“International Workshop on Condensed Matter Physics AdS/CFT”

29 May 2015

Kavli IPMU, The University of Tokyo
(Kashiwa campus)

Exploring quantum many-body physics using ultracold atoms in an optical lattice

Kyoto University

Yoshiro Takahashi

NOTE:

This is a review talk
on recent experimental progress in the study of
condensed matter physics using ultracold atoms.

No discussion related with AdS/CFT correspondence

In (Near) Future,
consider ultracold atoms for AdS/CFT correspondence

Outline of This Talk

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, pre-thermalization, quantum transport

III) Ultracold Atoms in an Optical Lattice

Superfluid-Mott insulator transition, quantum-gas-microscope, Higgs mode, frustrated magnetism

IV) (our recent work) Ultraold Atoms in a Flat Band

localization/delocalization on flat band

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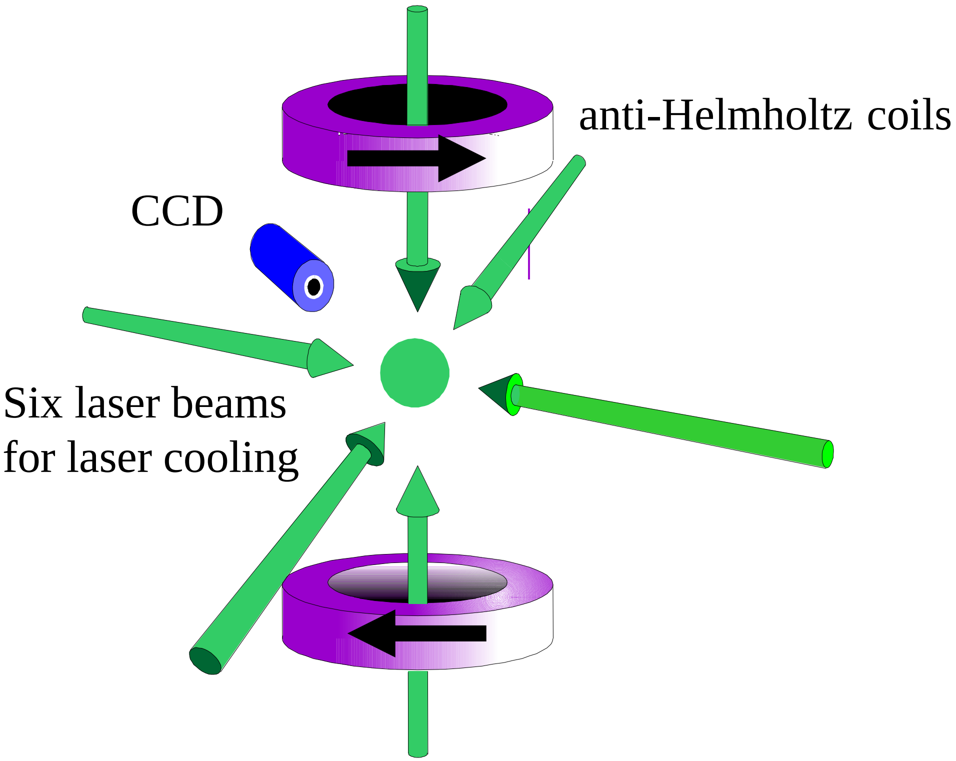
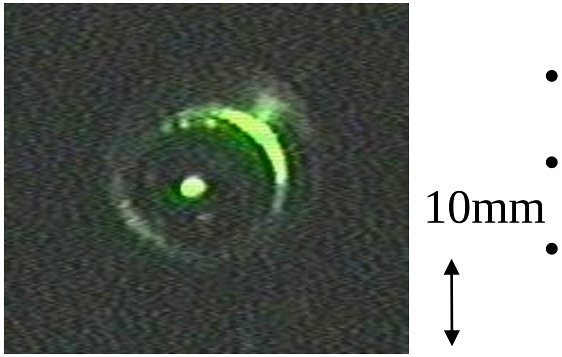
Laser Cooling and Trapping



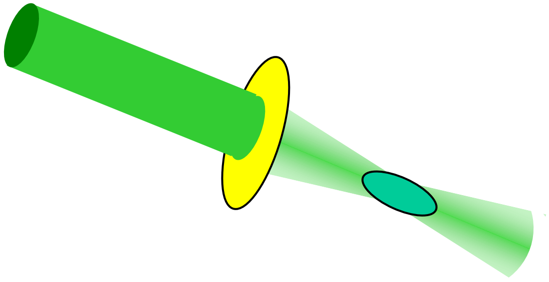


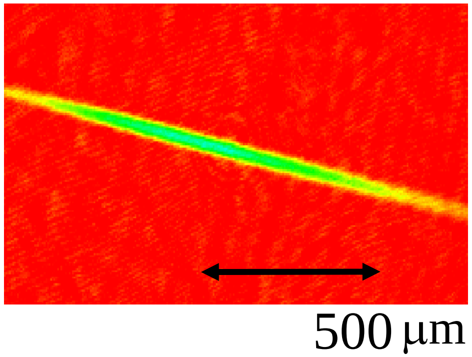
- Number: 10^7
- Density: $10^{11}/\text{cm}^3$
- Temperature: 10μK

"Magneto-optical Trap"

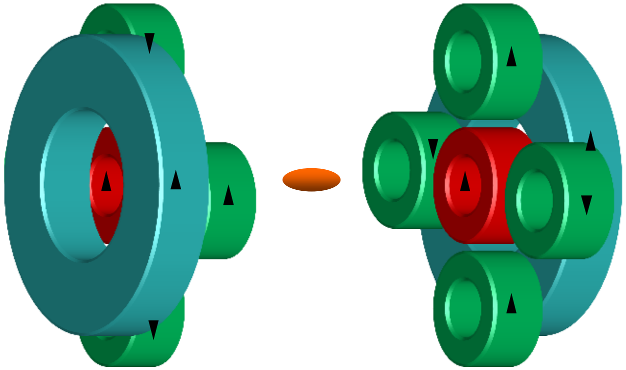
"optical trap"

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





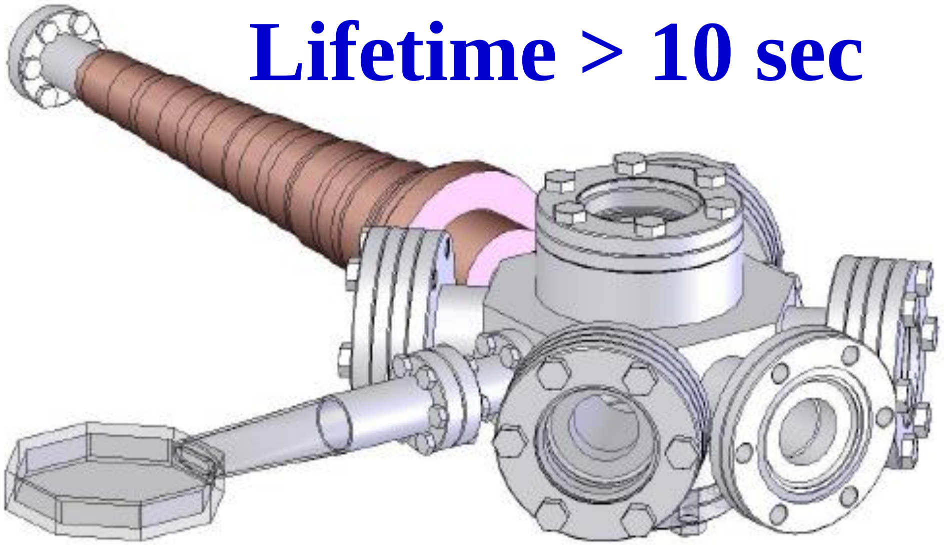
"magnetic trap" $V_{\text{int}} = -\mu \cdot B$



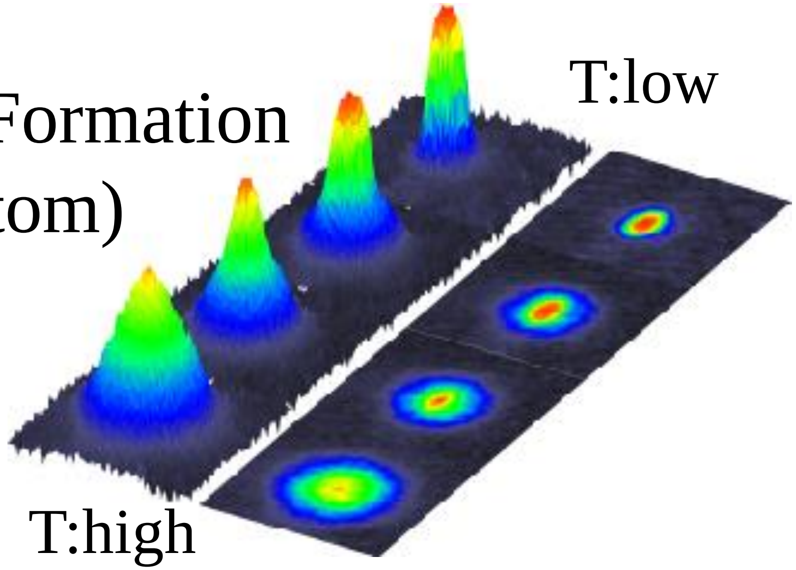
Cooling to Quantum Degeneracy

Pressure ~10^{-12} torr

Lifetime > 10 sec



BEC Formation
(Yb atom)

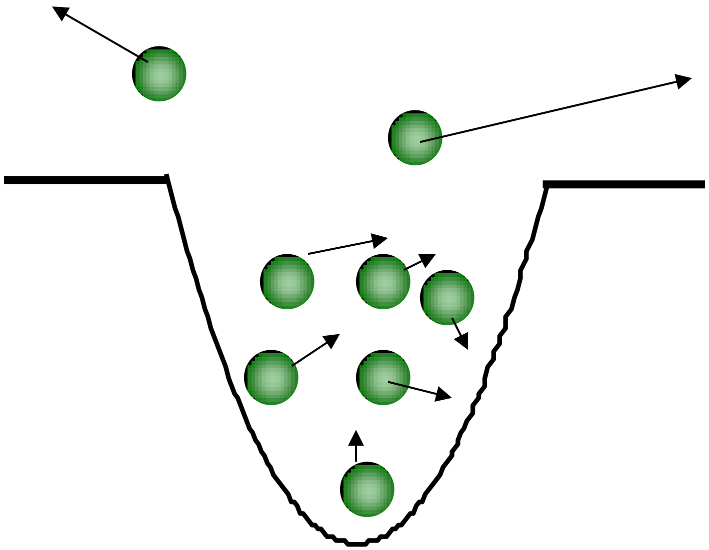


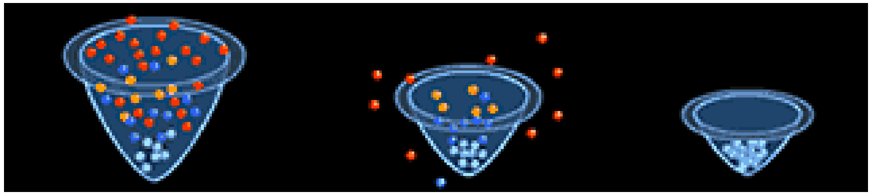
T:low

T:high

Momentum distribution

"Evaporative cooling"

