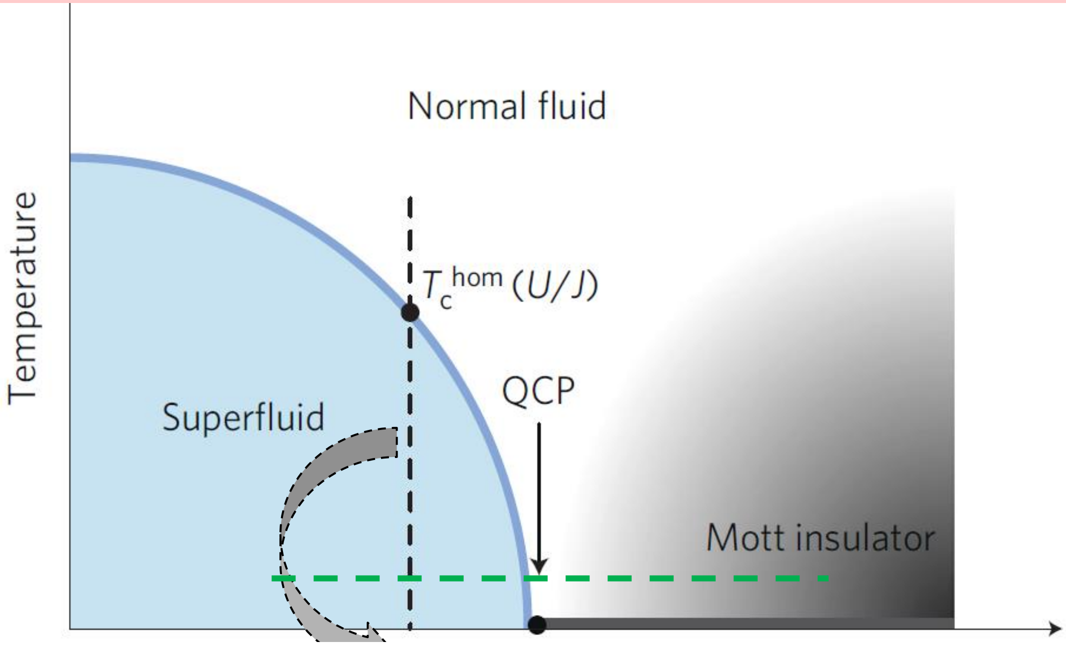


"An interference fringe is the direct signature of the phase coherence"

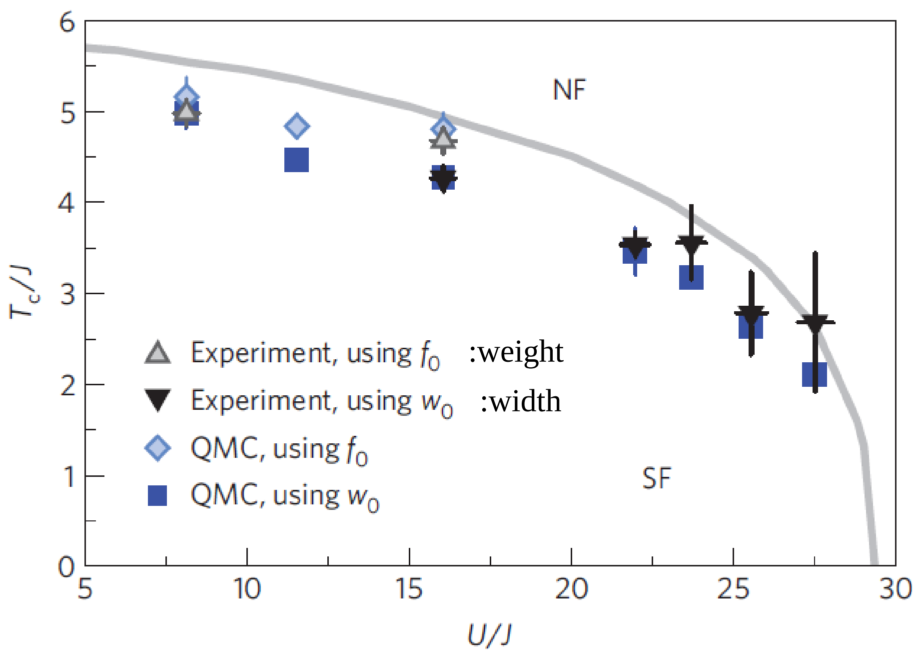


S. Trotzky, et al, Nature Physics **6**, *998(2010)*

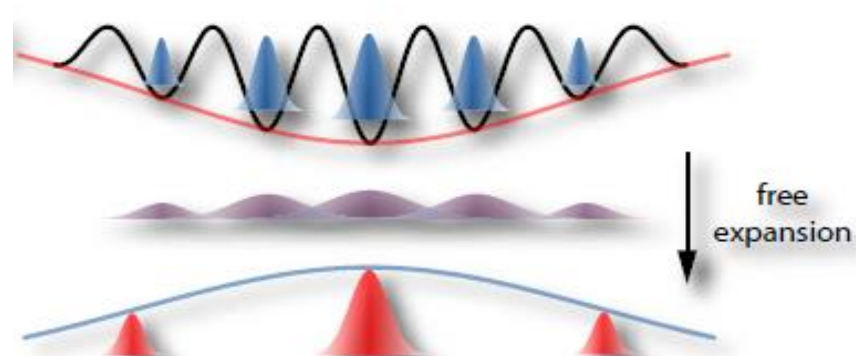
Phase Diagram of Bose-Hubbard Model (T>0)



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



"An interference fringe is the direct signature of the phase coherence"



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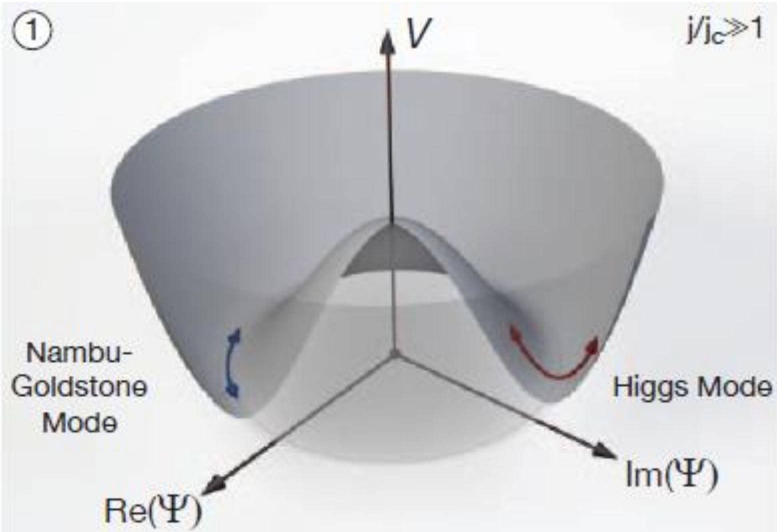
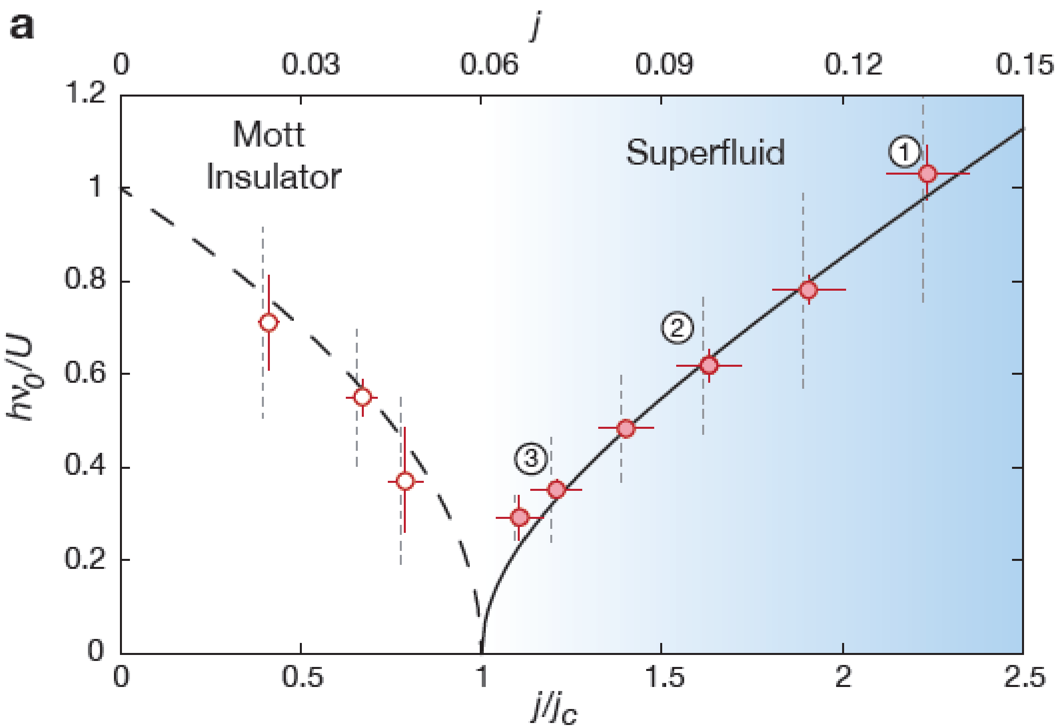
“amplitude-(Higgs-)mode”

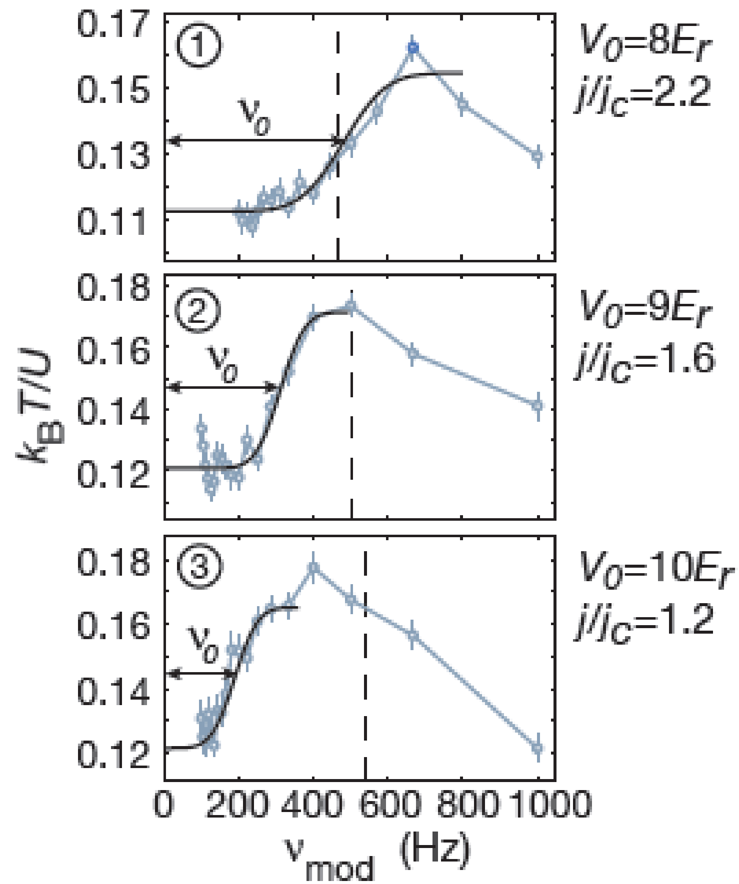


The `Higgs' Amplitude Mode at the Two-Dimensional Supefruid-Mott Insulator Transition

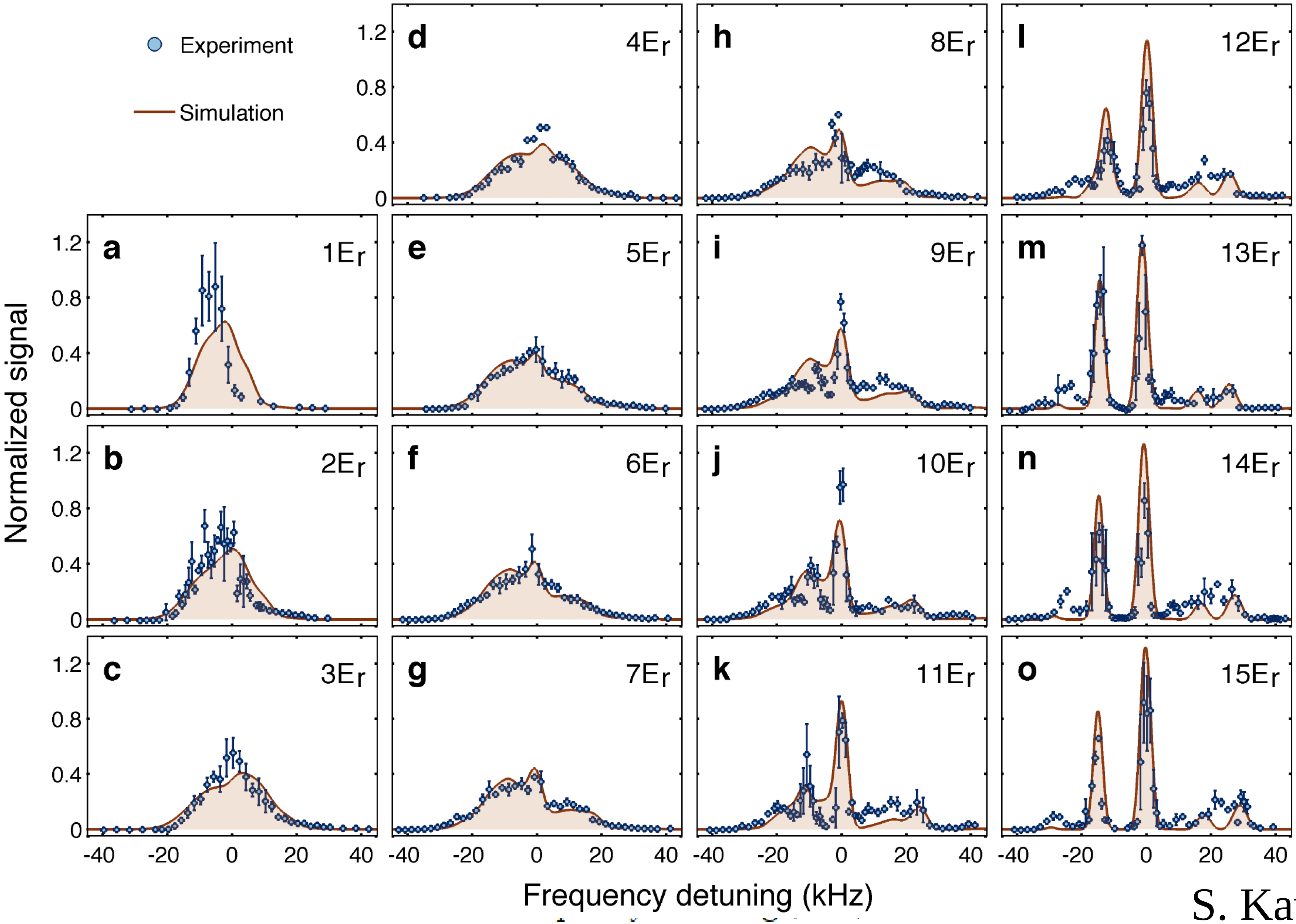
M. Endres *et al* (2012)



Lattice modulation spectra



Spectroscopy of Superfluid-Mott Insulator Transition



S. Kato et al.,

quantum simulation of antiferromagnetic spin chains in an optical lattice

[J. Simon, *et al.*, Nature, **472,** 307(2011)]

1D Bose-Hubbard Model: $\longrightarrow$ $H = J\sum_i \left(S_z^i S_z^{i+1} - h_z^i S_z^i - h_x^i S_x^i\right)$