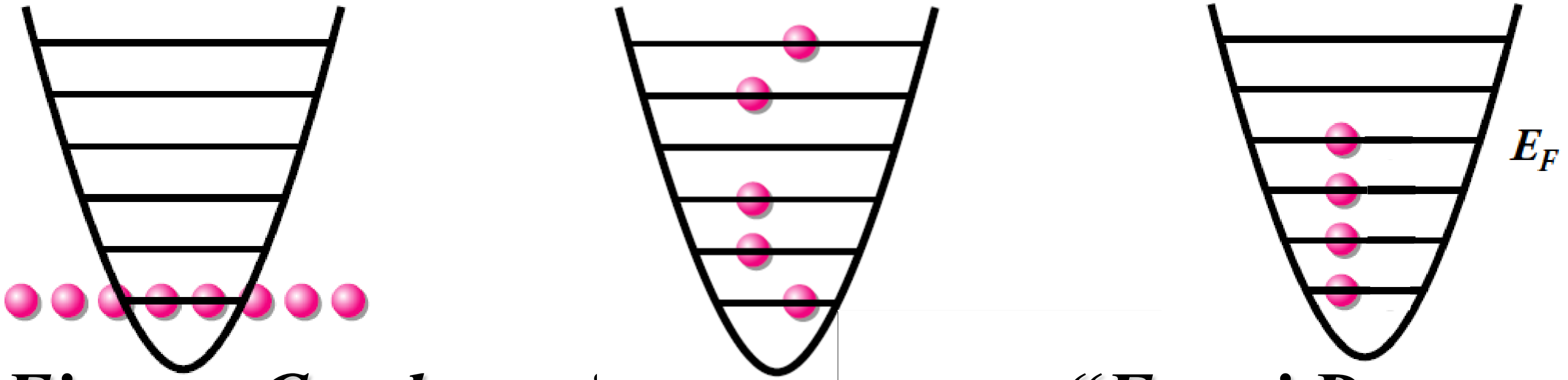




T~100 nK N~ 10^5

Cooling to Quantum Degeneracy

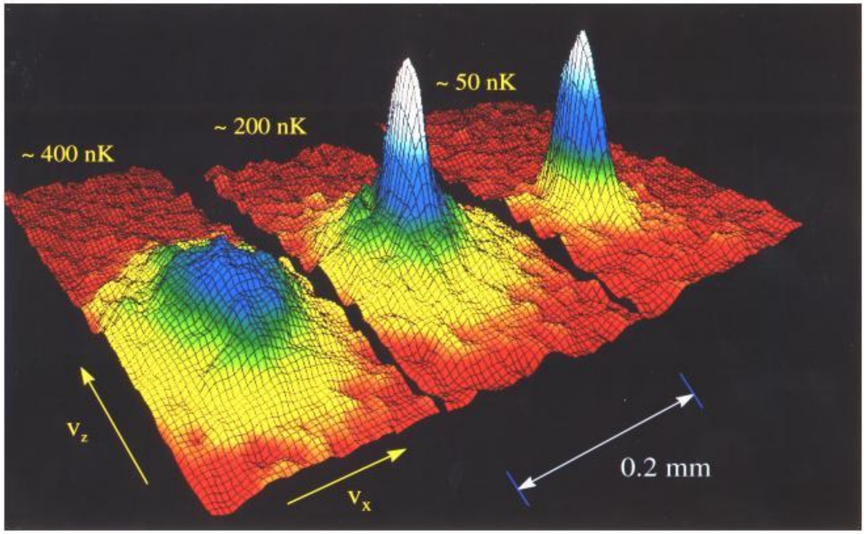
“Boson versus Fermion”



“Bose-Einsten Condensation”

“Fermi Degeneracy”

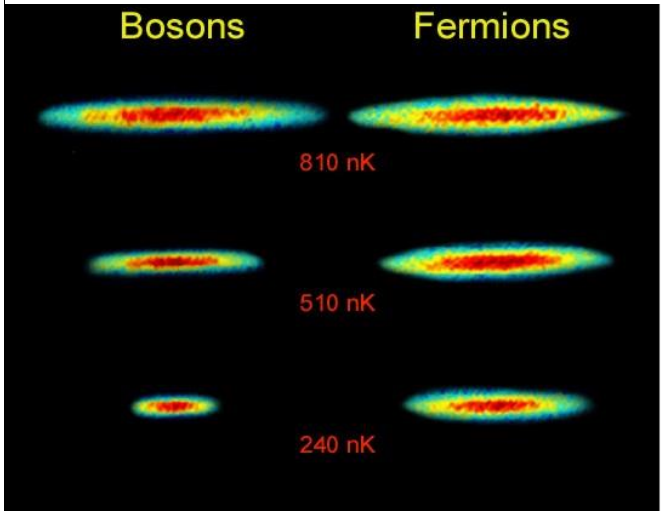
^{87}Rb



Momentum Distribution

[E. Cornell et al, (1995)]

^{6}Li and ^{7}Li

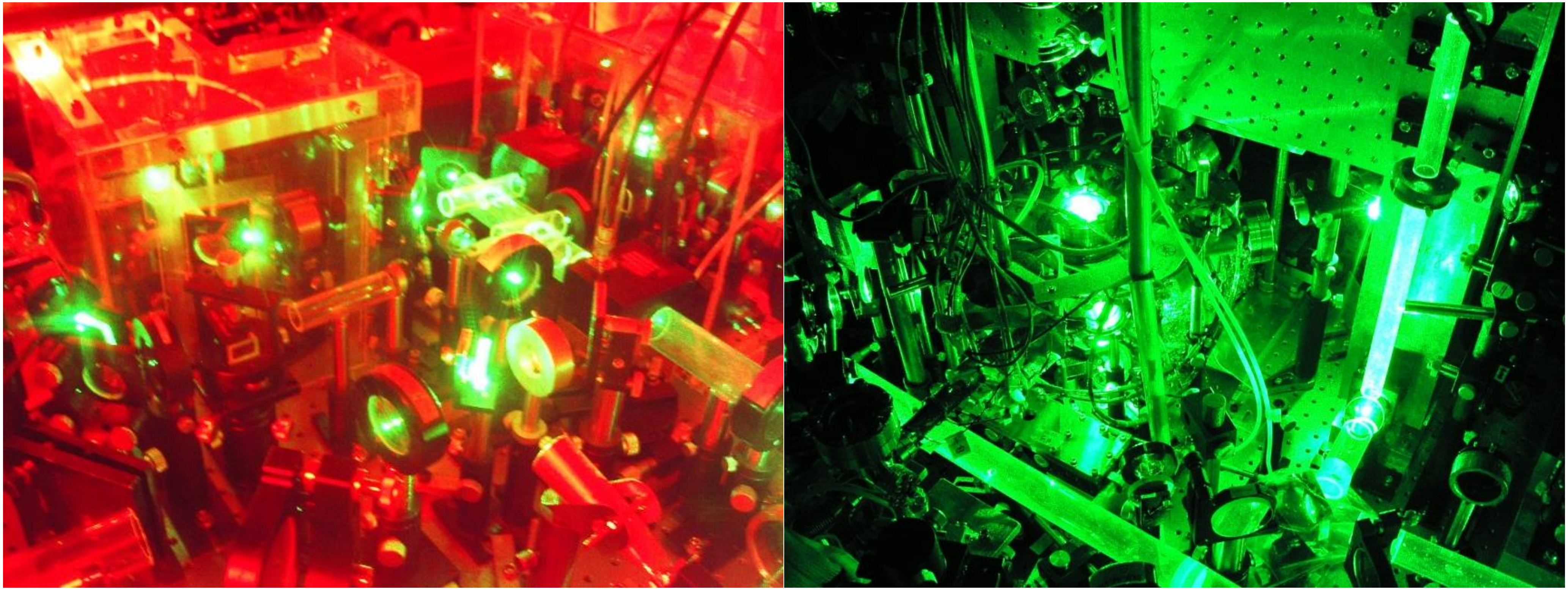


Fermi Pressure

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*

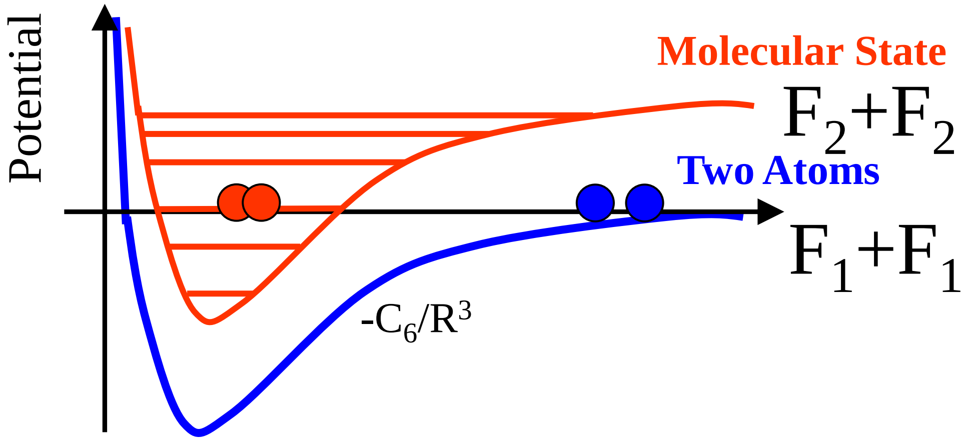
$$a_s = -\delta_l / k$$

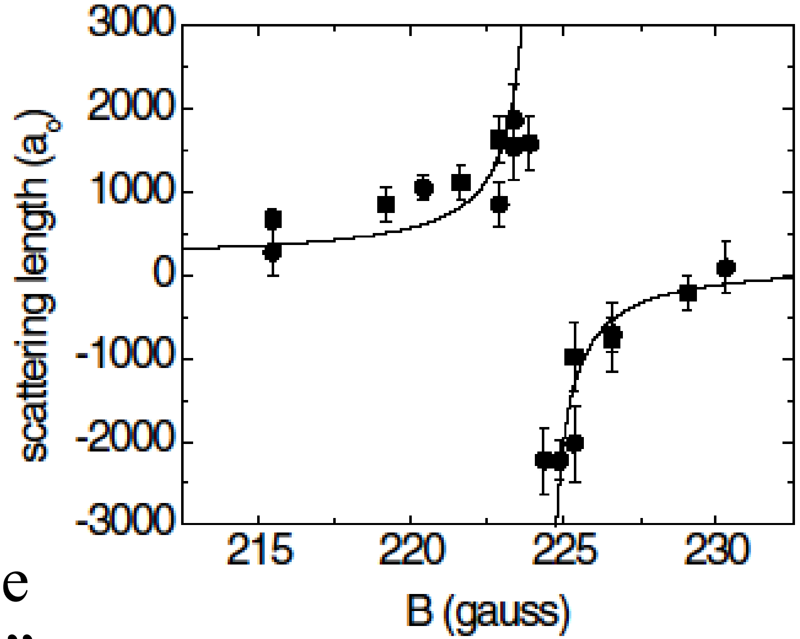
$$\sigma_0 = 4\pi |f_0|^2 = 4\pi |a_s|^2$$

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

→ Control of Interaction(a_s)