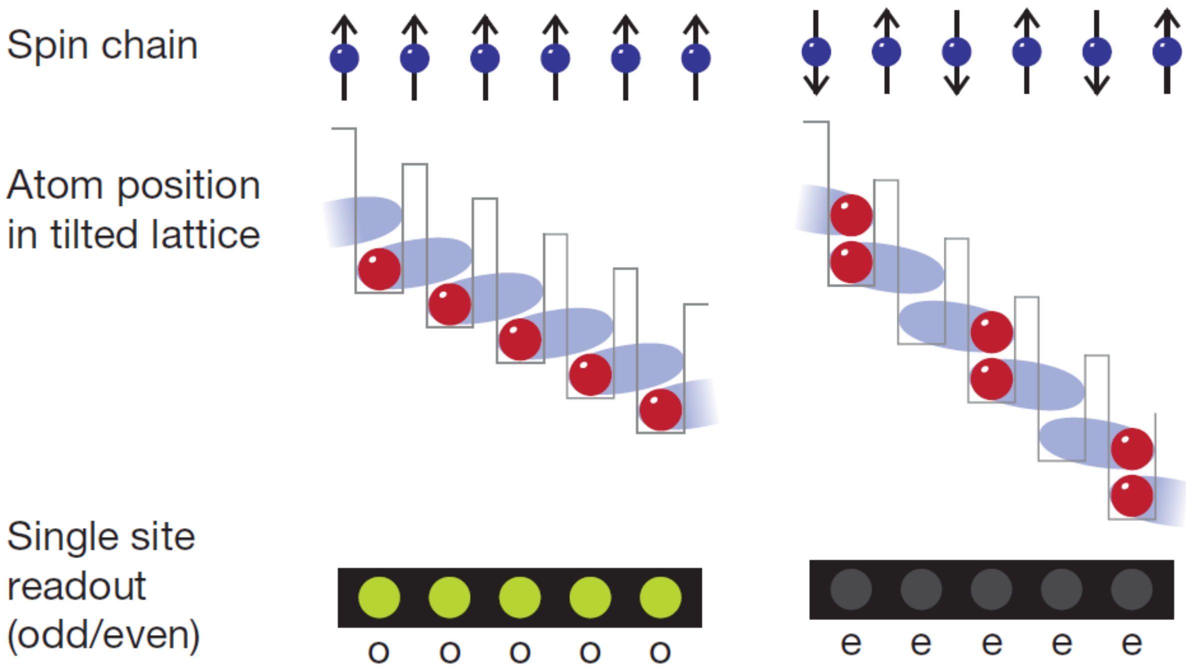
$$H = -t\sum_j \left(a_j^\dagger a_{j+1} + a_j a_{j+1}^\dagger\right) + \frac{U}{2}\sum_j n_j(n_j-1) - E\sum_j j n_j$$

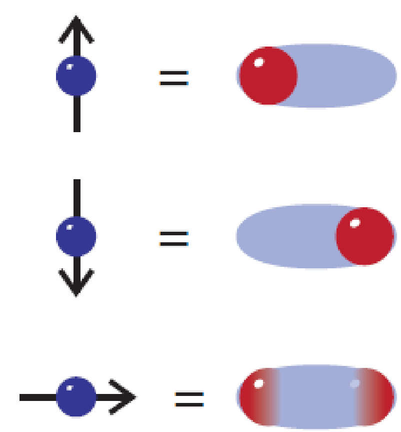
$$(h_z, h_x) = \left(1-\tilde{\Delta}, 2^{3/2}\tilde{t}\right)$$

“E < U” “E > U”

$$\tilde{t} = t/J$$

$$\tilde{\Delta} = \Delta/J = (E-U)/J$$

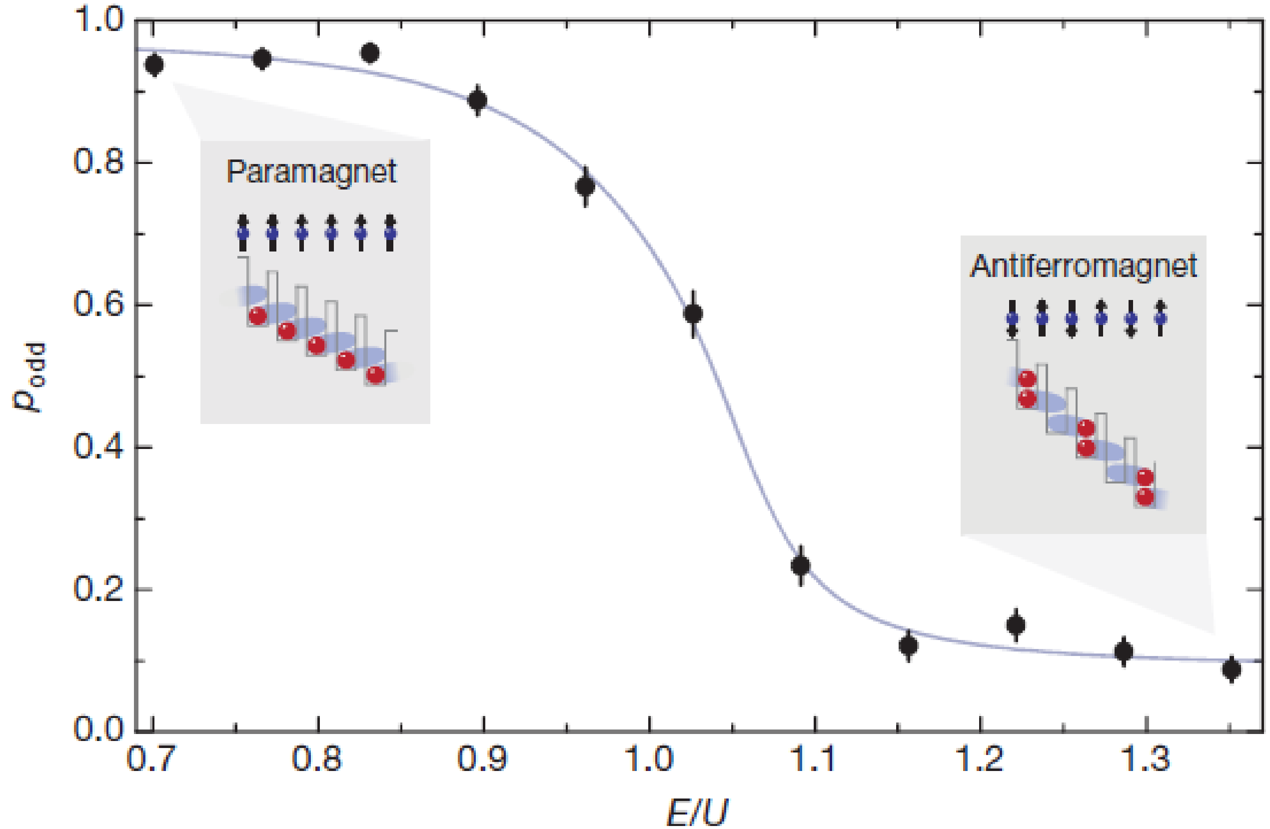




quantum simulation of antiferromagnetic spin chains in an optical lattice

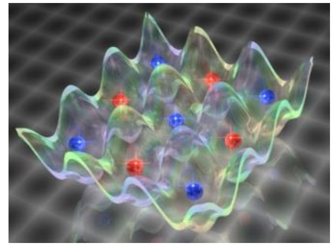
[J. Simon, *et al*., Nature, **472,** 307(2011)]

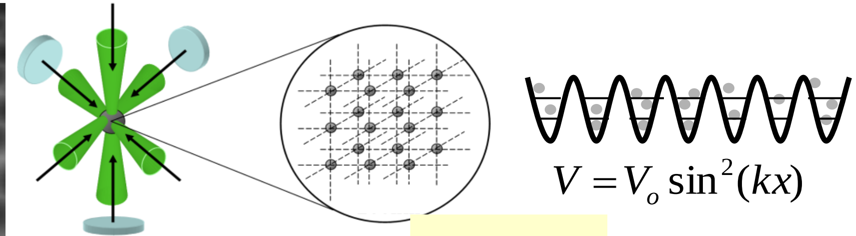
They successfully observe the transition from paramagnetic spin state to AF ordered state.



Nice Features of ultracold Atoms in an Optical lattice

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





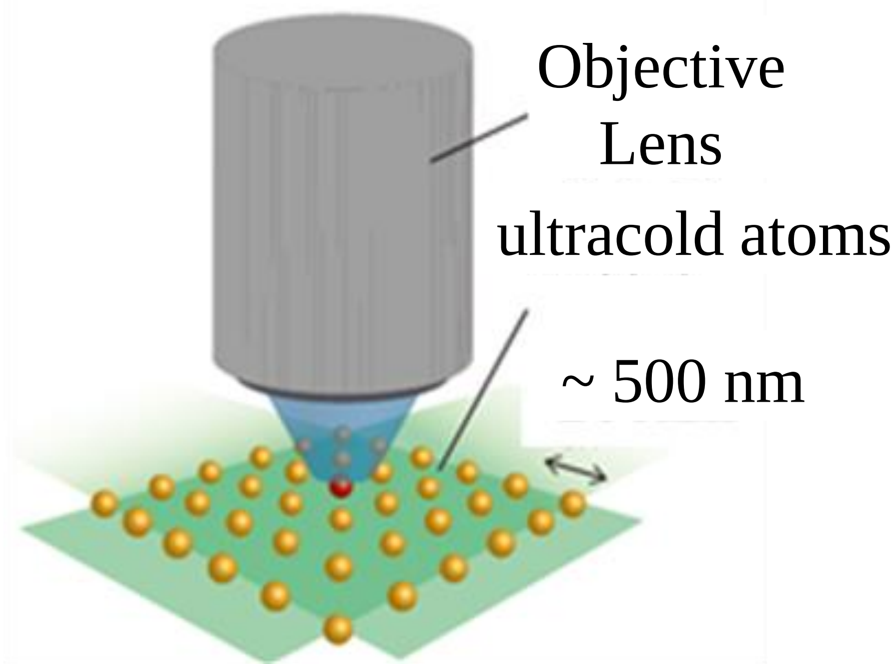
$V = V_o \sin^2(kx)$

^{87}Rb

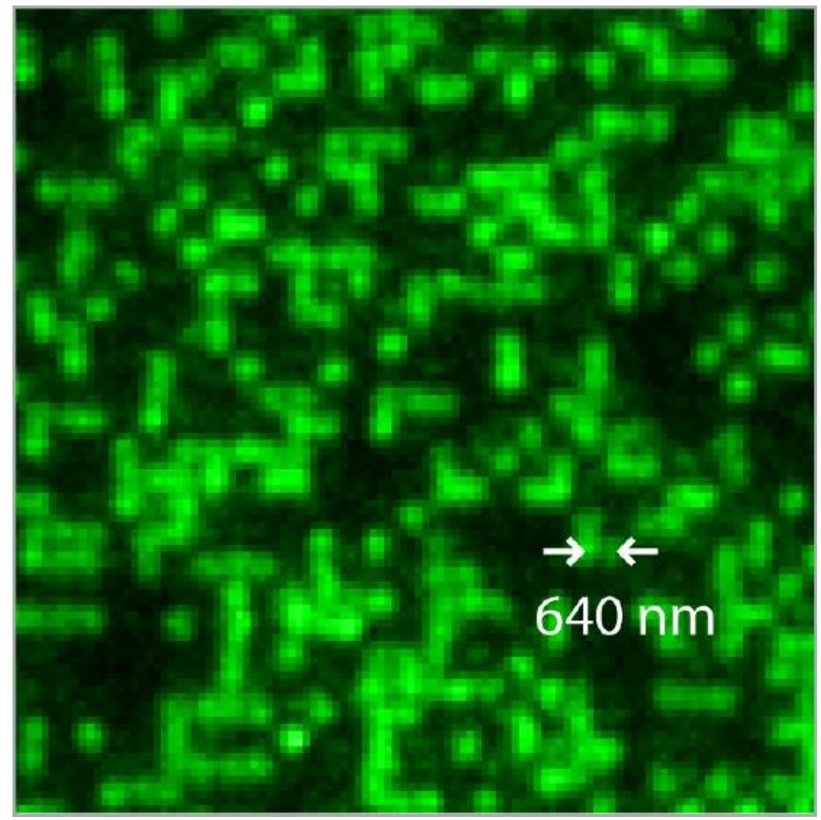
4) Powerful Measurement Methods:

***in situ* imaging**

by Quantum Gas Microscope



Fluorescence Imaging



[WS. Bakr, et al Nature 462,5 (2009)]

Single Site Resolved Detection of SF-MI Transition

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

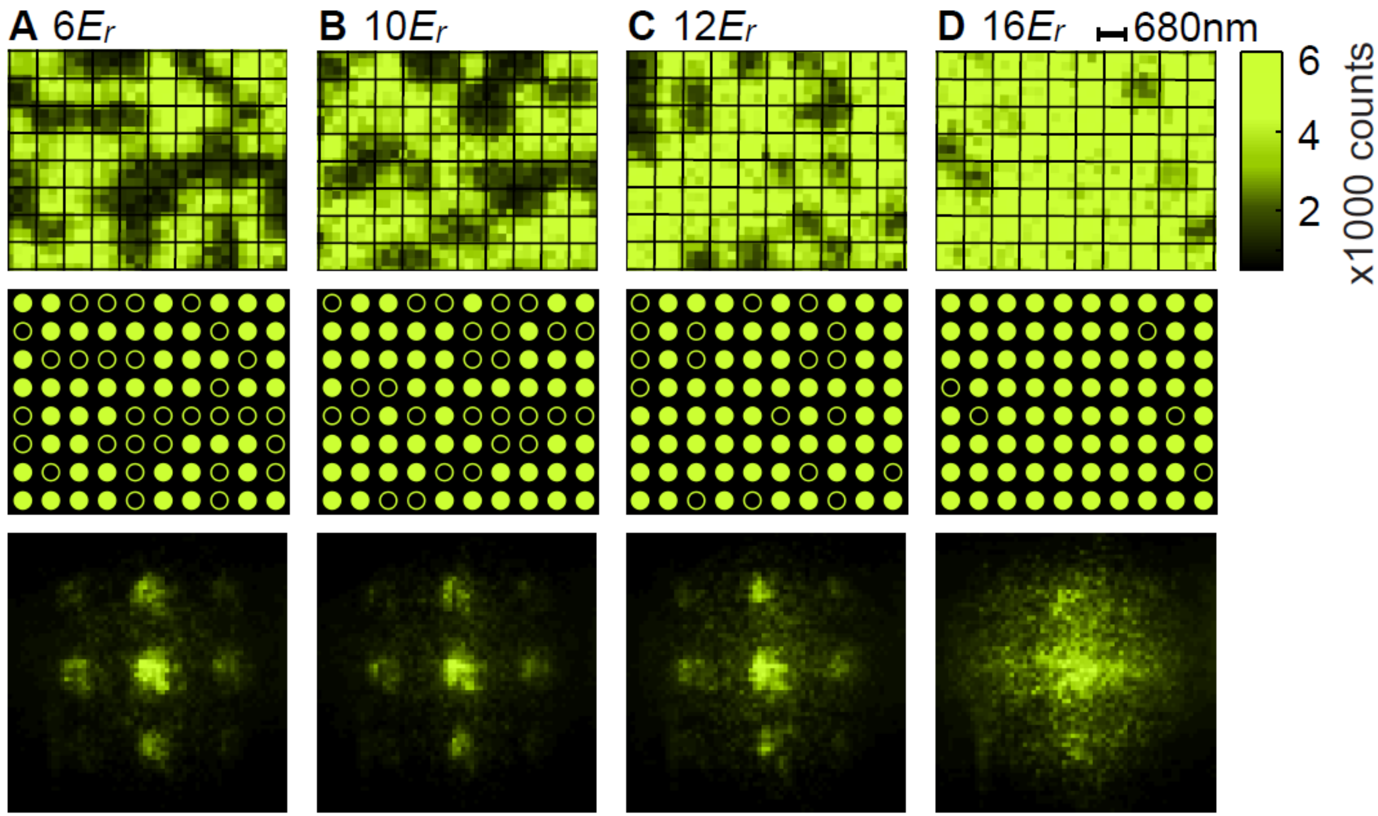
^{87}Rb

SF ⟷ MI

In Situ-image

after analysis

TOF-image



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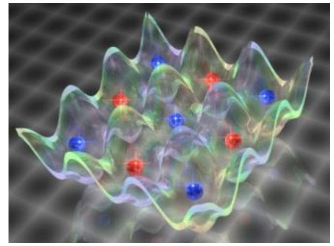
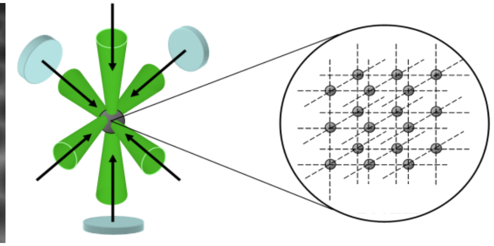
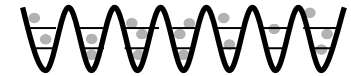






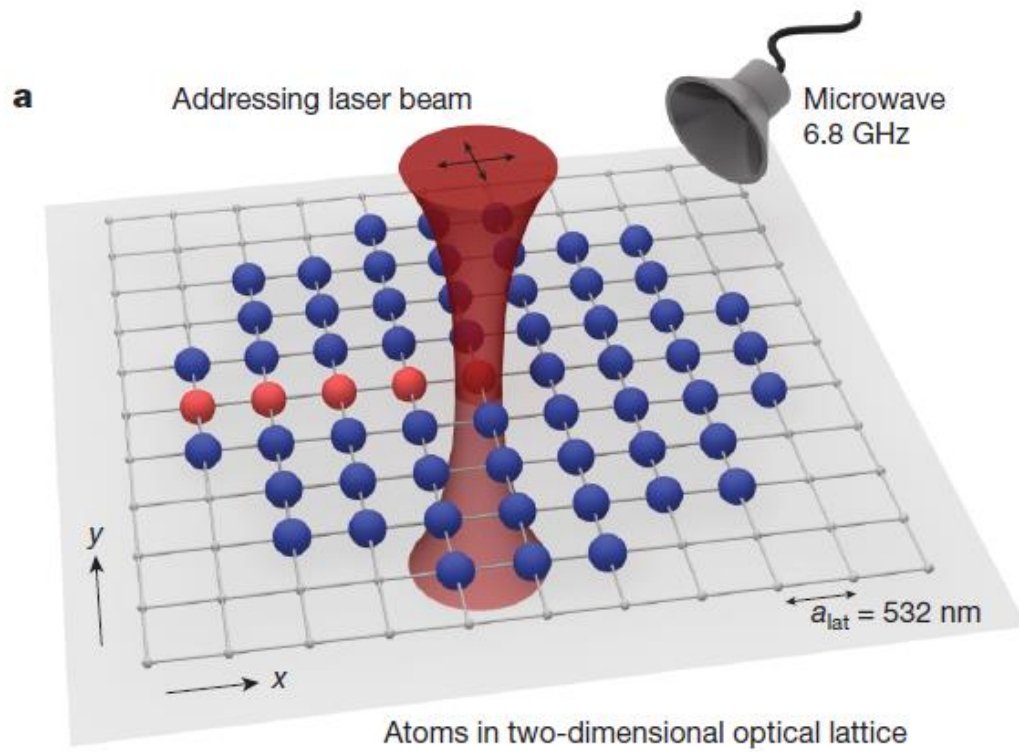
$V = V_o \sin^2(kx)$

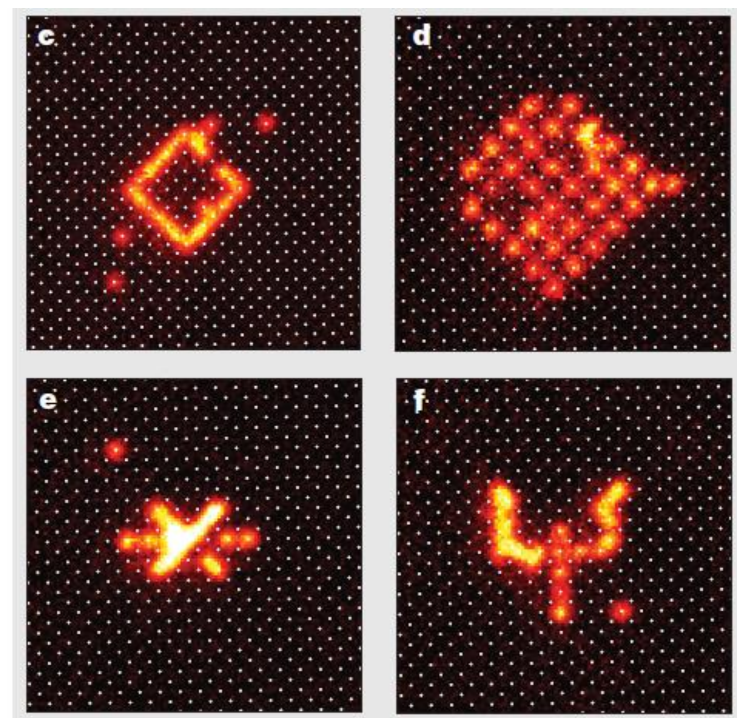
4) Powerful Measurement Methods:

Single-site manipulation

by Quantum Gas Microscope

^{87}Rb



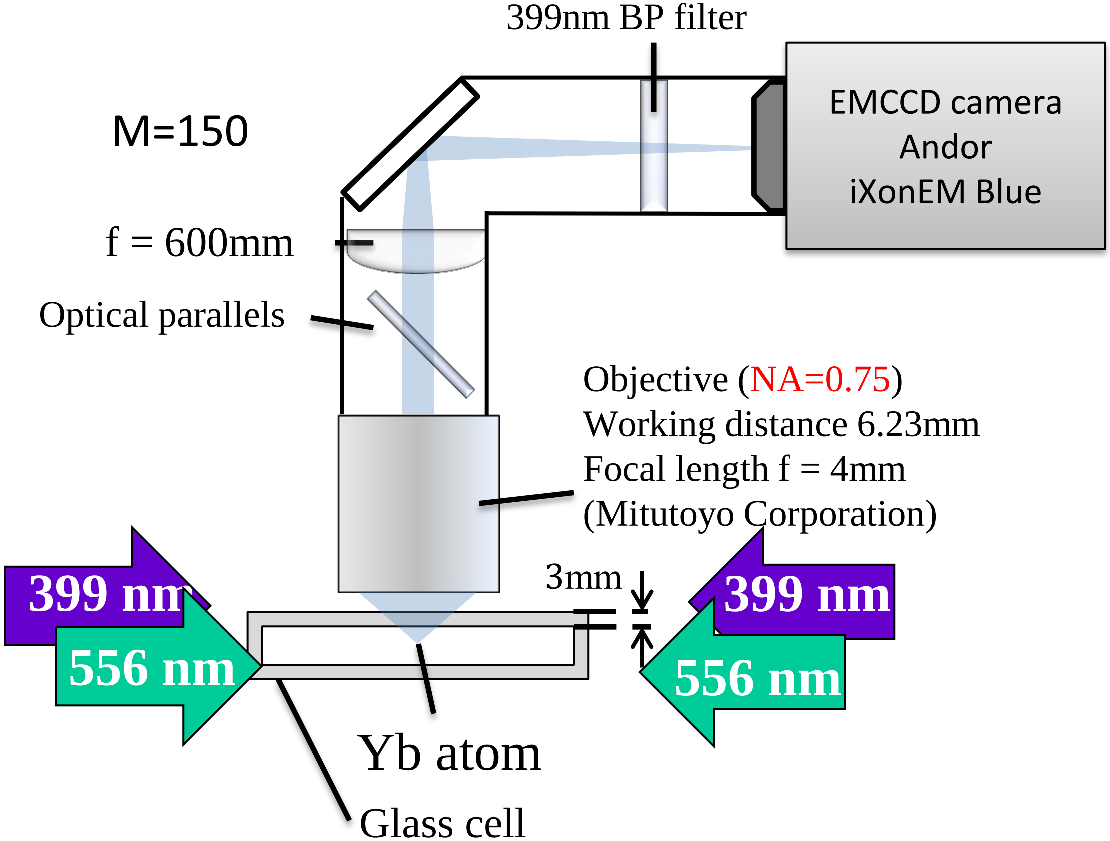


[C. Ewitenberg *et al*, Nature 471, 319(2011)]

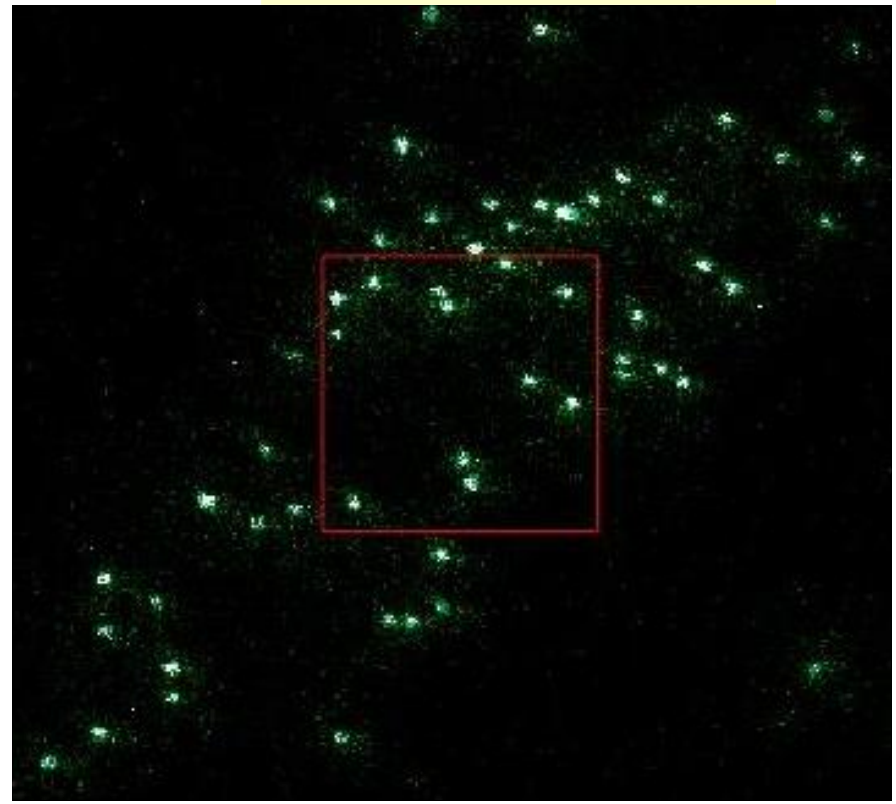
Ytterbium Quantum Gas Microscope

“Observation of Single Yb Atoms in an Optical Lattice with *Hubbard Regime*”

“dual molasses“



^{174}Yb (boson)



~30 μm

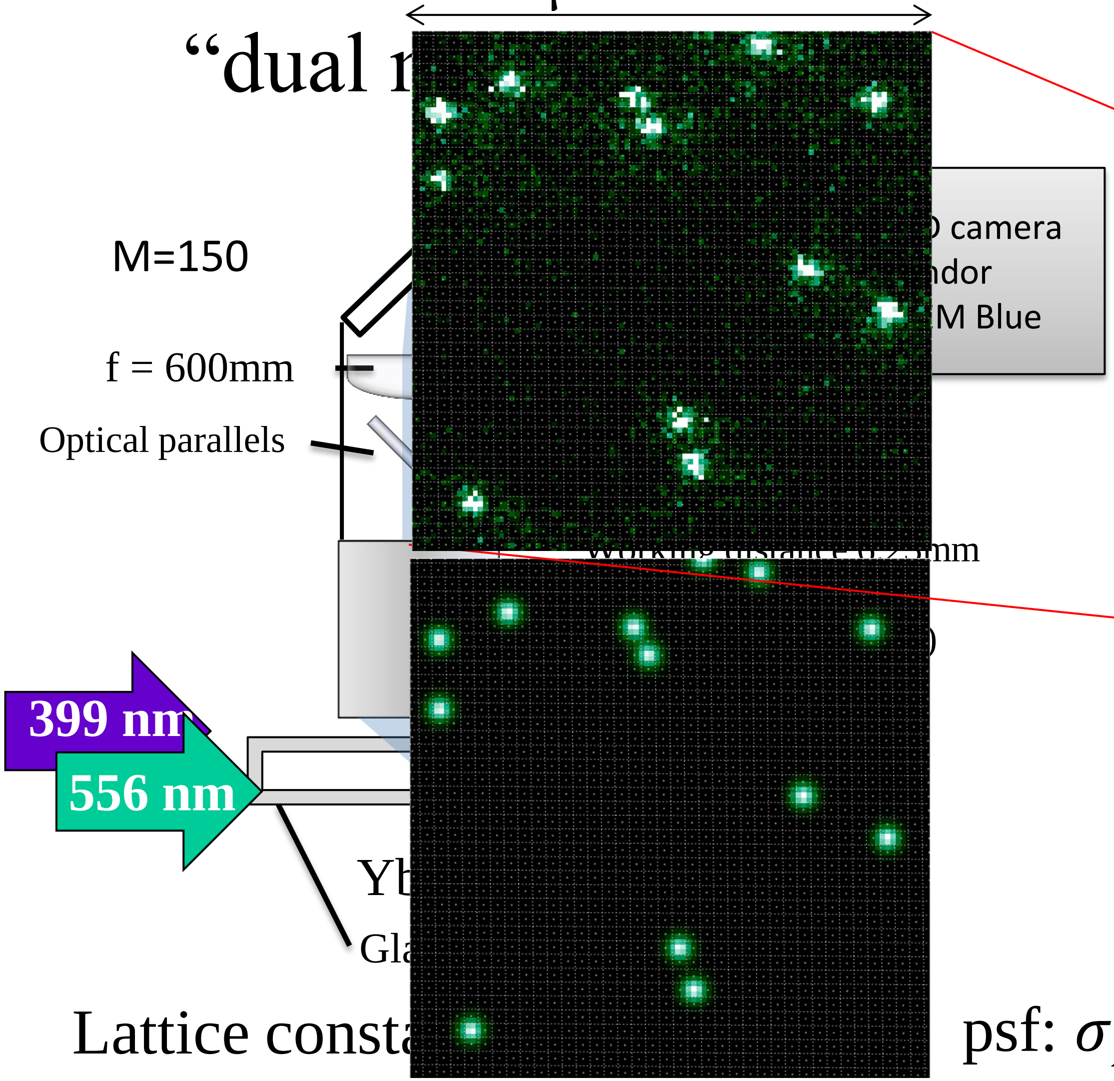
Lattice constant: d=266 nm

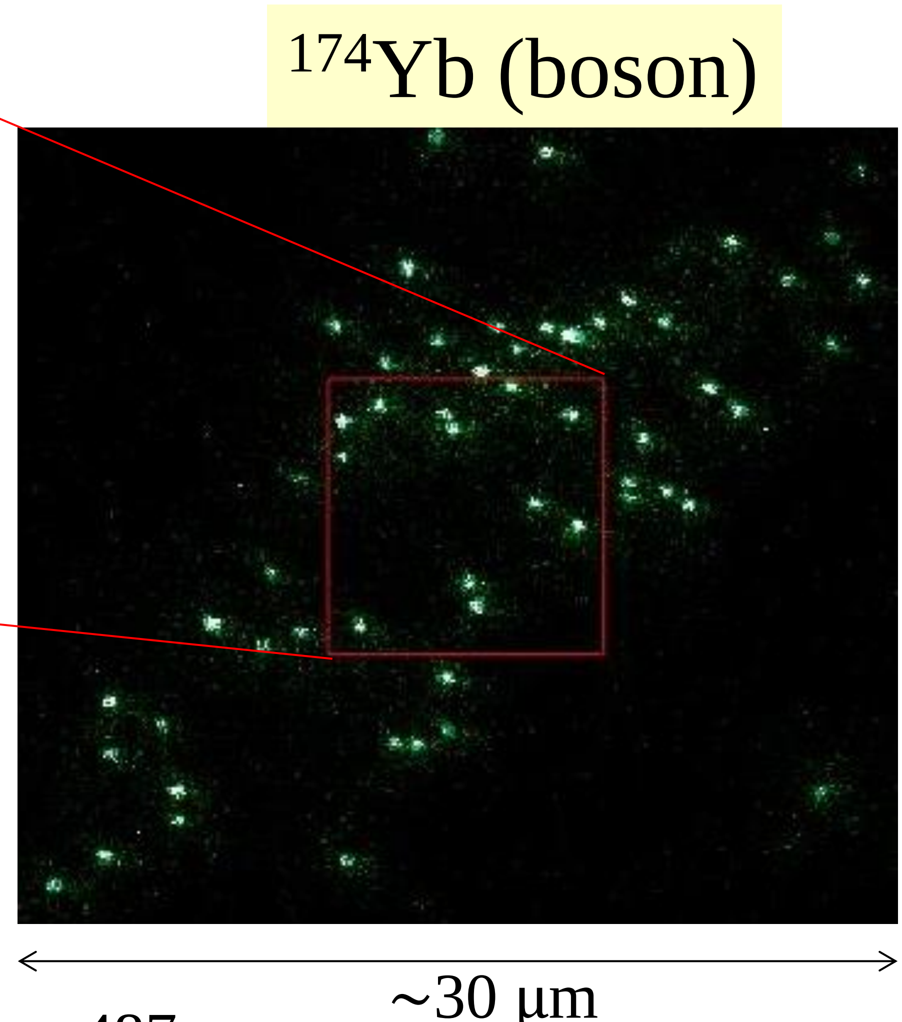
psf: σ_A =487 nm

Ytterbium Quantum Gas Microscope

“Observation of Single Yb Atoms in an Optical Lattice with *Hubbard Regime*”

“dual r





Lattice consta

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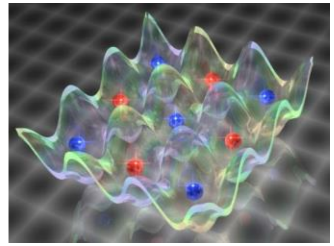
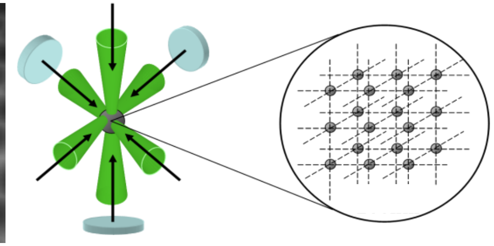
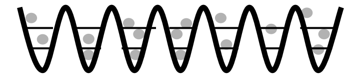