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





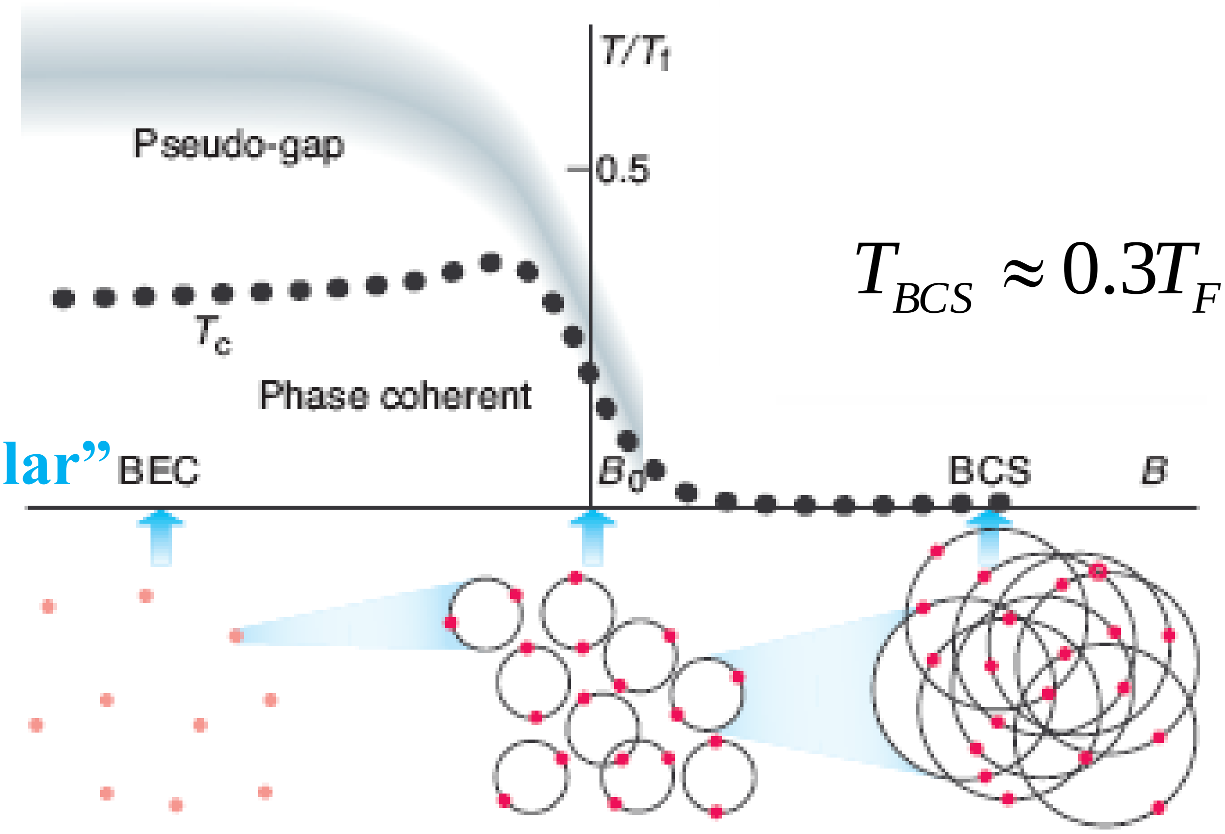
"Magnetic field tunes the energy difference between closed channel and open channel"

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

BEC – BCS Crossover

Leggett

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



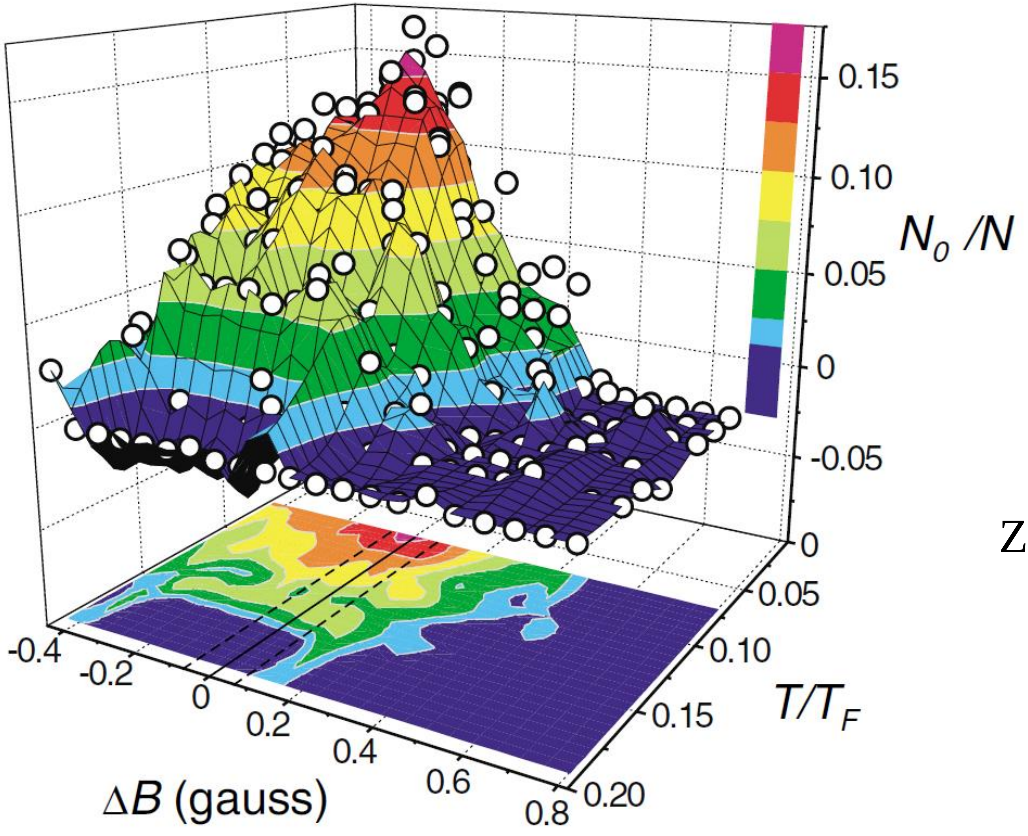
"molecular"

"Unitary Gas"

$+\infty$ 0 $-\infty$

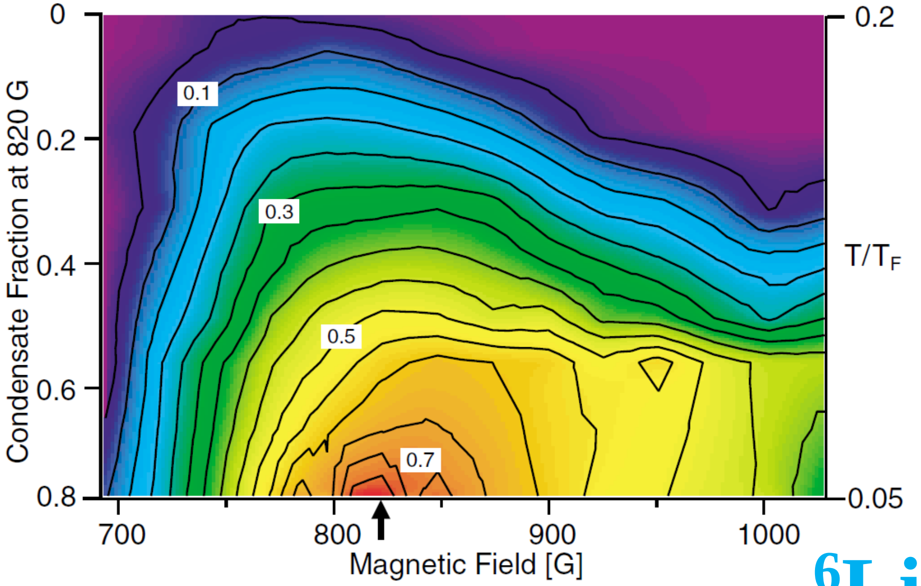
$1/(k_F a)$

BEC – BCS Crossover: experiments



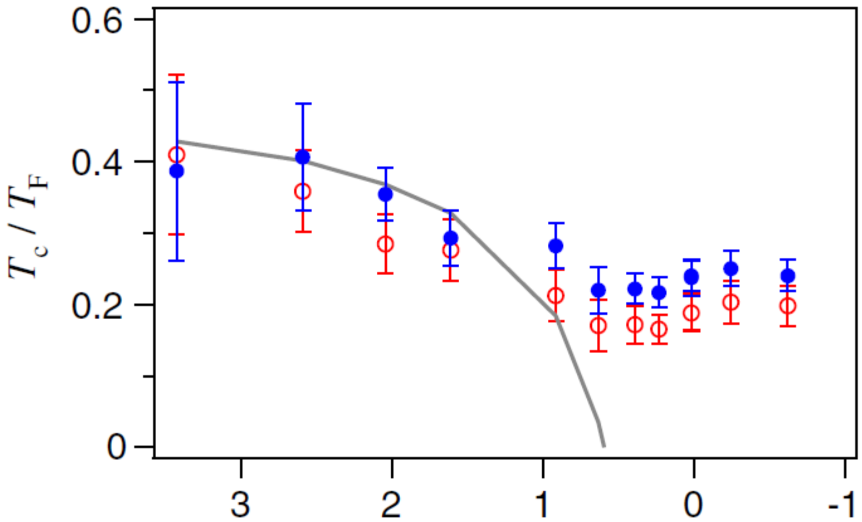
Regal et al., PRL(2004)

^{40}K



Zwierlein et al., PRL(2004)

^{6}Li



Inada et al., PRL(2008)