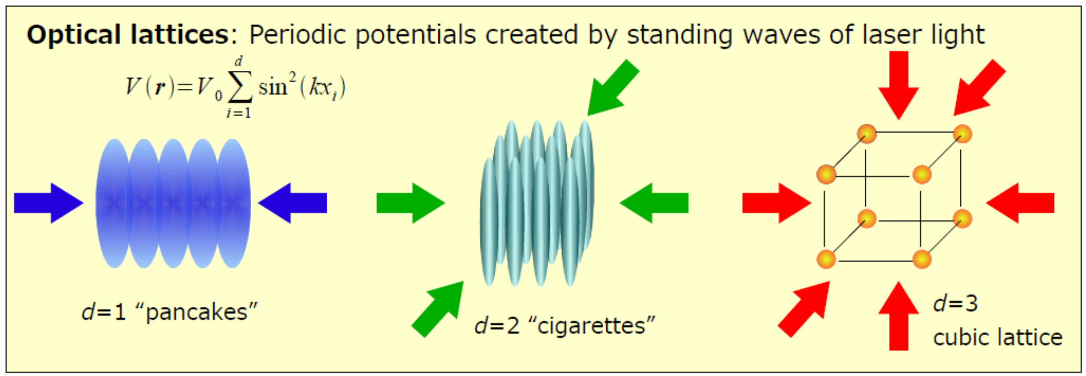




$V = V_o \sin^2(kx)$

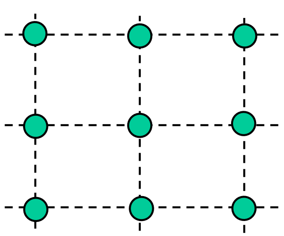
5)Various Lattice Geometries :

Dimensionality:

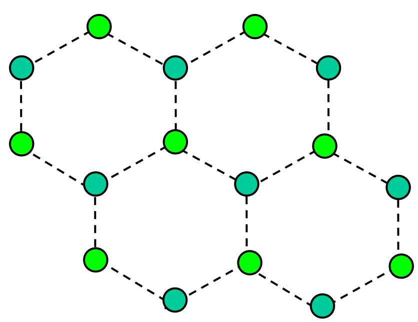


Standard and Non-standard Lattices:

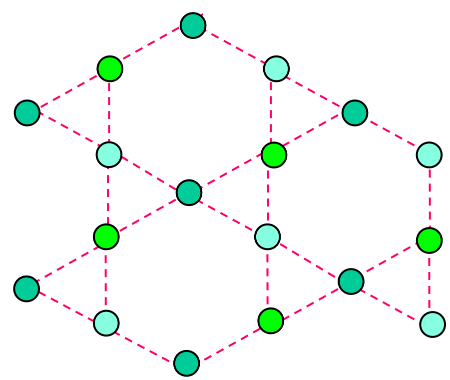
Cubic(Square)



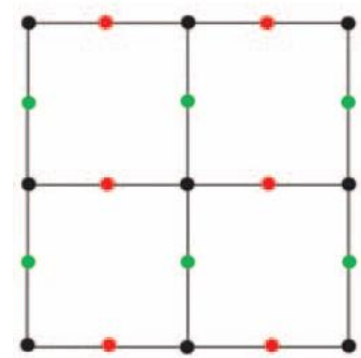
Honeycomb
(hexagonal)

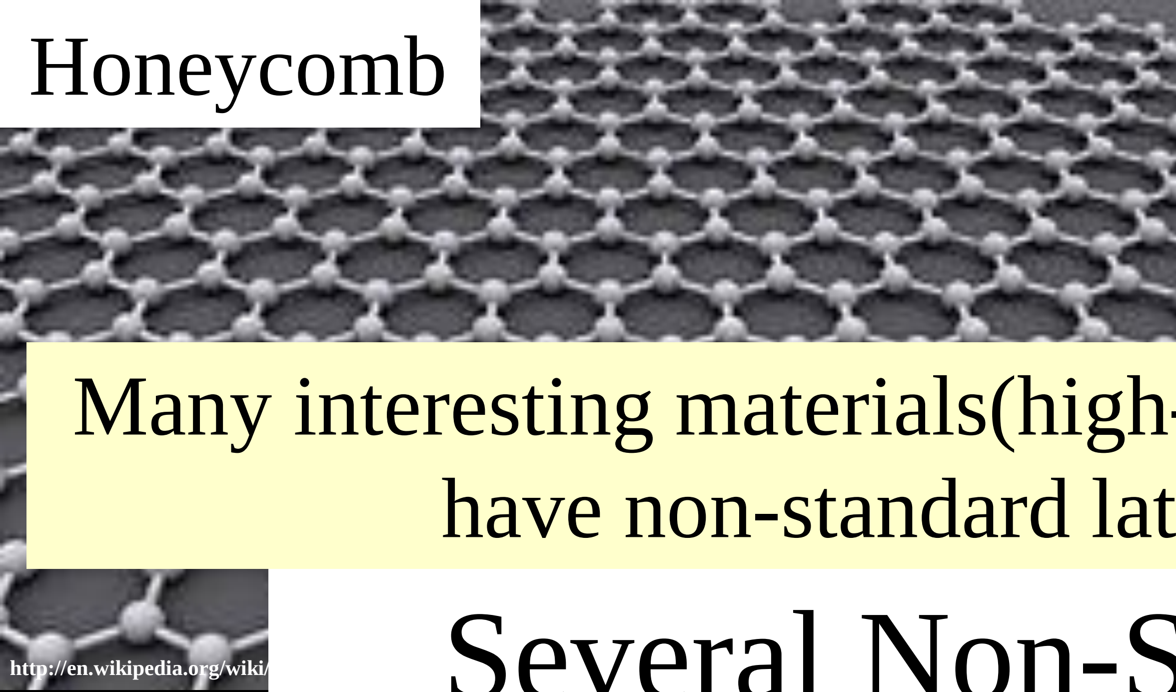


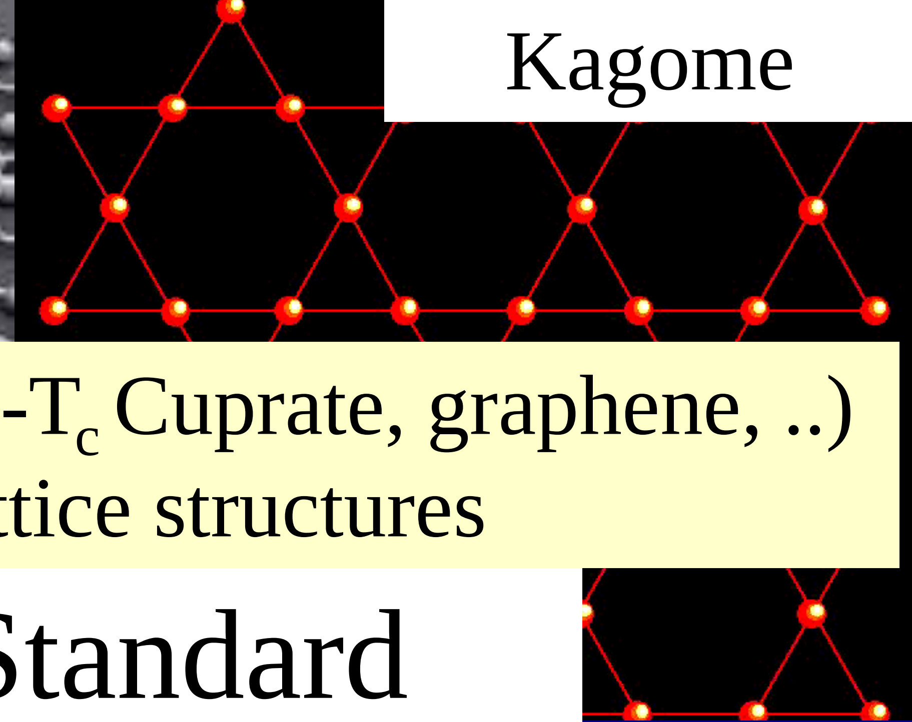
Kagome



Lieb

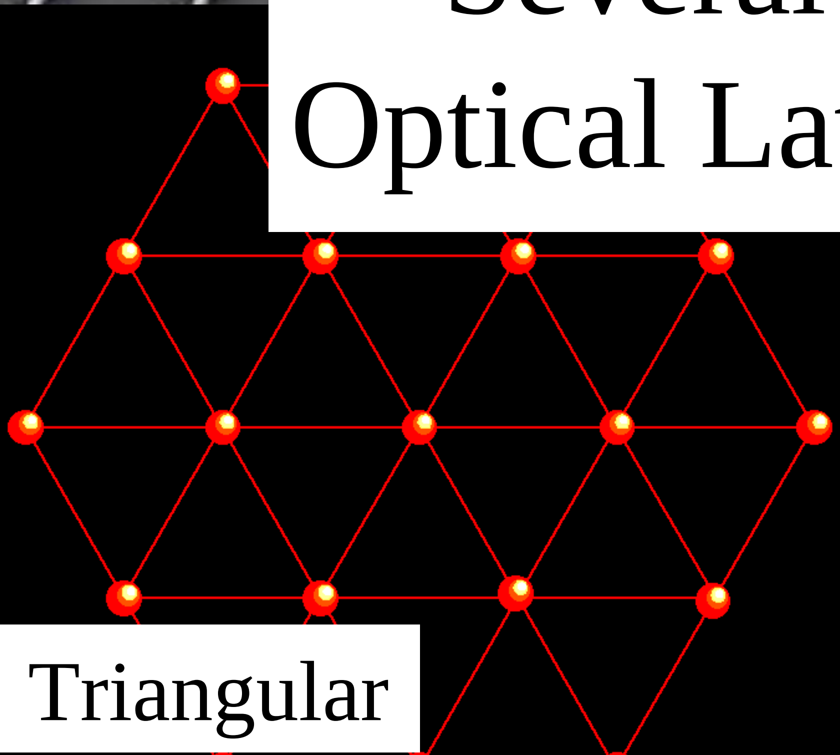


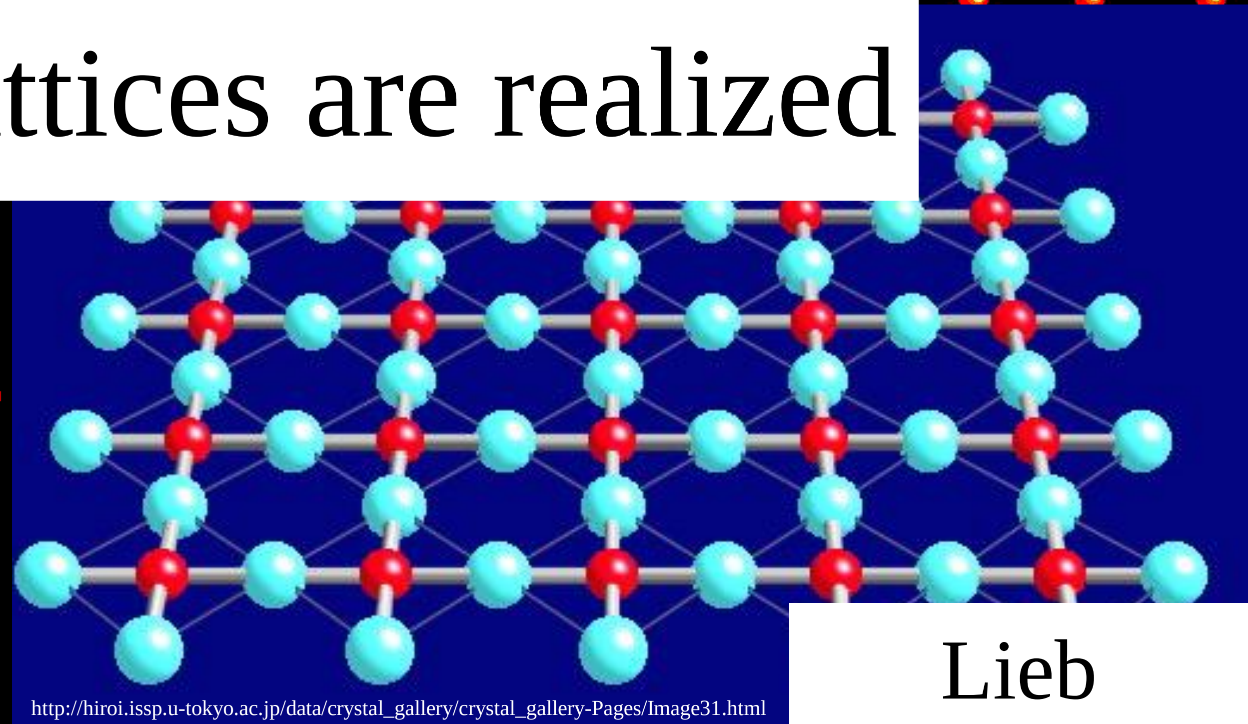




Many interesting materials(high-T_c Cuprate, graphene, ..) have non-standard lattice structures

Several Non-Standard Optical Lattices are realized

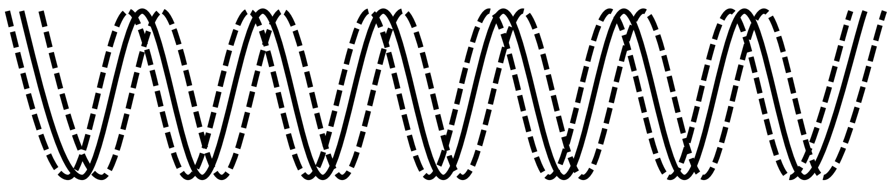




Quantum Simulation of Frustrated Magnetism in a Triangular Lattice

[J. Struck et al, Science (2011)]

Phase Modulation of Optical Lattice:

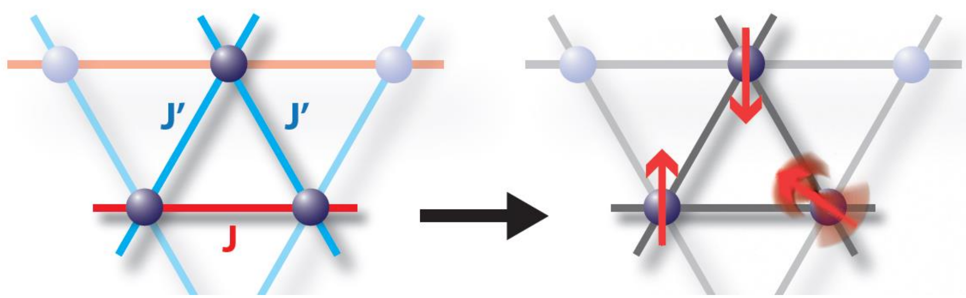


K$\cos(\omega t)$

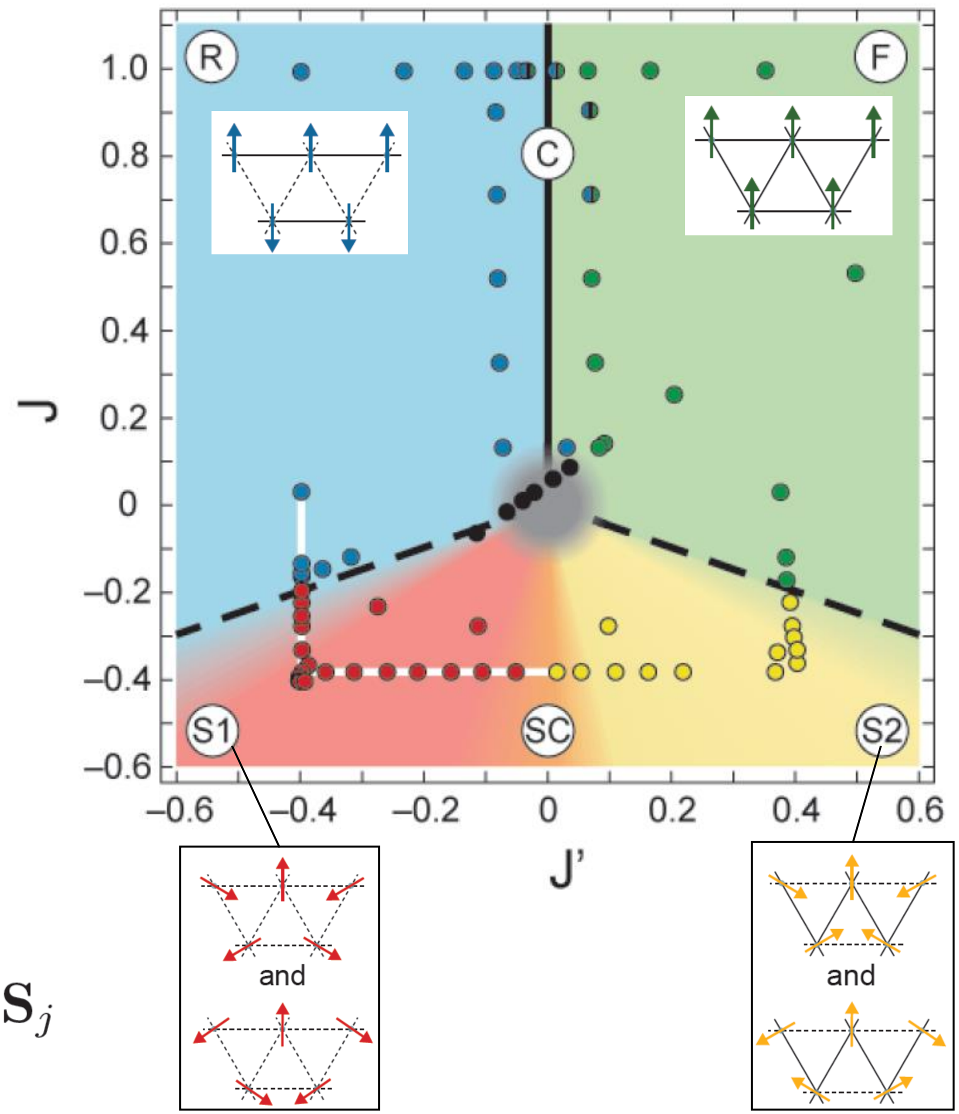
$$J \to J \times J_0(\beta)$$

:Zero-th order Bessel Function

β=K/ω



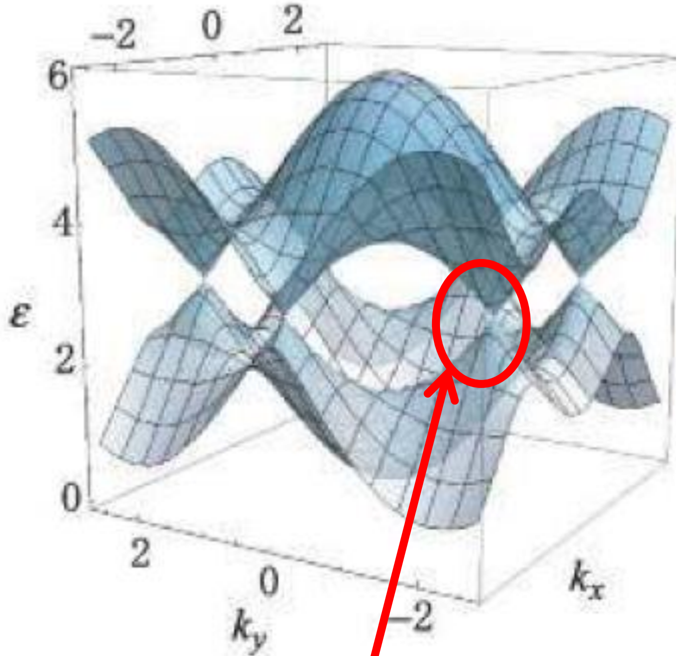
$$E(\theta_i) = -\sum_{\langle i,j\rangle} J_{ij}\cos(\theta_i-\theta_j) = -\sum_{\langle i,j\rangle} J_{ij}\mathbf{S}_i\cdot\mathbf{S}_j$$



Novel Band Structures

[from Katsura & Maruyama(2014)]

Honeycomb

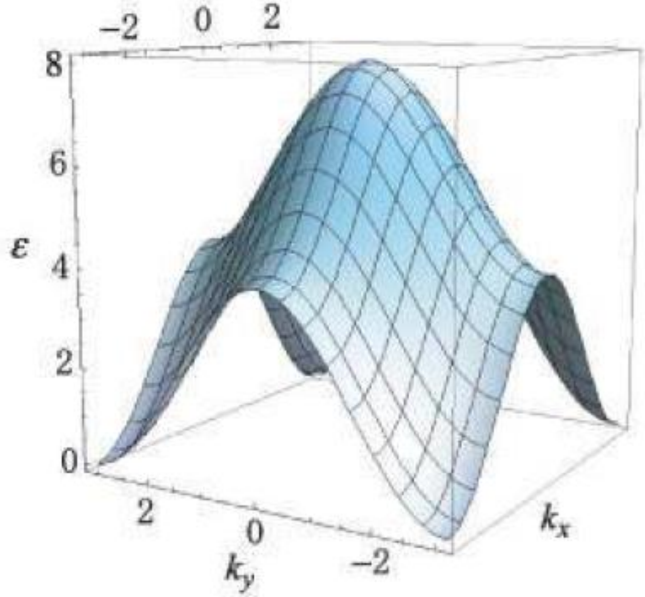


Dirac Cone:
linear dispersion

$E(k)=c\,k$

:massless Dirac particle

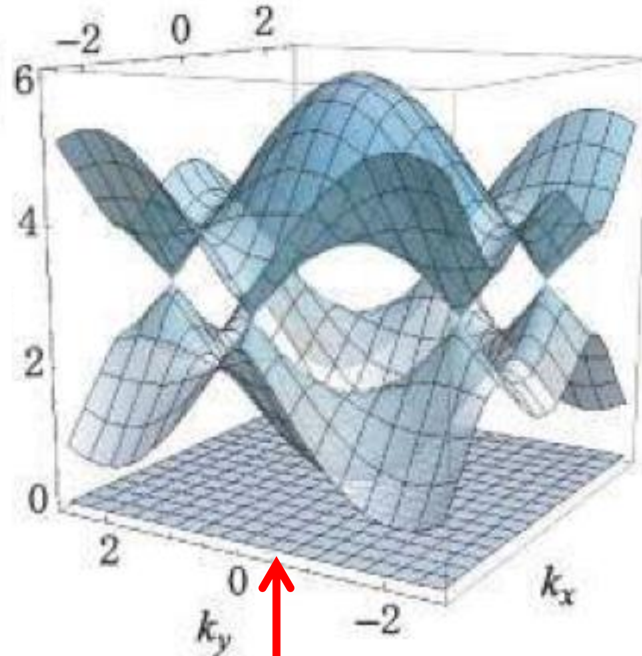
Square
(standard)



Cosine Band:

$E(k)=J\cos(kd)$

Kagome



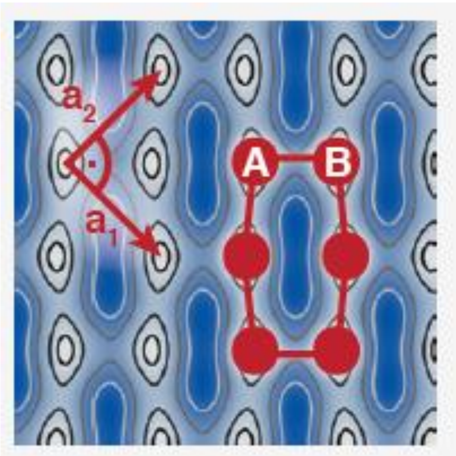
Flat Band:

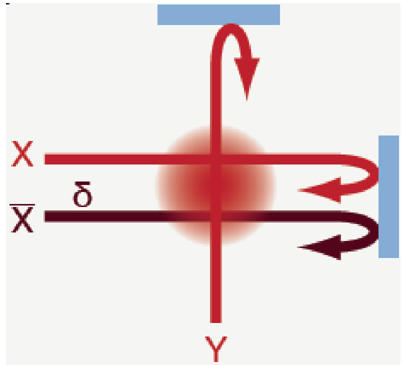
$E(k)=const.$

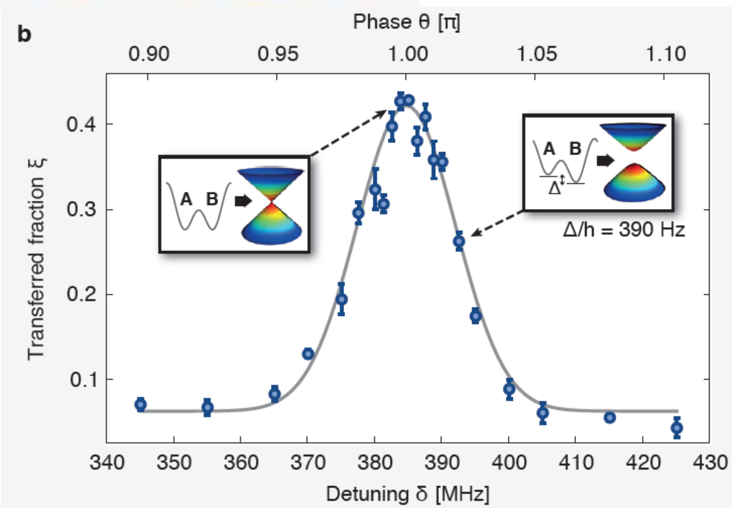
: infinite mass/localization

Novel Band Structures

Honeycomb

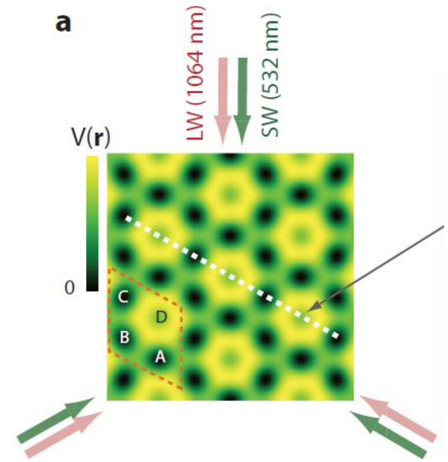


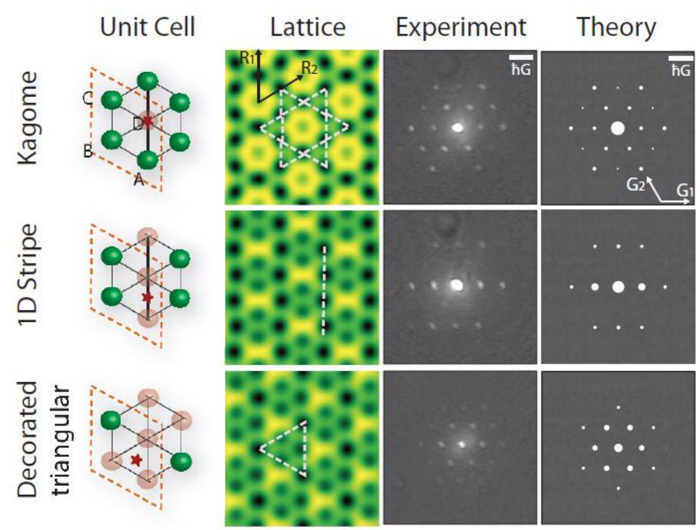




"Creating, moving, and merging Dirac points with a Fermi gas in a tunable honeycomb lattice", Tarruell, *et al Nature (2011)*

Kagome





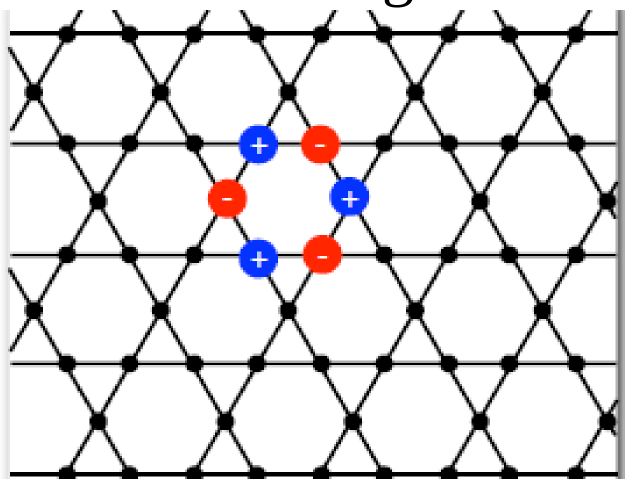
"Ultracold atoms in a Tunable Optical Kagome Lattice"
Gyu-Boong Jo, *et al*, *PRL (2012)*

“Ultracold atoms in a flat band”

(case of Kagome lattice)

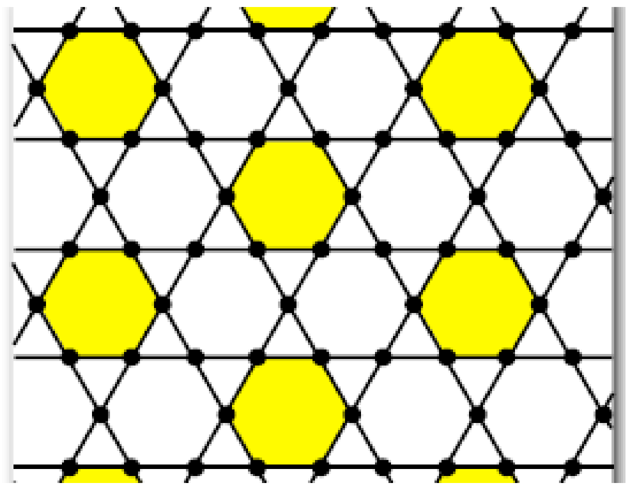
resonating **hexagon**:

“localized eigenstate”



closed packing

at ν_c=1/9



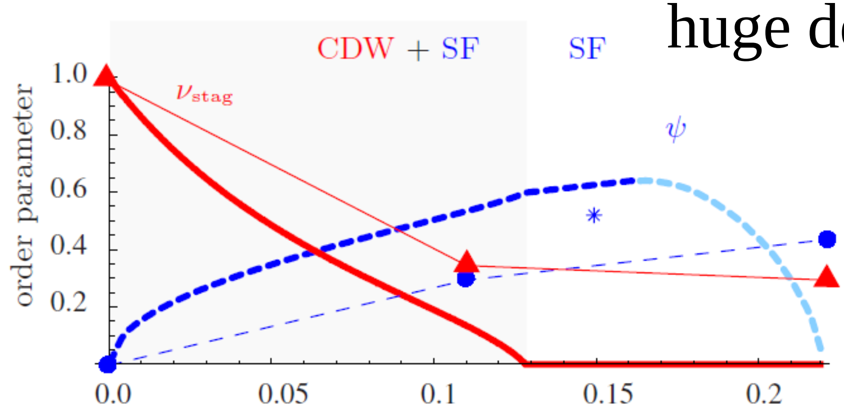
huge degeneracy !

$\nu > \nu_c$

Spatial overlap between hexagons

Exotic strongly correlated state:

Super-Solid



$\nu - \nu_c$

Prediction of super-solid for bosons in Kagome lattice

Huber & Altman PRB 82, 184502 (2010)

[Discussion with S. Furukawa]

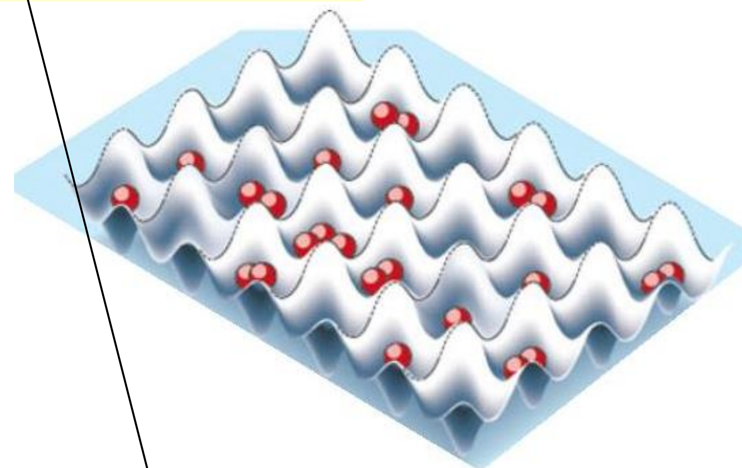
What is Super-Solid ?

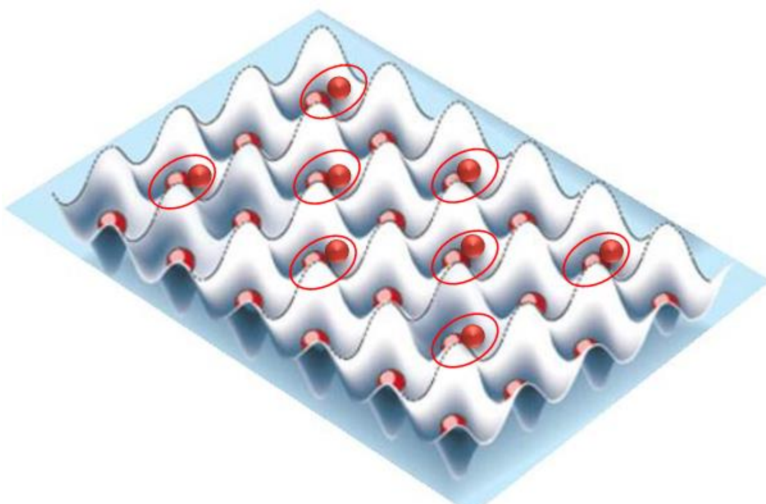
"superfluid"

(Off-Diagonal Long-Range Order)

$$G^{(1)}(\mathbf{x},\mathbf{x}') = \langle \mathbf{x}'|\hat{\rho}_1|\mathbf{x}\rangle = \langle \hat{\psi}^\dagger(\mathbf{x})\hat{\psi}(\mathbf{x}')\rangle$$

$$\to n_0$$





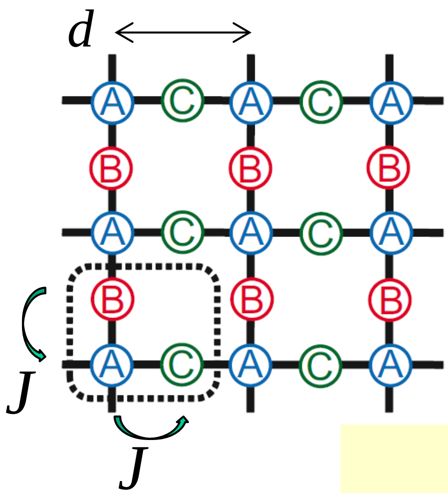
"Solid order"

(Density Long-Range Order / density wave)

$$\delta n(\mathrm{x}) = \delta n(\mathrm{x}+d)$$

Absence of Supersolidity in Solid Helium in Porous Vycor Glass:2013

Band Structure of Lieb Lattice



(Tight-Binding Approximation)

$$\hat{H}_{TB} = \sum_{\mathbf{k}} \begin{pmatrix} \hat{a}^{\dagger}_{\mathbf{k},A} & \hat{a}^{\dagger}_{\mathbf{k},B} & \hat{a}^{\dagger}_{\mathbf{k},C} \end{pmatrix} T_{Lieb} \begin{pmatrix} \hat{a}_{\mathbf{k},A} \\ \hat{a}_{\mathbf{k},B} \\ \hat{a}_{\mathbf{k},C} \end{pmatrix}$$

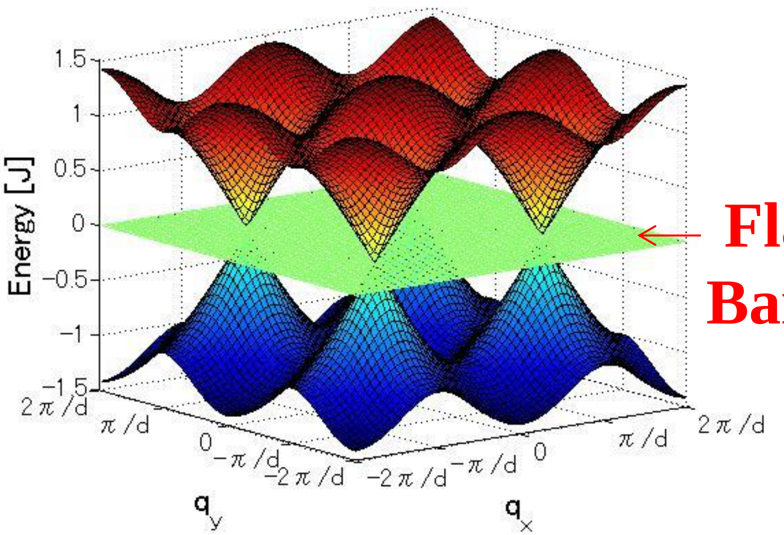
Operators in k-space:

$$\hat{a}_{i,S} = 1/\sqrt{N} \sum_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}_{i,S}} \hat{a}_{\mathbf{k},S}$$

S=A,B,C

$$T_{Lieb} = \begin{pmatrix} 0 & -2J\cos(k_x d/2) & -2J\cos(k_z d/2) \\ -2J\cos(k_x d/2) & 0 & 0 \\ -2J\cos(k_z d/2) & 0 & 0 \end{pmatrix}$$

By diagonalization, we obtain 3 eigenvalues;



Flat Band

$$E_{\pm} = \pm 2J\sqrt{\cos^2(k_x d/2) + \cos^2(k_z d/2)},$$

$$\boxed{E_0 = 0,}$$

($\tan\theta_k = \cos(k_x d/2)/\cos(k_z d/2)$)

$$|\mathbf{k}, 1\mathrm{st}\rangle = \frac{1}{\sqrt{2}}\left(|\mathbf{k}, A\rangle + \sin\theta_{\mathbf{k}}|\mathbf{k}, B\rangle + \cos\theta_{\mathbf{k}}|\mathbf{k}, C\rangle\right),$$

$$\boxed{|\mathbf{k}, 2\mathrm{nd}\rangle = \cos\theta_{\mathbf{k}}|\mathbf{k}, B\rangle - \sin\theta_{\mathbf{k}}|\mathbf{k}, C\rangle,}$$

$$|\mathbf{k}, 3\mathrm{rd}\rangle = \frac{1}{\sqrt{2}}\left(|\mathbf{k}, A\rangle - \sin\theta_{\mathbf{k}}|\mathbf{k}, B\rangle - \cos\theta_{\mathbf{k}}|\mathbf{k}, C\rangle\right),$$

Ultracold Atoms in a Flat Band

In order to study interesting physics of flat band, we need to load ultracold atoms into flat band.

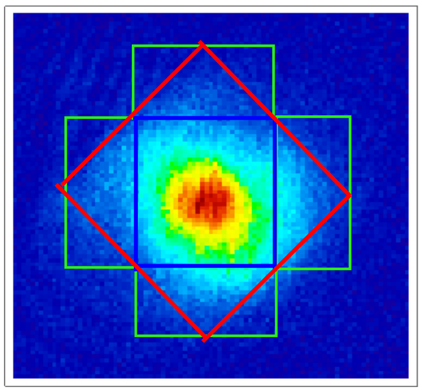
flat band: $|\mathbf{B}\rangle - |\mathbf{C}\rangle$ **(q=0)**

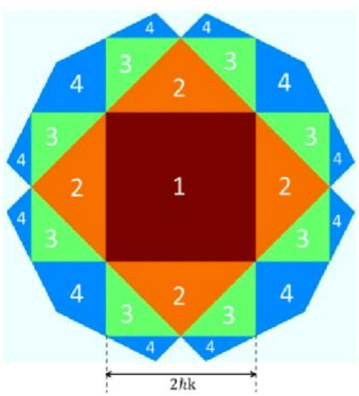
$$|\boldsymbol{q}, X\rangle = \frac{1}{\sqrt{N}} \sum_{i\in X} e^{i\boldsymbol{q}\cdot\boldsymbol{x}_i} c_i^\dagger |0\rangle$$

X=A, B, C

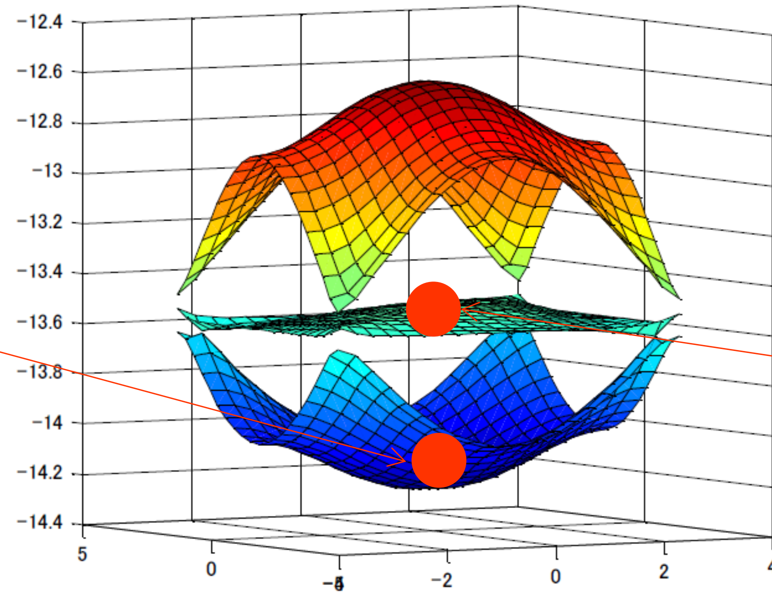
initially

$|\mathbf{B}\rangle + |\mathbf{C}\rangle$ **(q=0)**



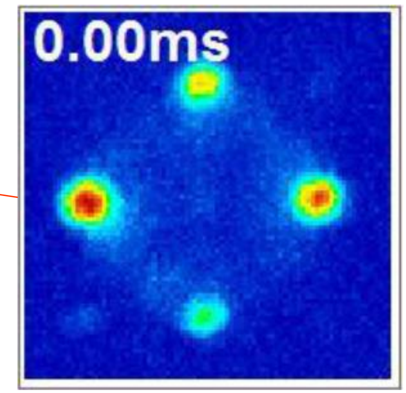


Brillouin Zones

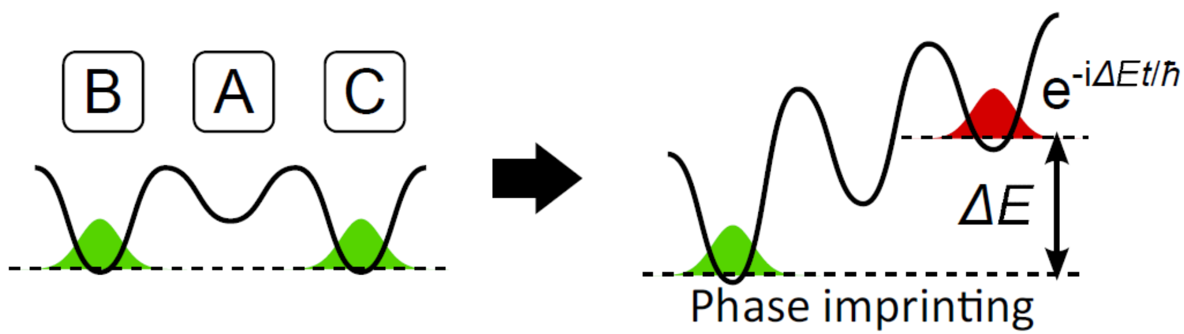


after Phase Imprinting

$|\mathbf{B}\rangle - |\mathbf{C}\rangle$ **(q=0)**

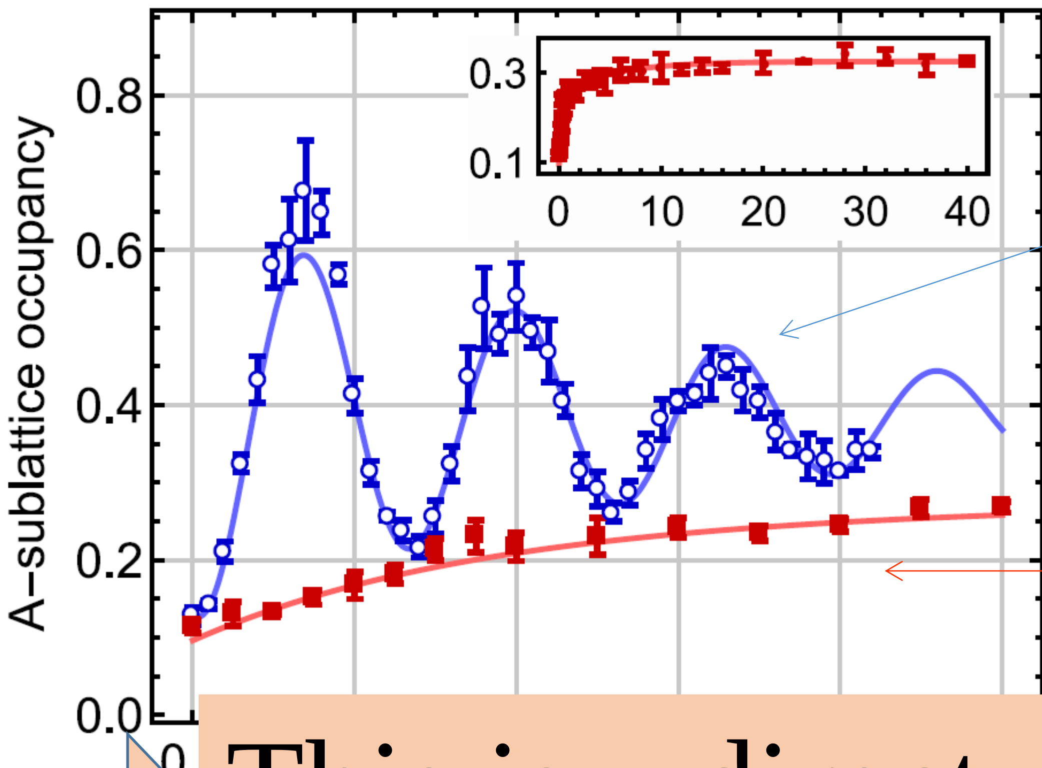


"Phase Imprinting Method"



Ultracold Atoms in a Flat Band

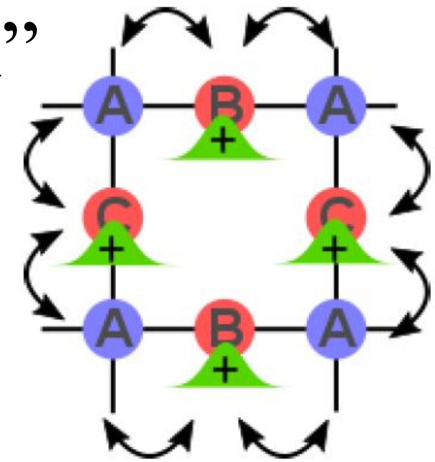
We could observe **Unique Dynamics** in Flat band by measuring A-site population.



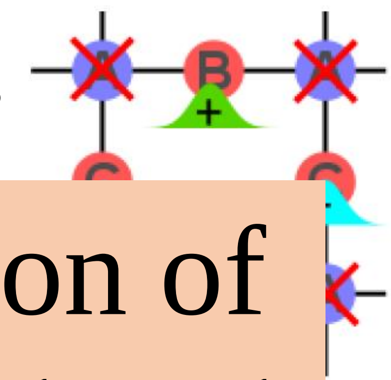
"Usual band"

|B⟩ + |C⟩

(q=0)



"Flat band"