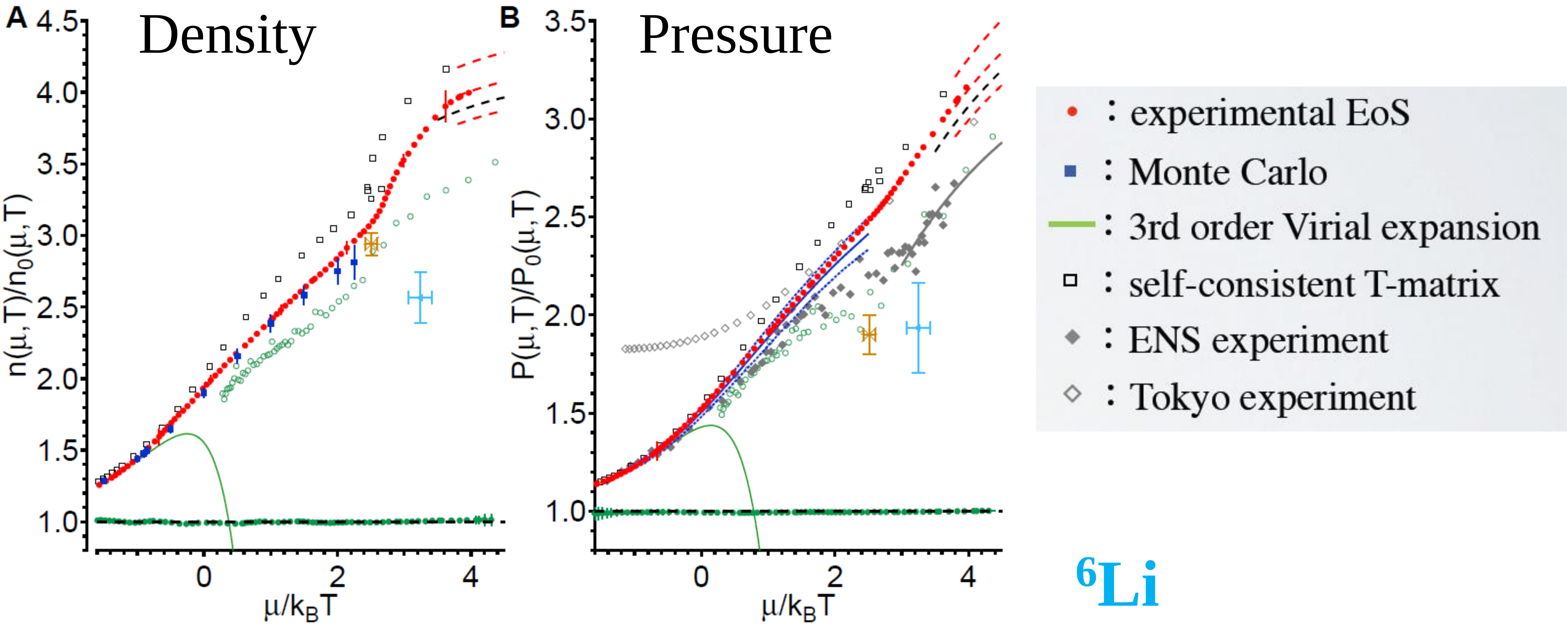
^{6}Li

Equation of State for Unitary Gas

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

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

de Broglie wavelength $\lambda = \sqrt{\dfrac{2\pi\hbar^2}{m k_B T}}$



^{6}Li

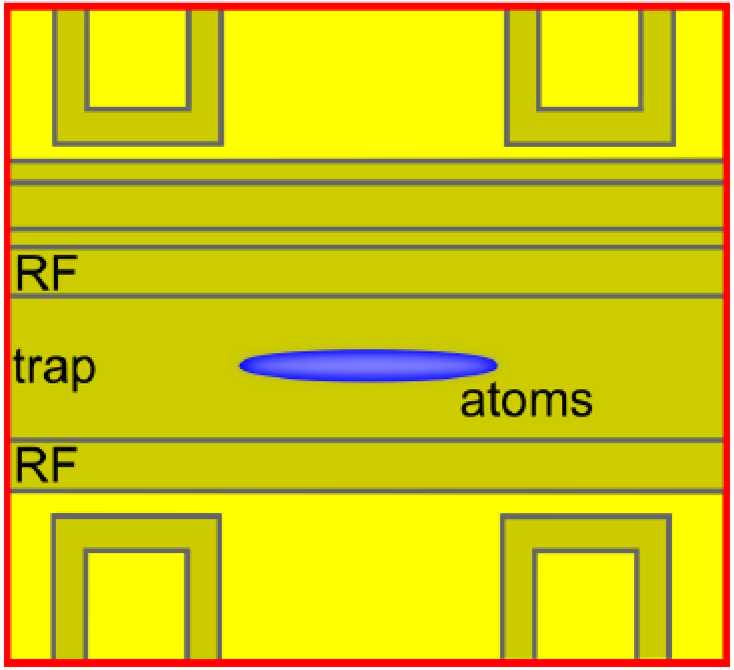
> *"A system of ultracold atoms provides unique opportunity to experimentally* ***study non-equilibrium dynamics*** *because of the almost perfect isolation from the environment"*

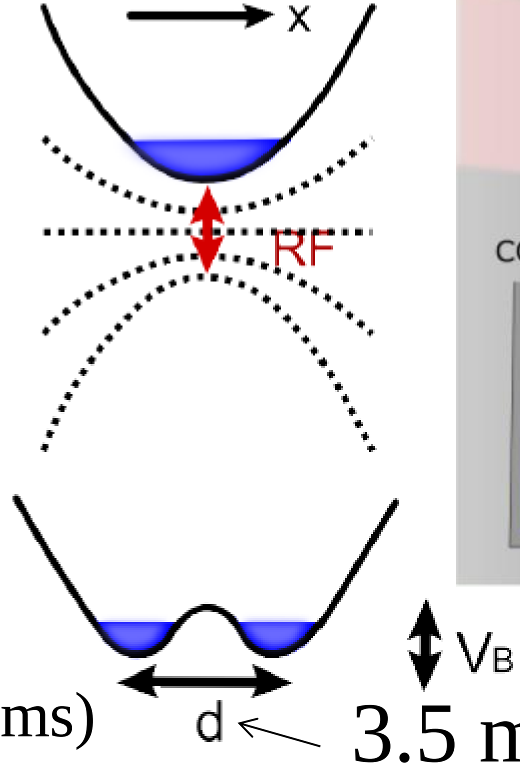
Pre-thermalization in an Isolated Quantum System

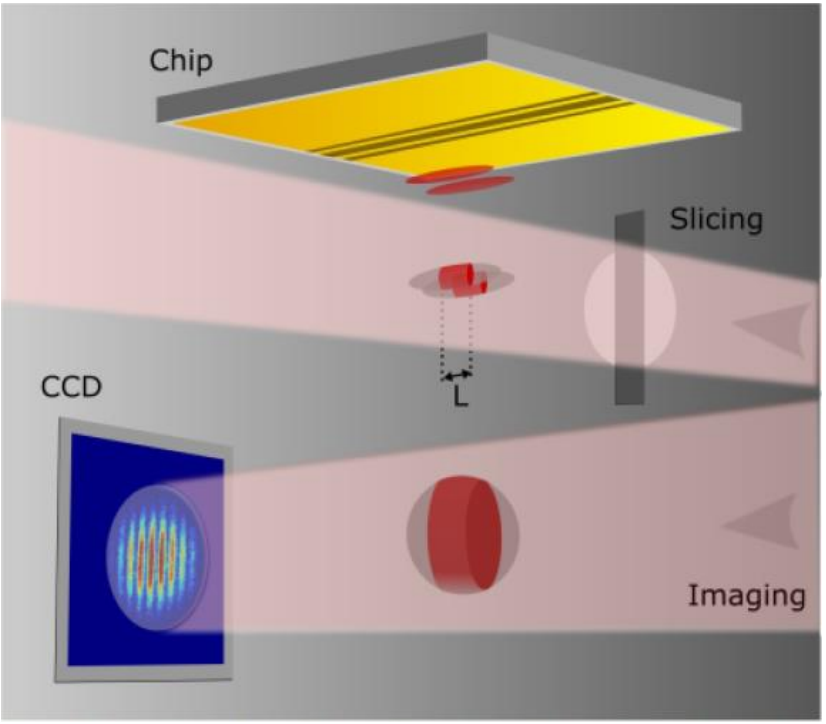
(J. Schmiedmayer Group, Science(2012))

1D Bose gas (^{87}Rb atoms) in an Atom Chip:

N: 2~10x10^3



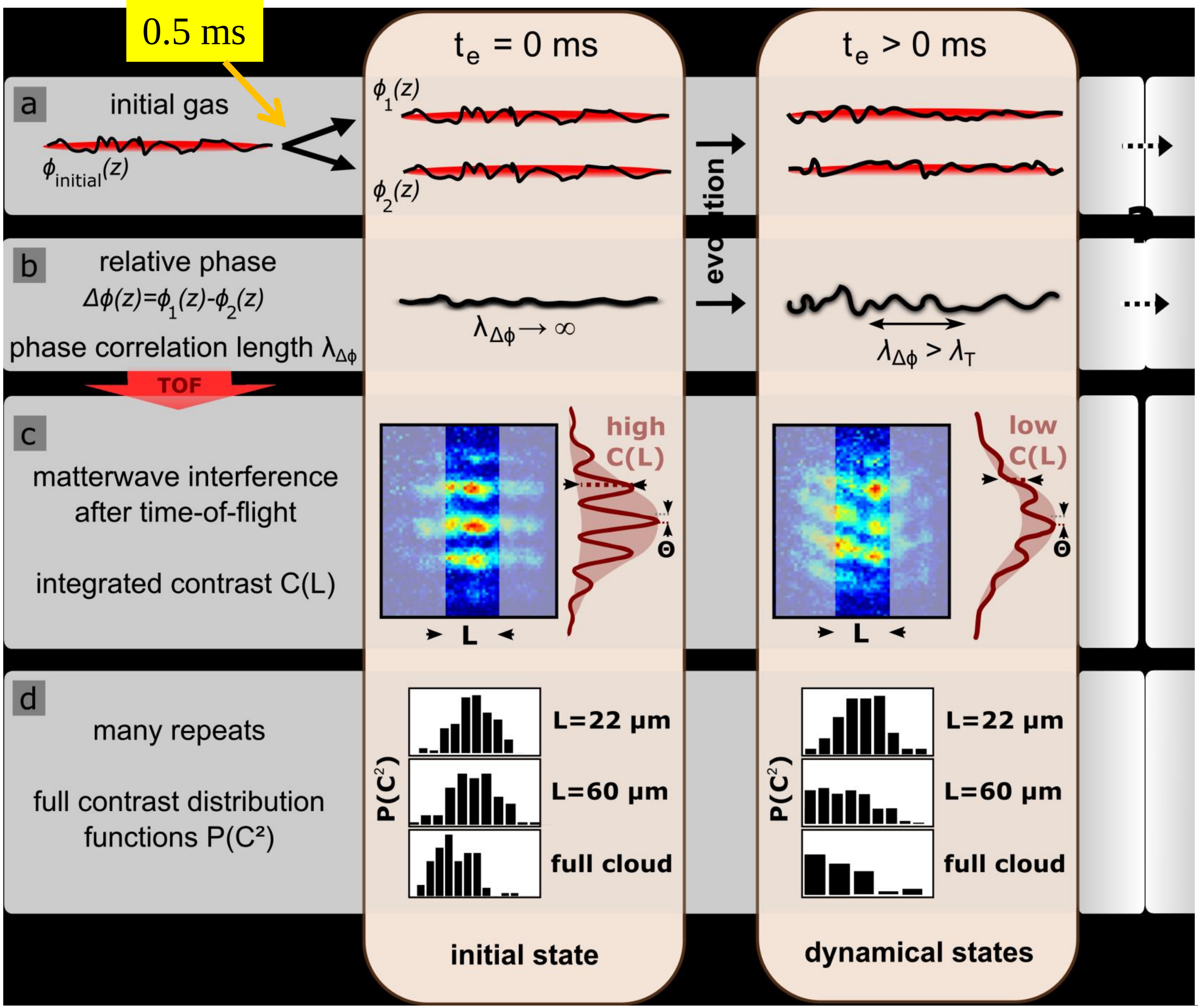




T: ~80 nK (heating: 0.1nK/ms)

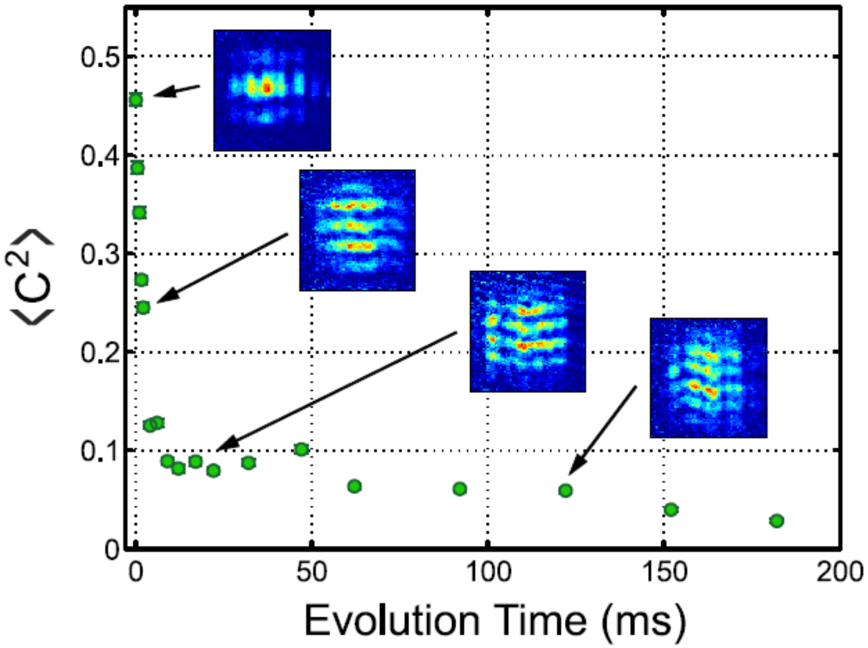
3.5 micron

Relaxation and Pre-thermalization in an Isolated Quantum System
(J. Schmiedmayer Group, Science(2012))

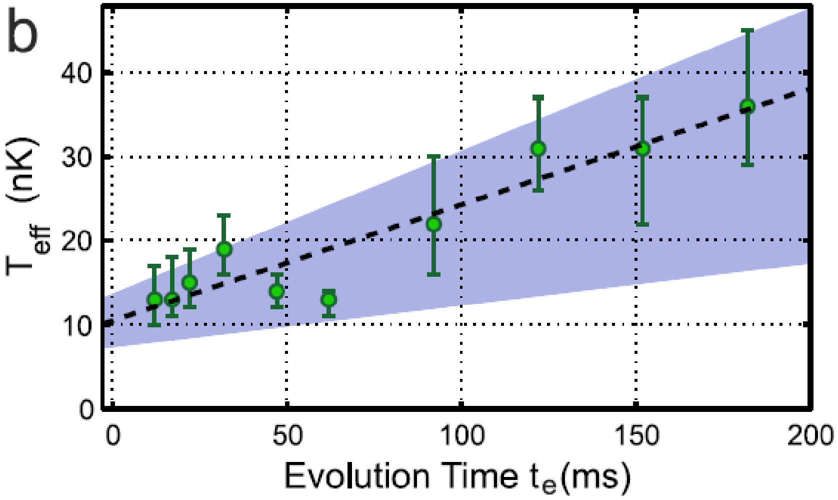


0.5 ms

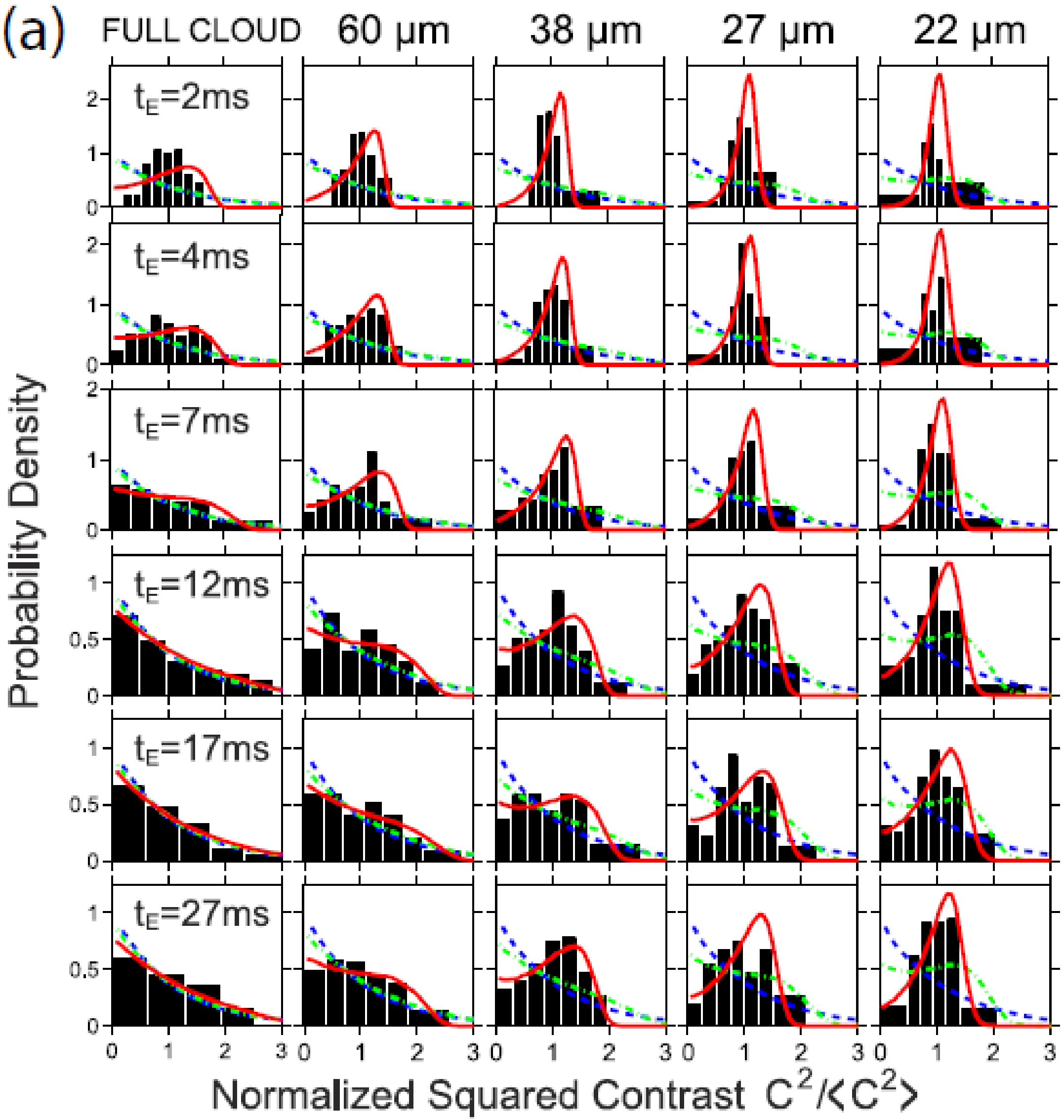
Relaxation and Pre-thermalization in an Isolated Quantum System
(J. Schmiedmayer Group, Science(2012))



b



(a)

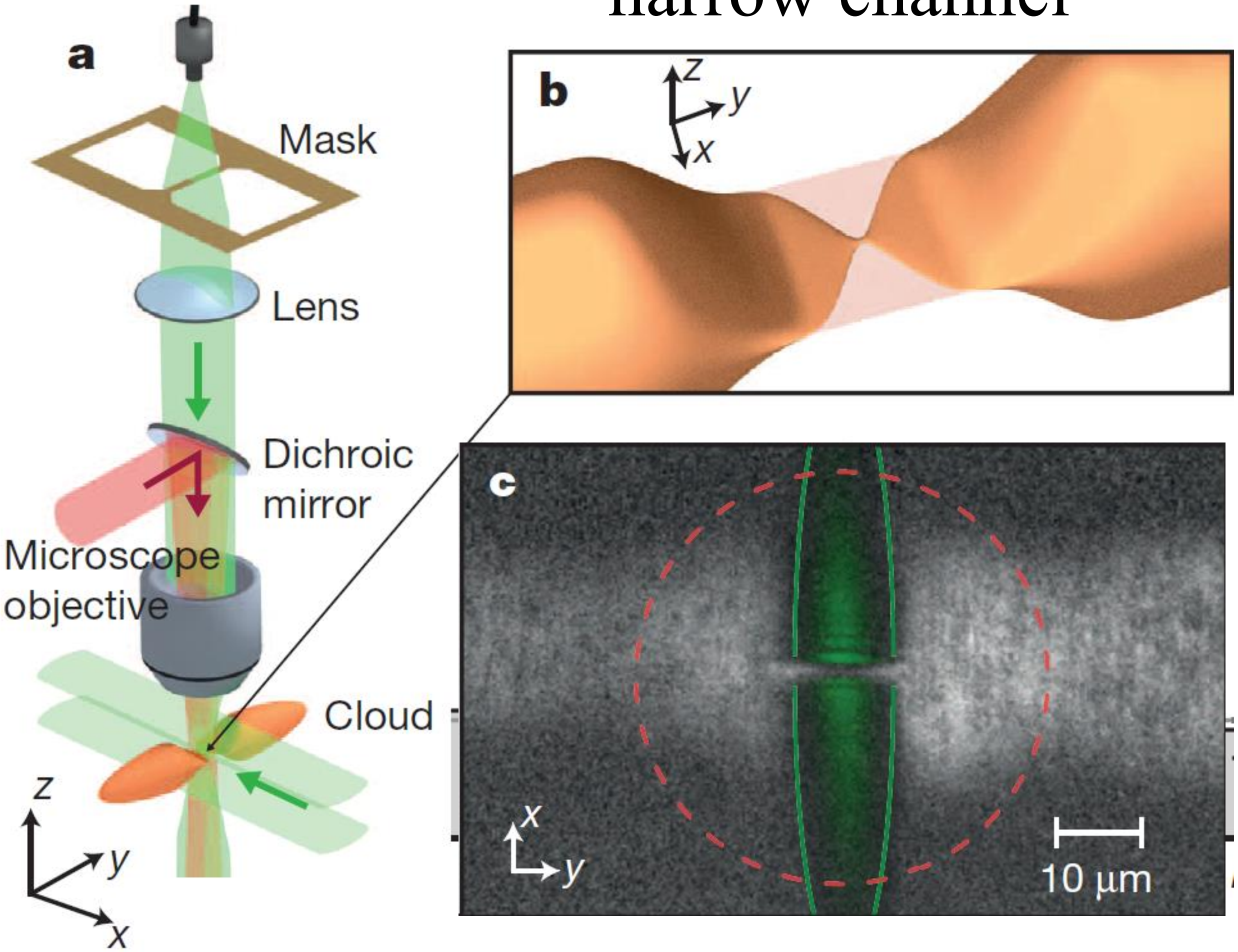


ETH group

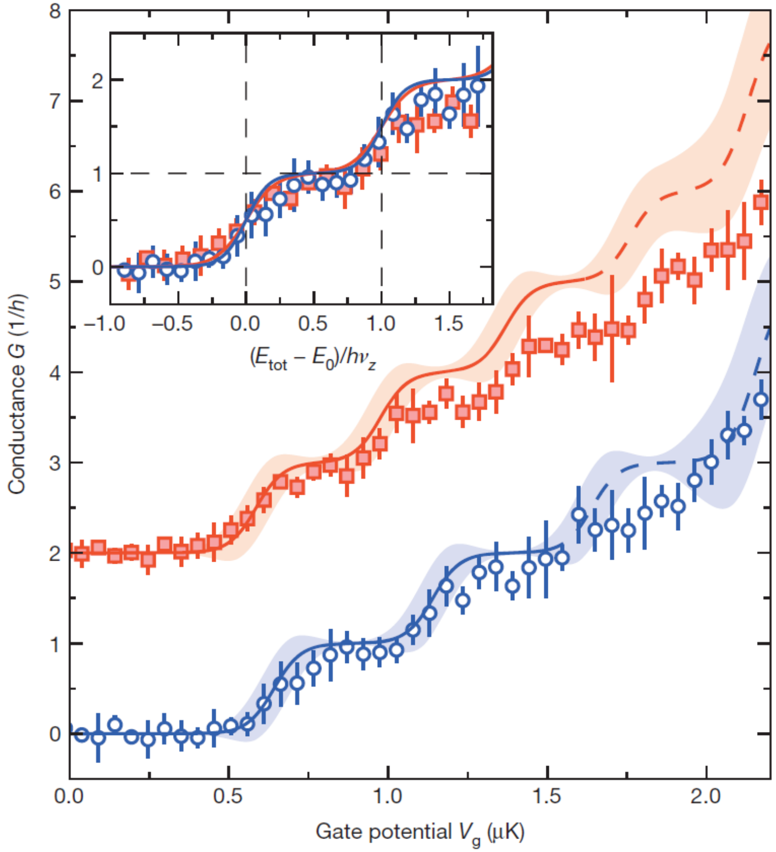
Study of Quantum Transport Using Cold Atoms