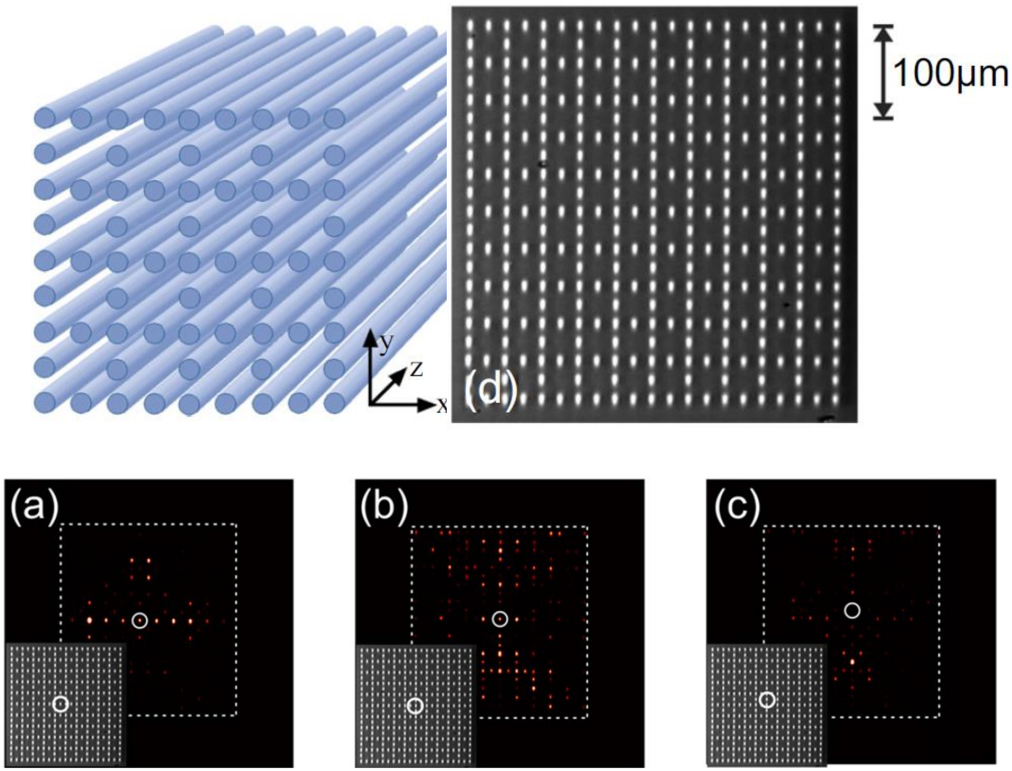


This is a direct confirmation of "localized state" in a flat band

Other Bosons in a Lieb lattice

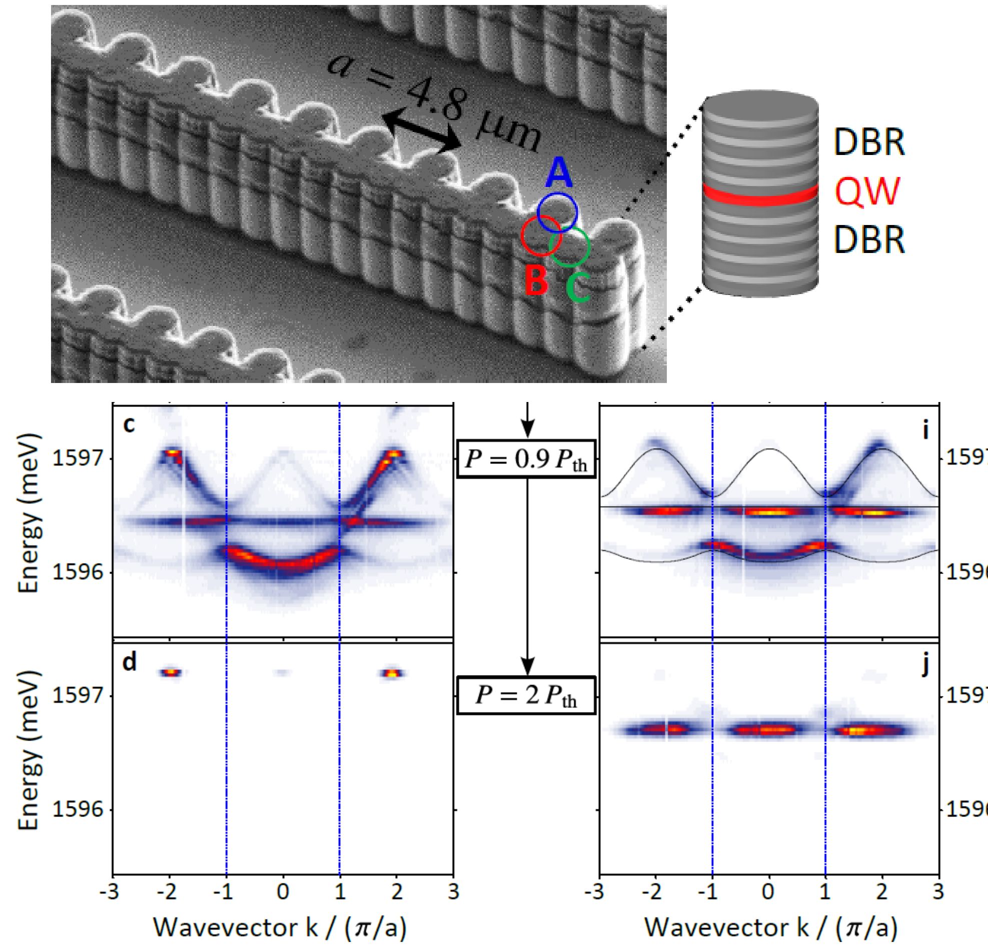
<u>Photonic Waveguide</u>

D. Guzman-Silva *et al.*,
NJP16, 063061(2014)



<u>Exciton-Polariton Condensate</u>

arXiv:1505.05652, F. Baboux *et al.*,

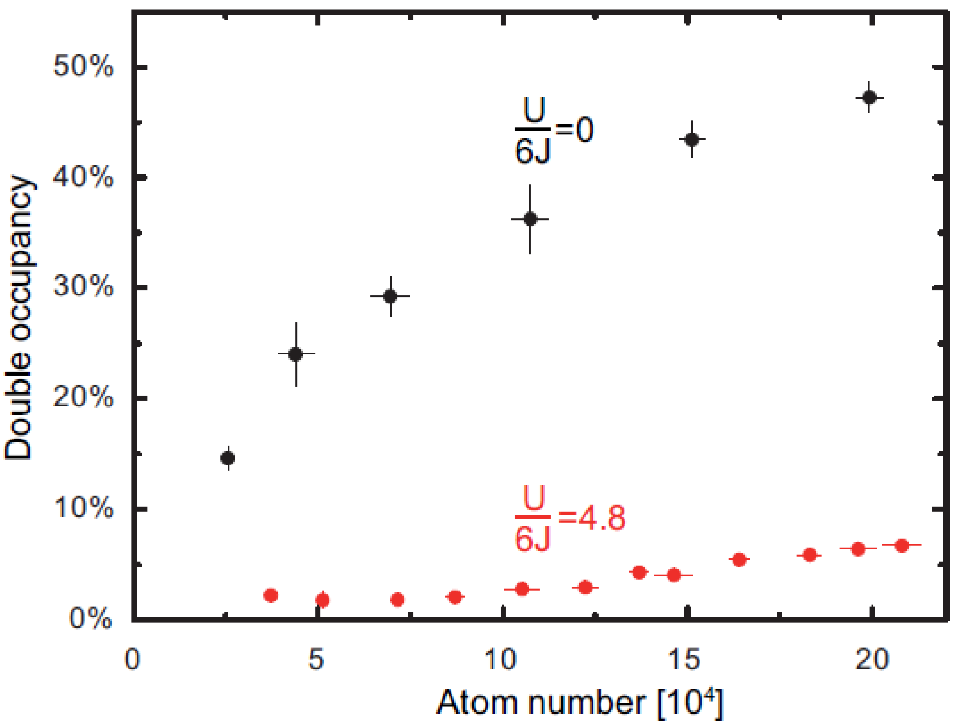


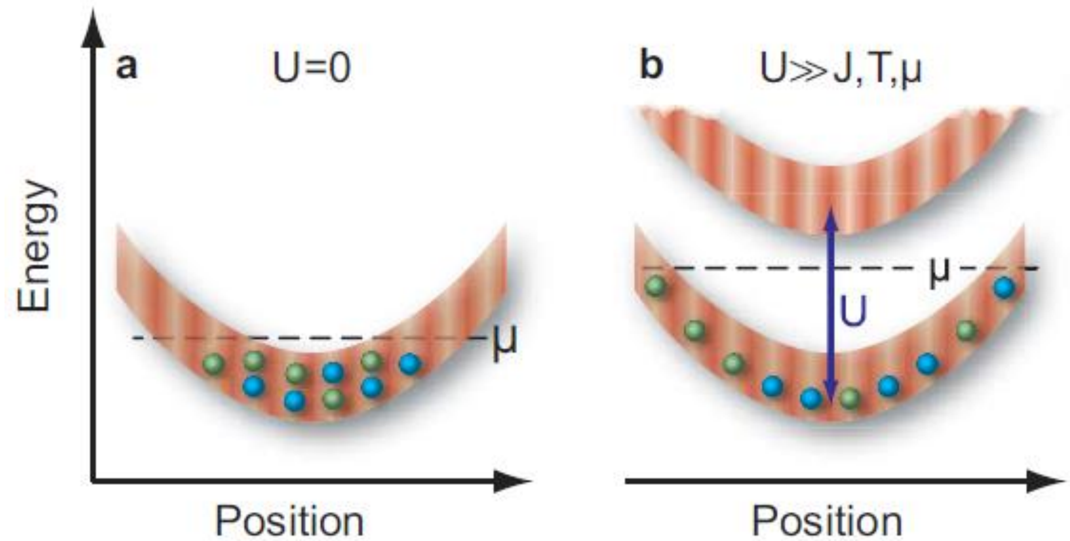
Fermions in an Optical Lattice

Fermi-Hubbard Model:

^{40}K **"A Mott insulator of ^{40}K atoms in an optical lattice"**

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





Fermions in an Optical Lattice

onset of anti-ferromagnetic correlation

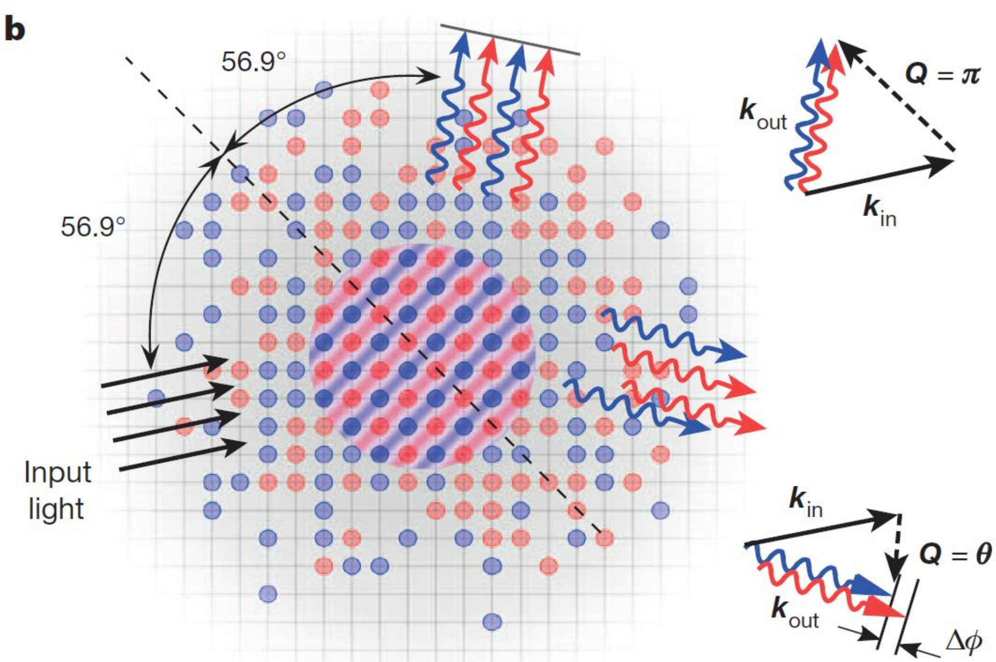
[R. A. Hart *et al.*, Nature **519**, 211 (2015)]

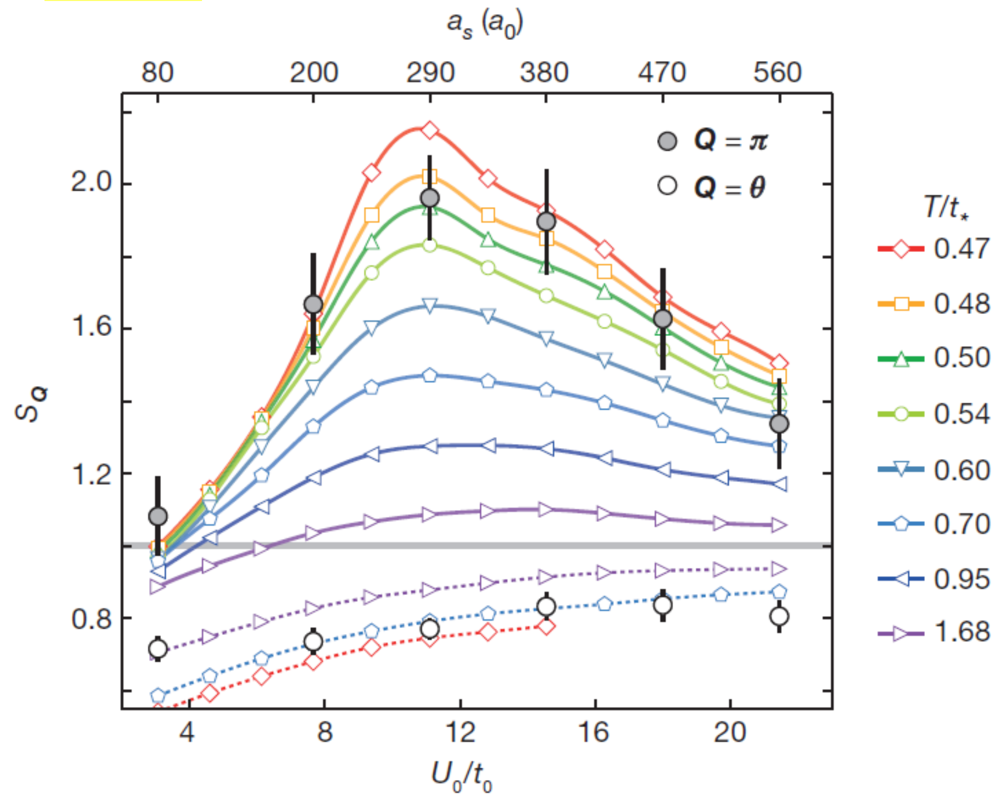
Spin-structure factor:

$$S_Q \equiv \frac{4}{N}\sum_{i,j} e^{iQ\cdot(R_i - R_j)} \langle \sigma_{zi}\sigma_{zj} \rangle$$

^{6}Li T~ 1.4T$_N$(=0.5t)

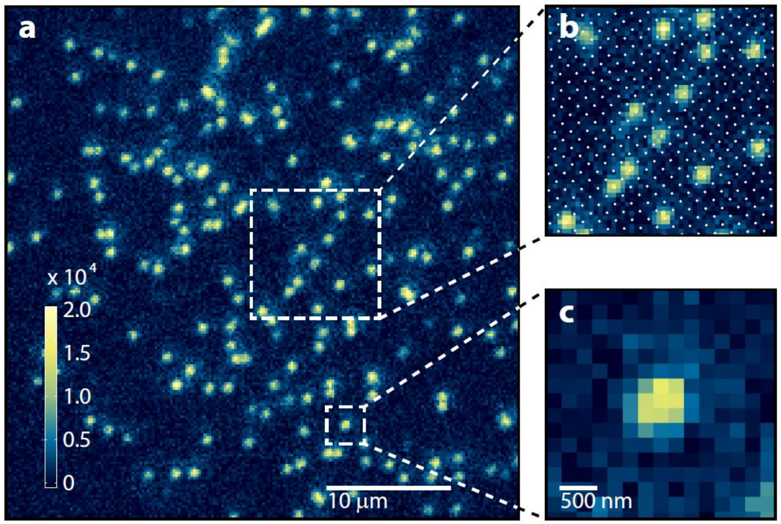
optical Bragg scattering





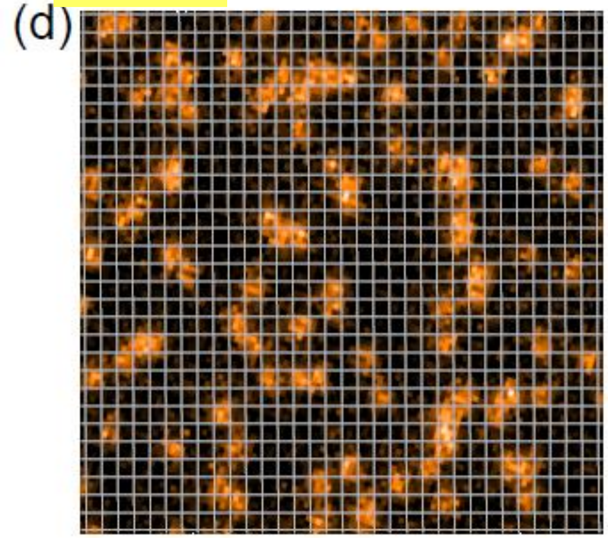
Fermionic quantum gas macroscope

^{40}K EIT-cooling



E. Haller et al., arXiv:1503.02005v2

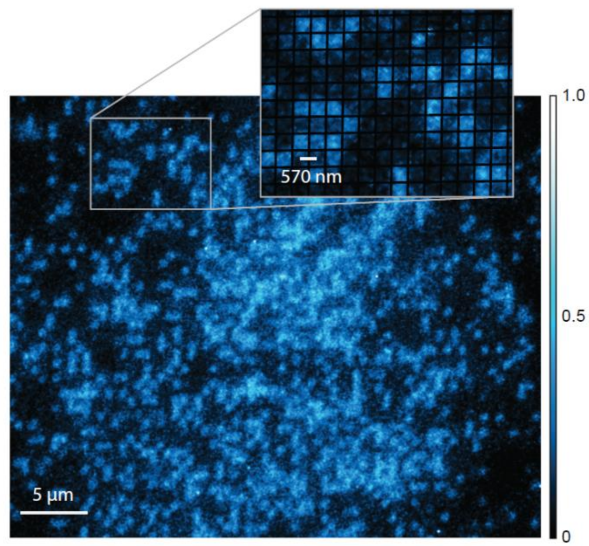
^{40}K Raman-sideband cooling



L. W. Cheuk et al., arXiv:1503.02648v1, PRL(2015)

^{6}Li Raman-sideband cooling

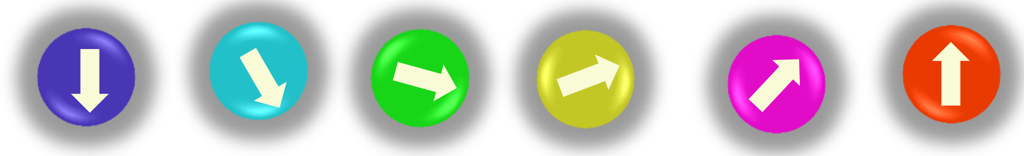
M. F. Parsons, et al, PRL(2015)