“observation of quantized conductance”

“narrow channel”



S. Krinner et al., Nature (2015)



^{6}Li

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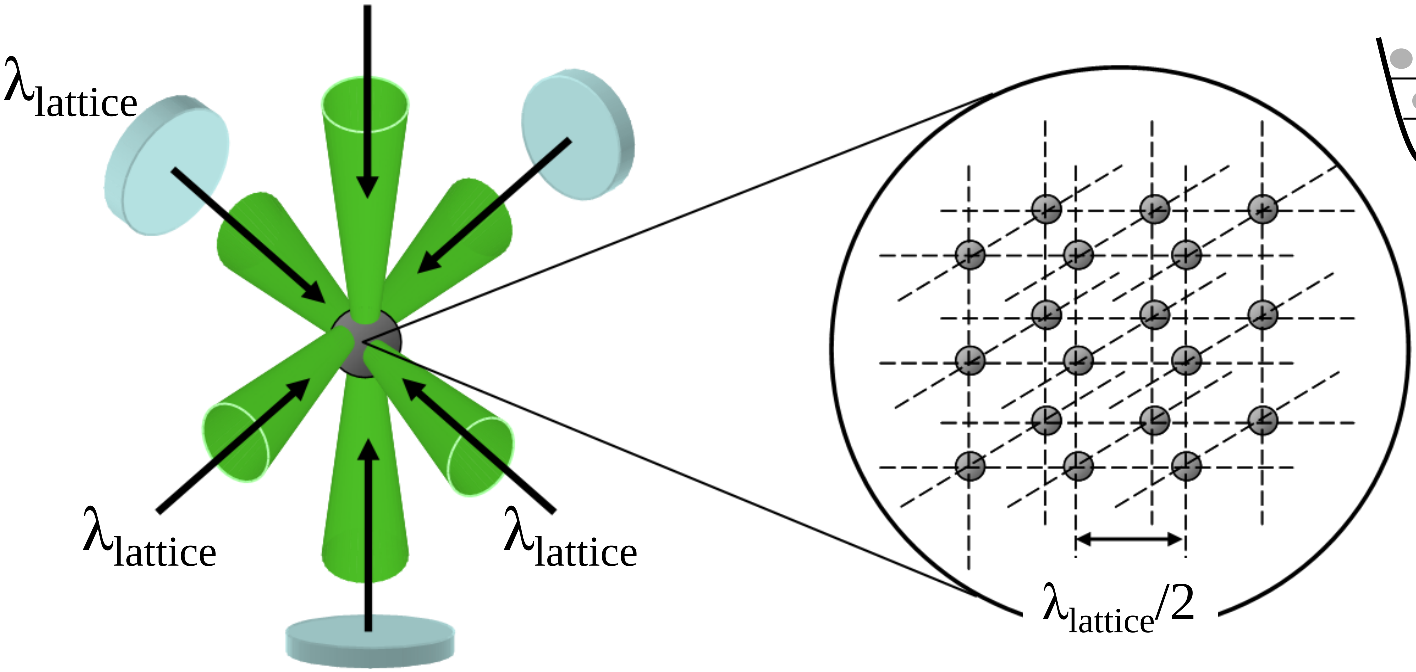
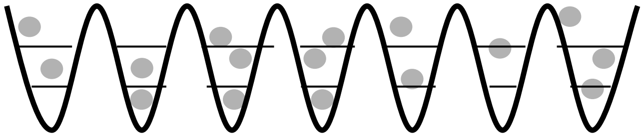
Quantum Simulation of Strongly Correlated Electron System



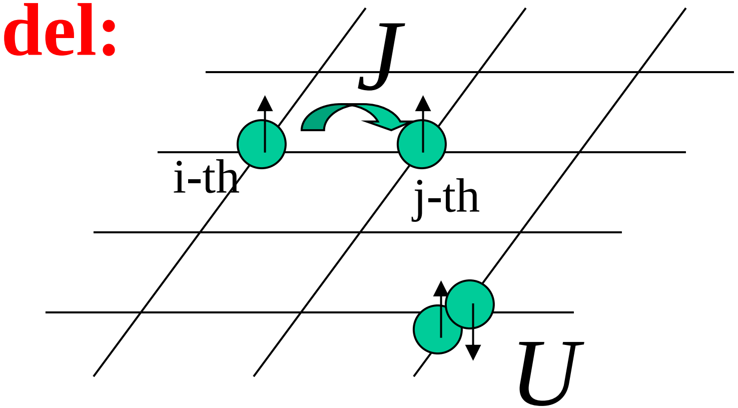


$$V_o(x) = V_o \sin^2(k_L x)$$

“ultracold atoms in an optical lattice”

ideal Quantum Simulator of **Hubbard Model:**

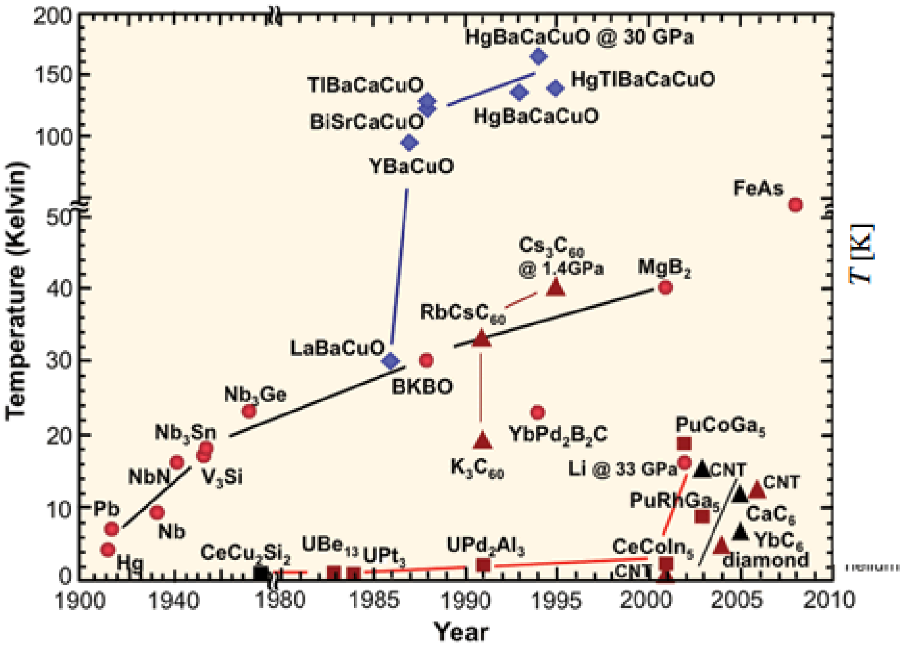
$$H = -J \sum_{<i,j>} c_i^+ c_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



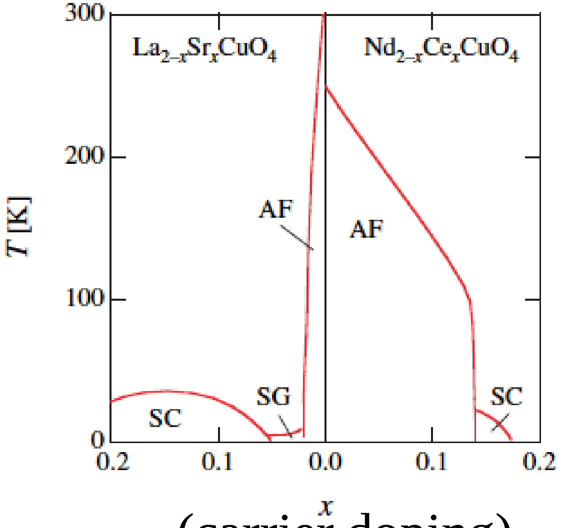
One motivation of the quantum simulation of Hubbard Model is
To get deeper understanding of

Cuprate High-T_c Superconductor:

strongly correlated electron system

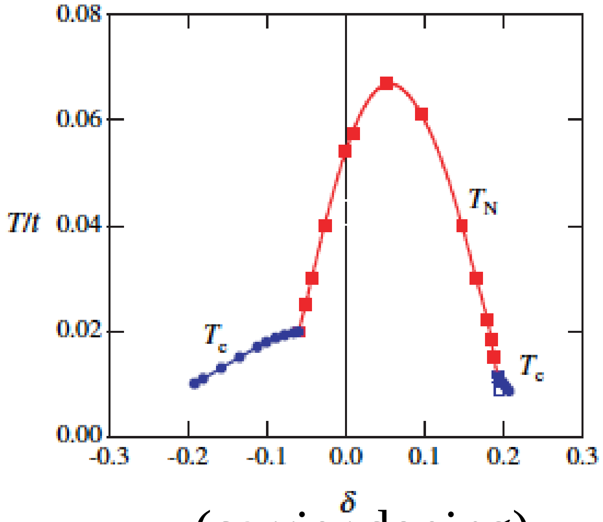


experiment



(carrier doping)

theory



(carrier doping)

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

extensive study of theory and experiment

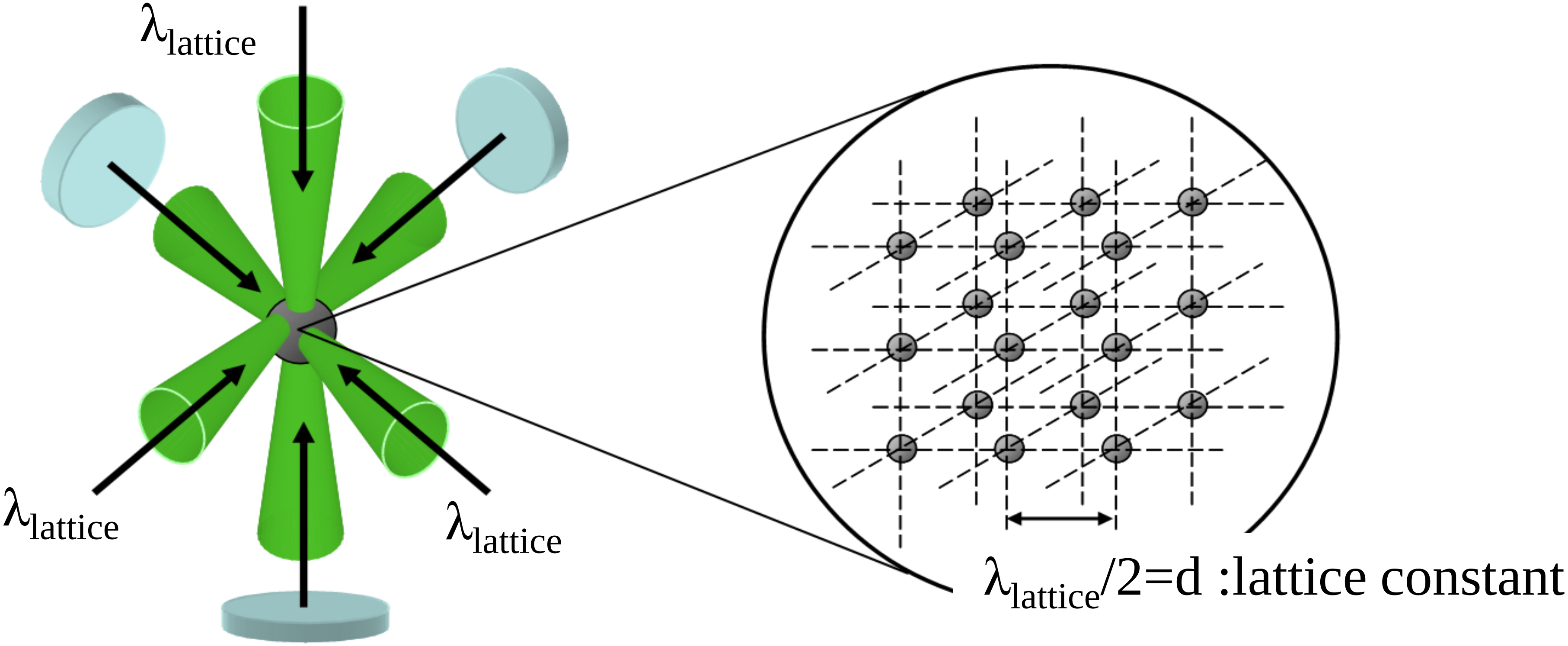
After about 30 years of discovery,

"Still Controversy on Behaviors of High-T_c Materials"

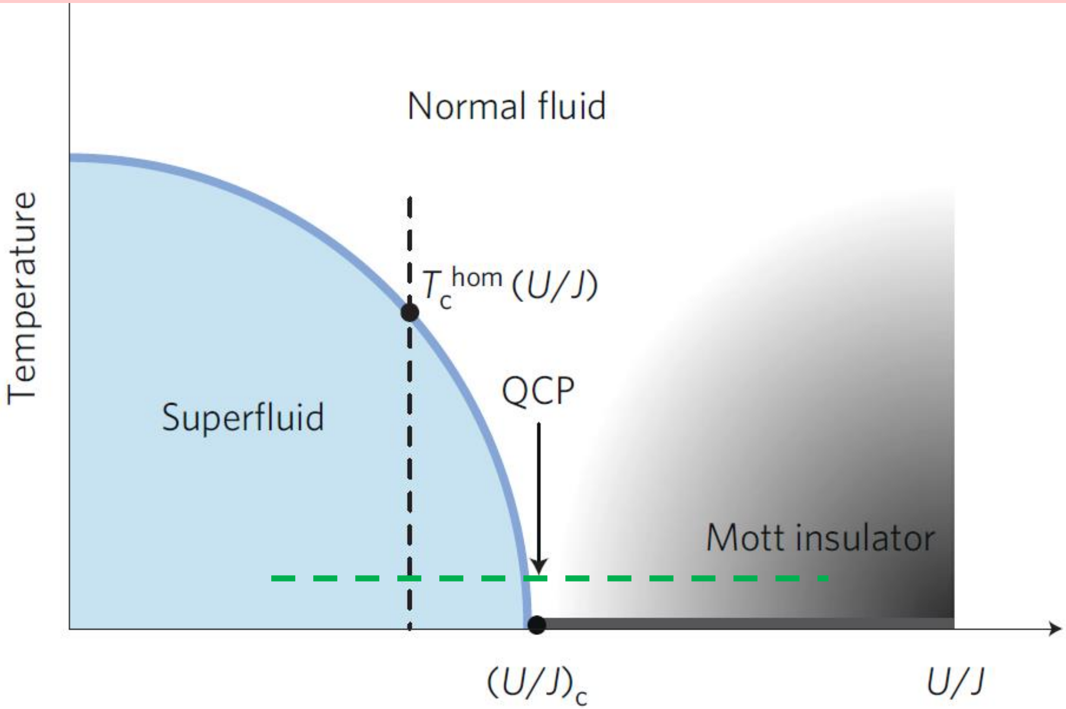
Bosons in a 3D optical lattice

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

"Bose-Hubbard Model"

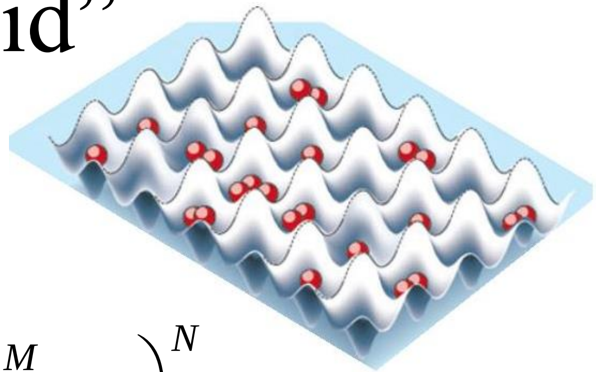


Phase Diagram of Bose-Hubbard Model (T>0)

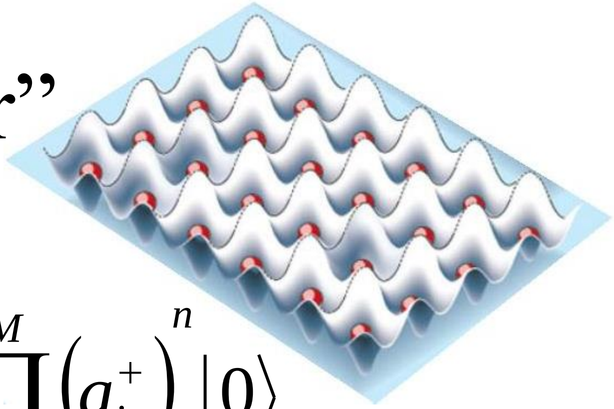


$$H = -J\sum_{<i,j>} a_i^+ a_j + \frac{U}{2}\sum_i n_i(n_i-1) + \sum_i \varepsilon_i n_i$$

“Superfluid”



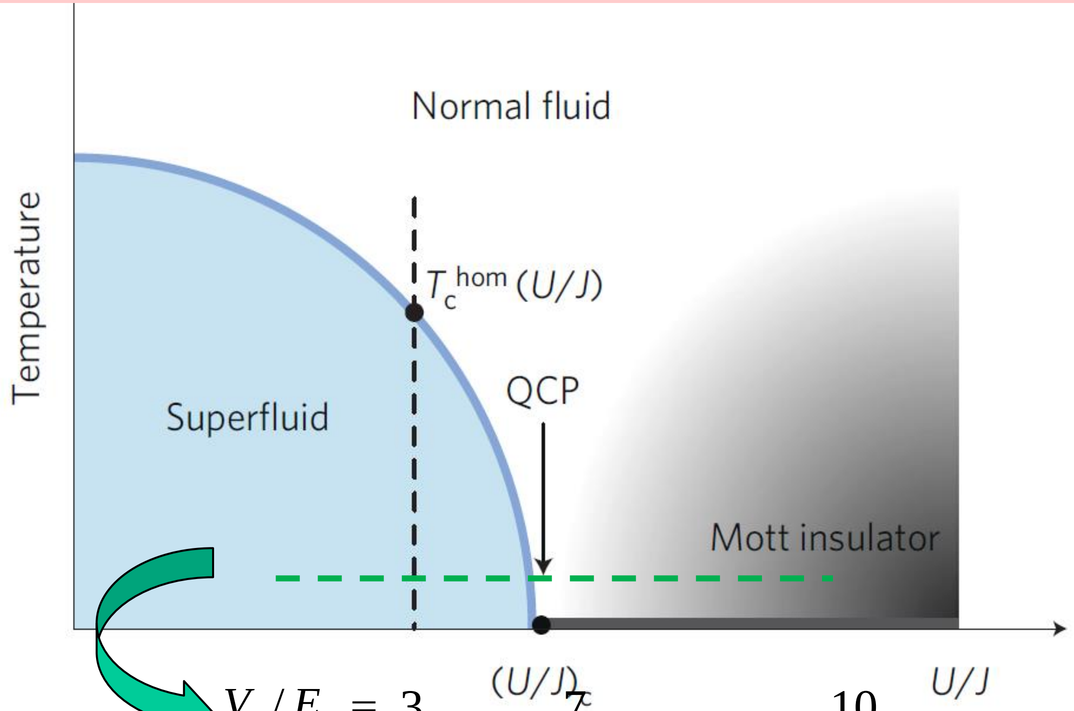
“Mott Insulator”



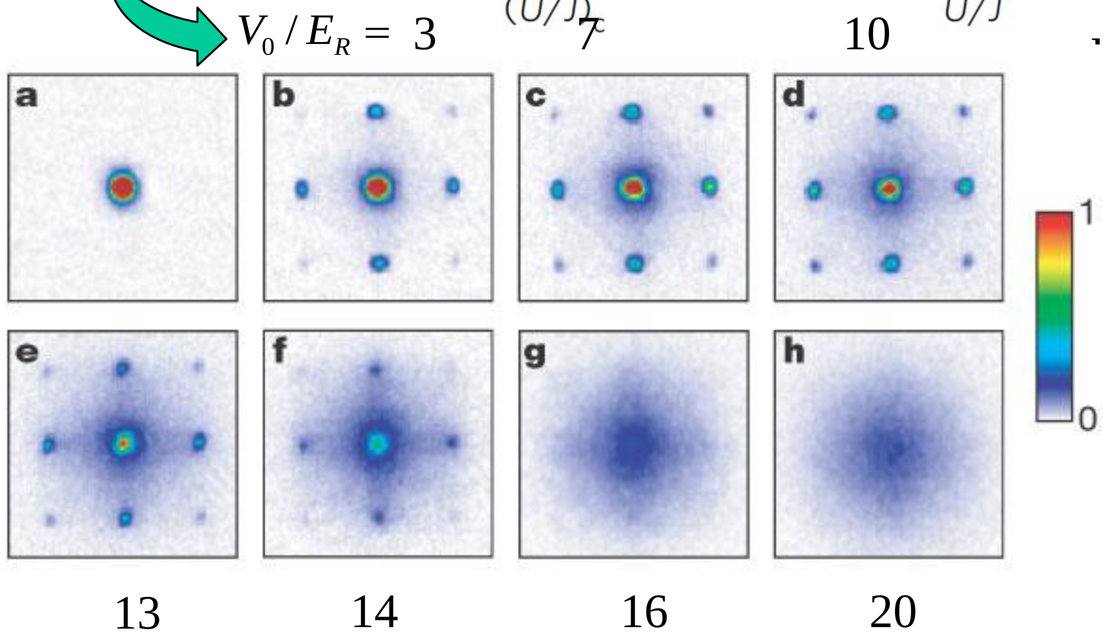
$$|\Psi_{SF}\rangle \propto \left(\frac{1}{\sqrt{M}}\sum_{i=1}^{M} a_i^+\right)^N |0\rangle$$