SU(N=6) Fermions in an Optical Lattice

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

SU(N=6) system



SU(N) Heisenberg model:

$$\boxed{H=\frac{2t^2}{U}\sum_{\langle i,j\rangle m,n} S_n^m(i)S_m^n(j)}$$

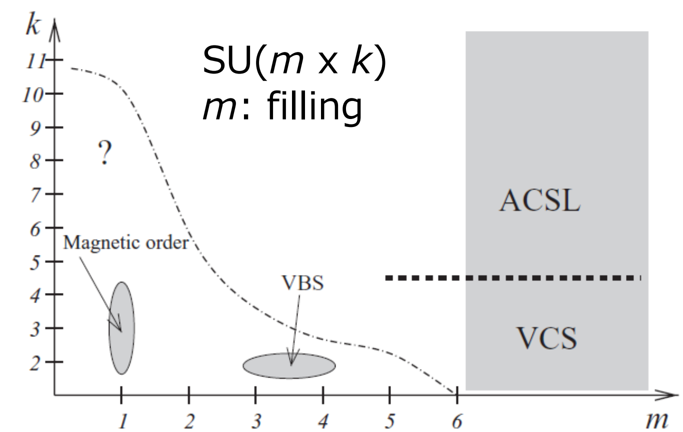
Nuclear spin permutation operators:

$$S_n^m \equiv c_n^+ c_m = |n\rangle\langle m|$$

*SU(N=6) Mott Insulator is already created [Taie *et al*, NP(2012)]

Novel magnetic phases:

Neel order, dimerization,
Valence-Bond-Solid,
Chiral Spin Liquid, …

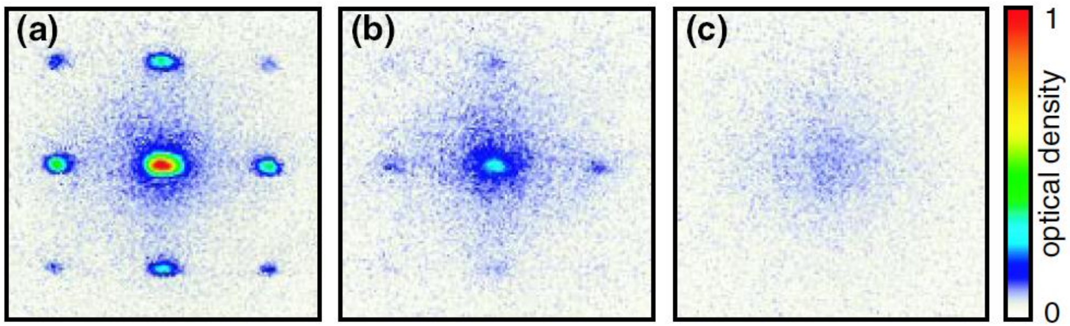


*Two-orbital SU(N) fermions is successfully created[MPQ, LENS,..]

Bose-Fermi Mixture in a 3D optical lattice

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

“ ^{40}K(Fermion)-^{87}Rb(Boson)” $\quad a_{BF}$ **= -10.9 nm**



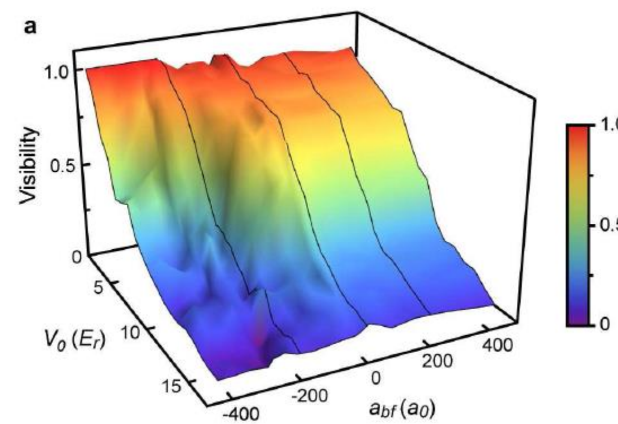
$N_F / N_B = 0$ $\quad$ $N_F / N_B = 0.08$ $\quad$ $N_F / N_B = 0.8$

[K. Günter, et al, PRL**96**, 180402 (2006)]

[S. Ospelkaus, et al, PRL**96**, 180403 (2006)]

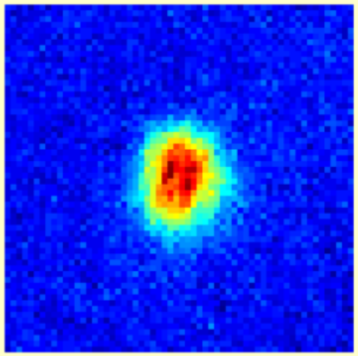
“Role of interactions in Rb-K Bose-Fermi mixtures in a 3D optical lattice”

[Th. Best, *et al*, PRL**102**, 030408 (2008)]

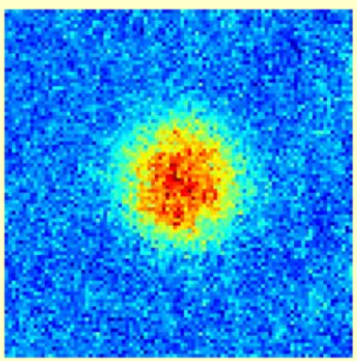


Bose-Fermi Mixture in a 3D Optical Lattice

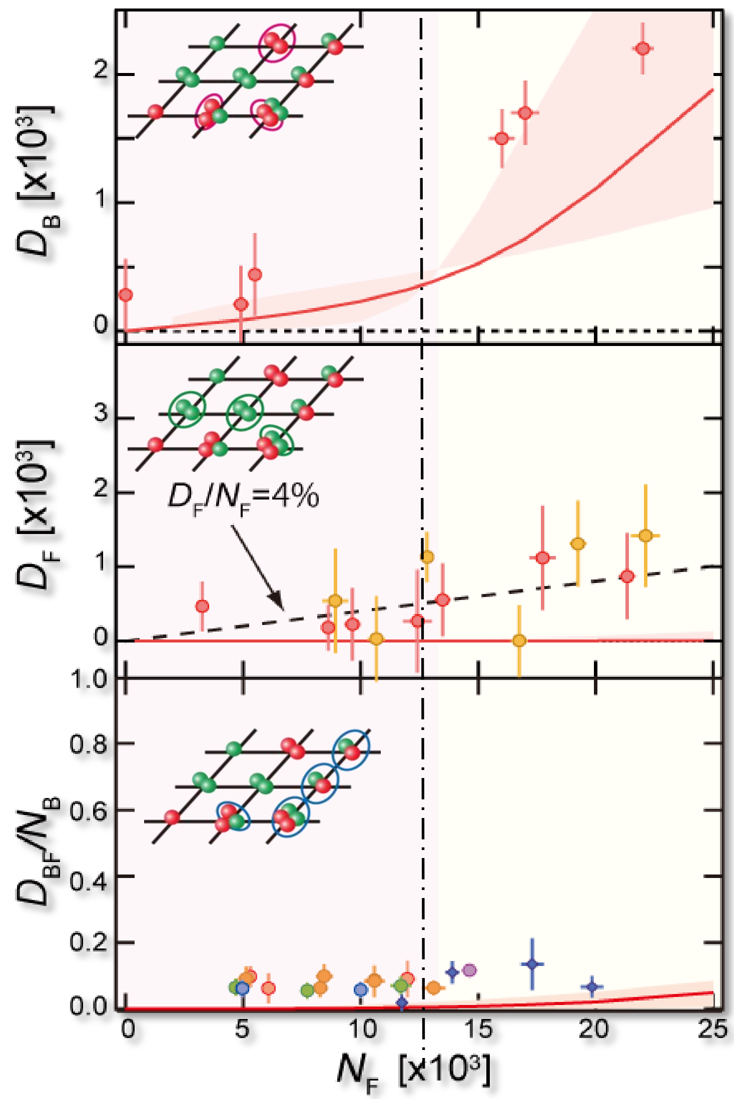
Boson
:^{174}Yb



Fermion
: ^{173}Yb

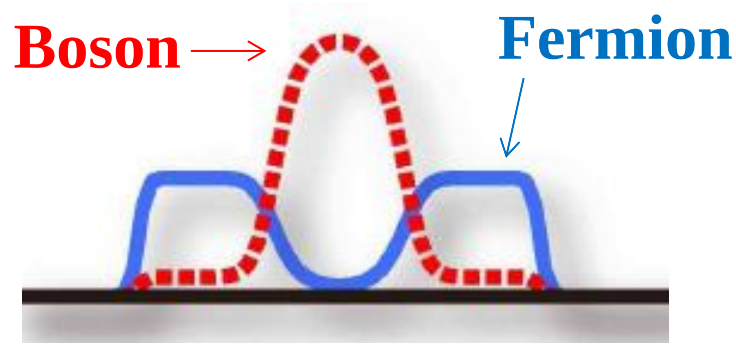


$T/T_F = 0.17$



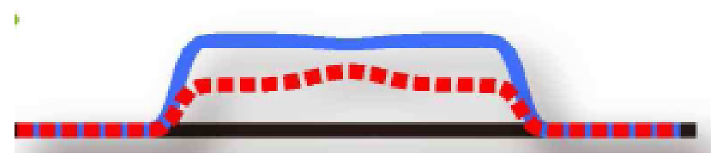
[S. Sugawa, *et al.*, NP.**7**, 642(2011)]

"Phase Separation"

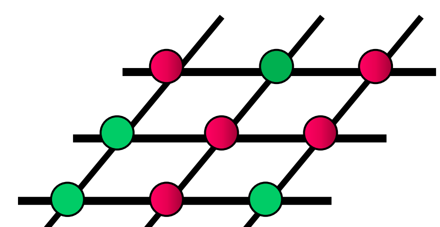


$N_F = 2\times10^4$

"Mixed Mott Insulator"



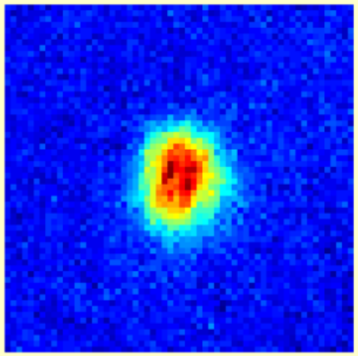
$N_F = 1\times10^4$

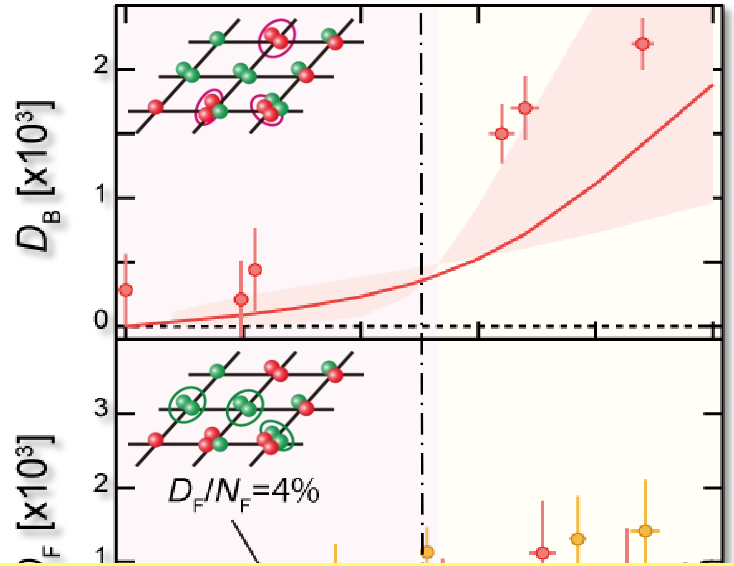


Bose-Fermi Mixture in a 3D Optical Lattice

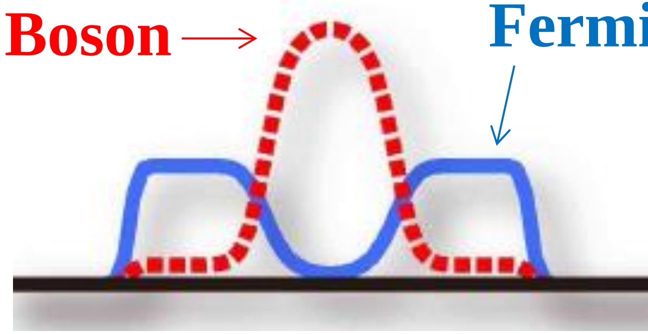
Boson

:^{174}Yb





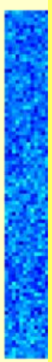
"Phase Separation"



N_F=2 ×10^4

Fe

: 17



Theory:

Ehud Altman, Eugene Demler, Achim Rosch

"Mott criticality and pseudogap in Bose-Fermi mixtures"PRL(2013)

I. Danshita and L. Mathey

"Counterflow superfluid of polaron pairs in Bose-Fermi mixtures in optical lattices"PRA(2013)

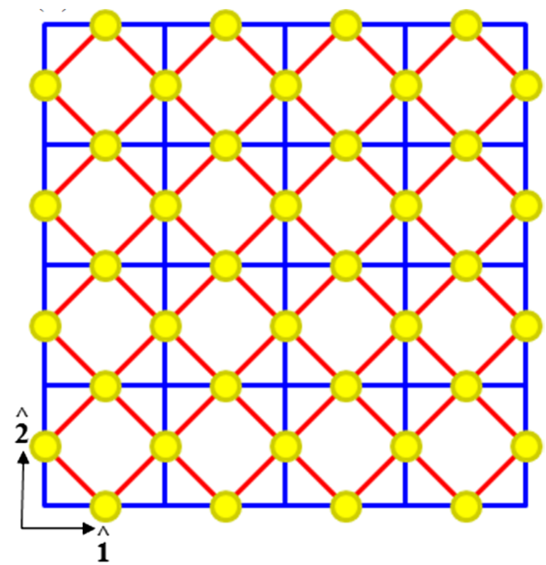
T/T_F=0.17

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

Quantum Simulation of Lattice-Gauge-Higgs-Model

Kasamatsu *et al*, PRL(2013), Kuno et al, NJP(2015)

Mielke Lattice



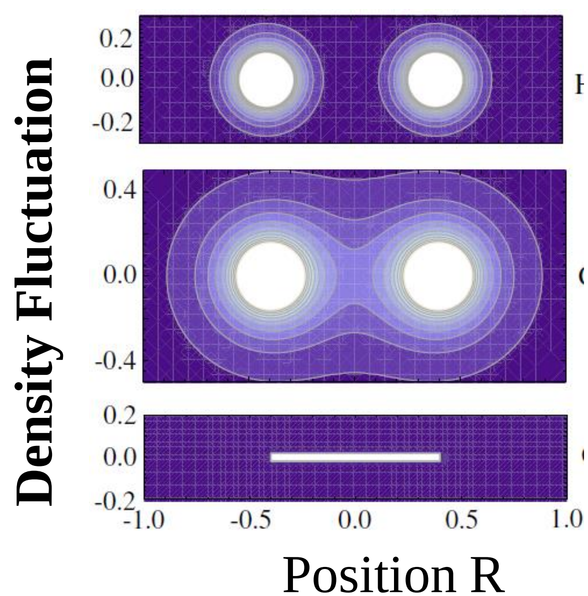
Bose-Hubbard Model with Off-Site Interaction：

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

hopping
（red＋blue lines）

On-site inteaction
（yellow circles）

Off-site Interaction
（red＋blue lines）



Higgs Phase:
exp(-mR)/R

Coulomb Phase：
1/R

Confinement Phase:
R

Summary

I) Preparation of Quantum Gas

Laser cooling and trapping, evaporative cooling, Bose-Einstein condensate, Fermi Degenerate Gas

II) Ultracold Atoms in a Harmonic Trap

Feshbach resonance, Cooper paring, BEC-BCS crossover, unitary gas, spin-orbit interaction

III) Ultracold Atoms in an Optical Lattice

Superfluid-Mott insulator transition, quantum-gas-microscope, Higgs mode, Non-standard lattices(frustrated magnetism, flat band), Fermi-Hubbard model, Bose-Fermi mixture

Group Members

Thank you very much for attention

16 August   Mount Daimonji at Kyoto