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

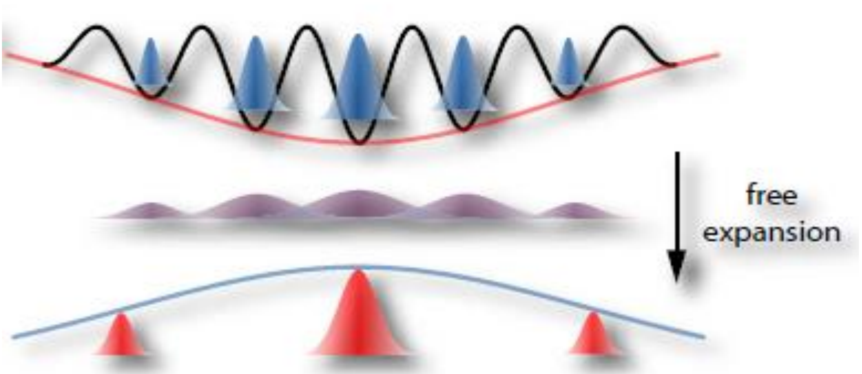
Phase Diagram of Bose-Hubbard Model (T>0)



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

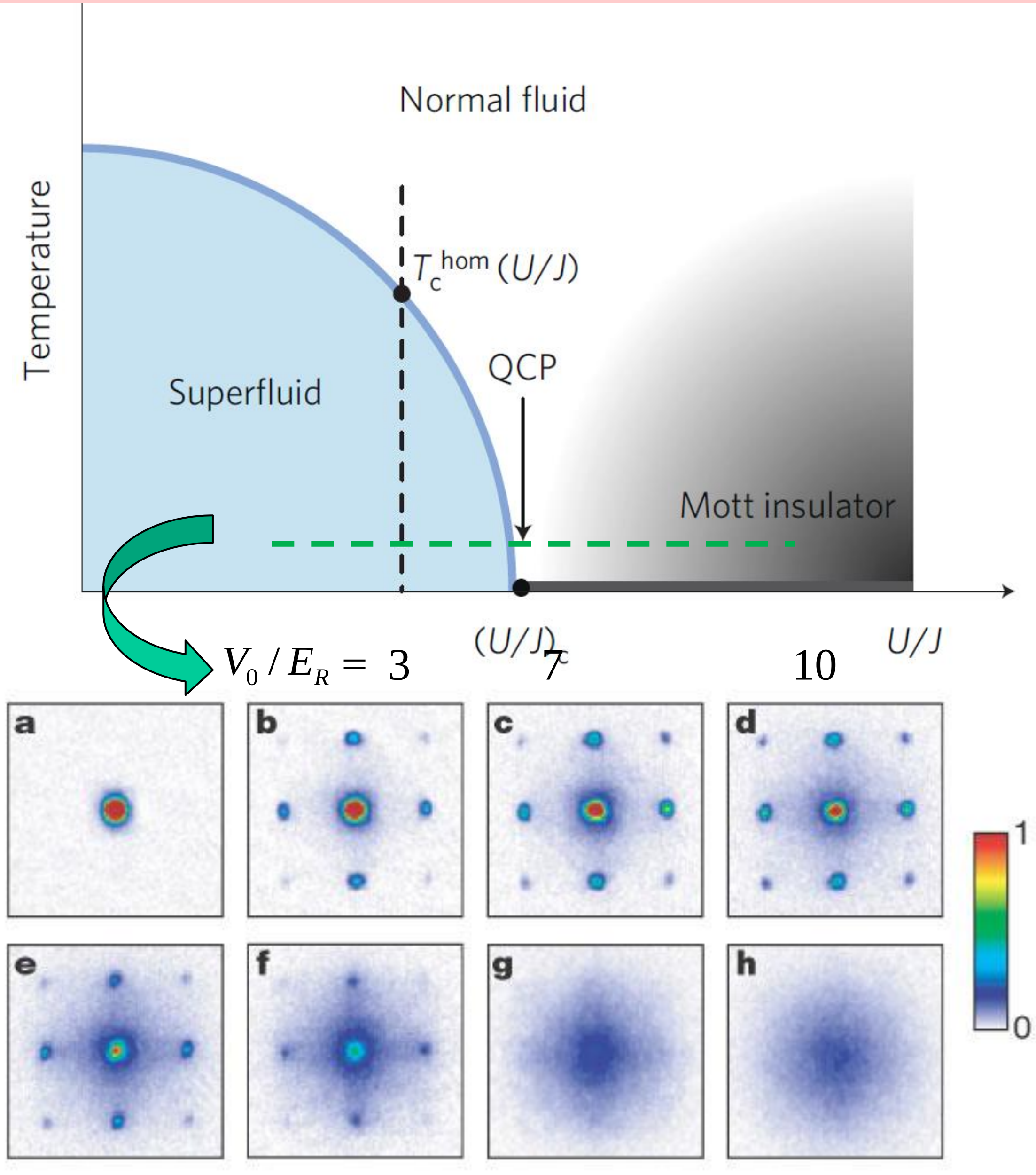


“An interference fringe is
e direct signature of the phase coherence”



$$U/J = a_s k_L \sqrt{2}\exp(+2\sqrt{V_0/E_R})$$

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



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

Theory (n=1):

mean-field cal.

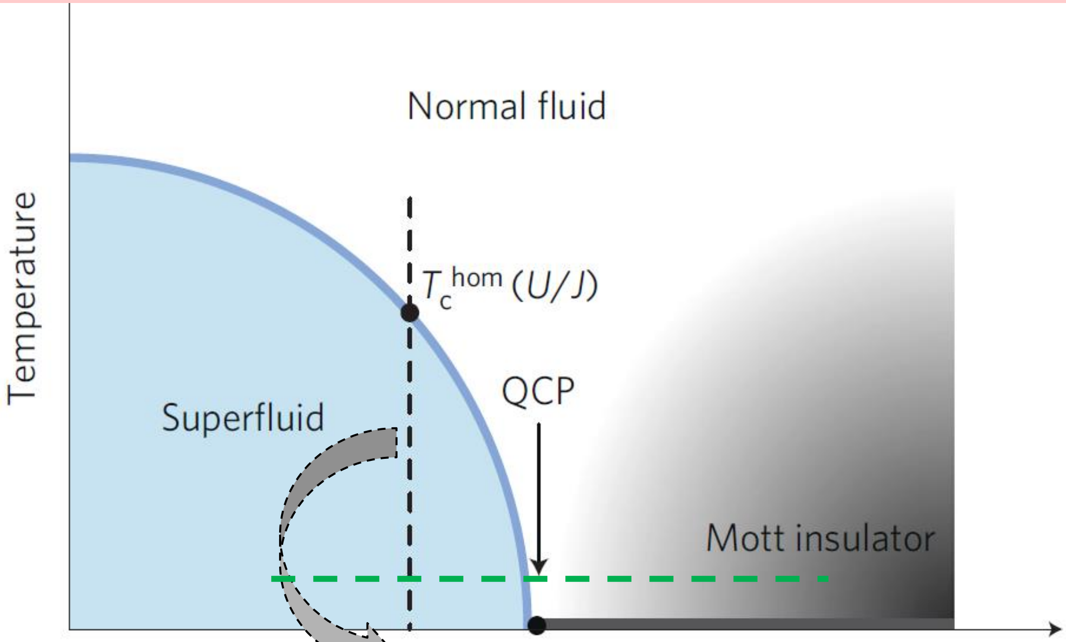
→$(U/J)_c$=6×5.8

QMC

→$(U/J)_c$=29.36

$$U/J = a_s k_L \sqrt{2}\exp(+2\sqrt{V_0/E_R})$$

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



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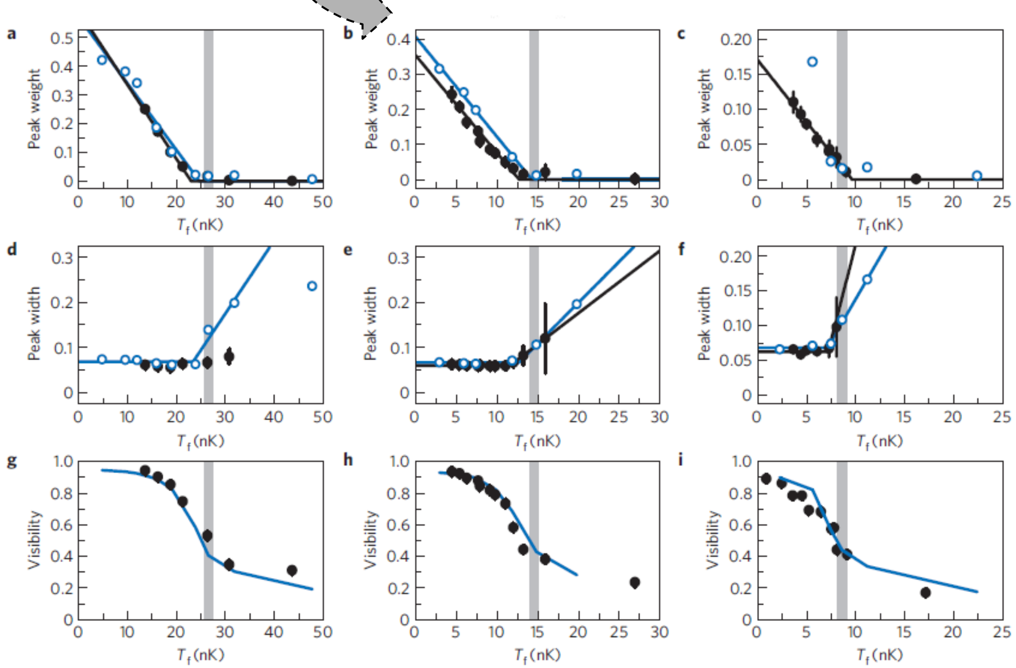
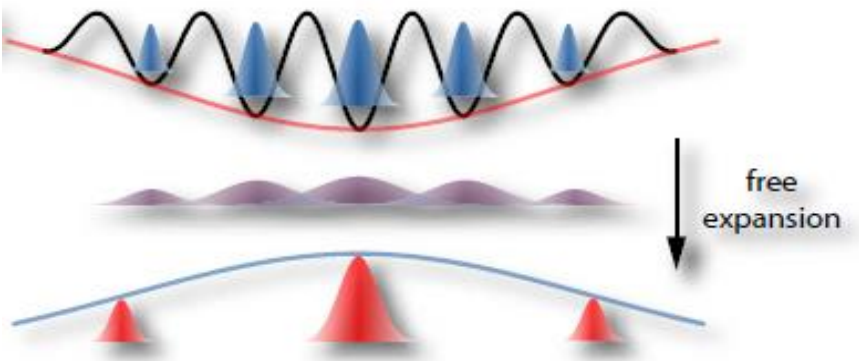


"An interference fringe is
the direct signature of the phase coherence"



Nature Physics ***6**, 998(2010)*

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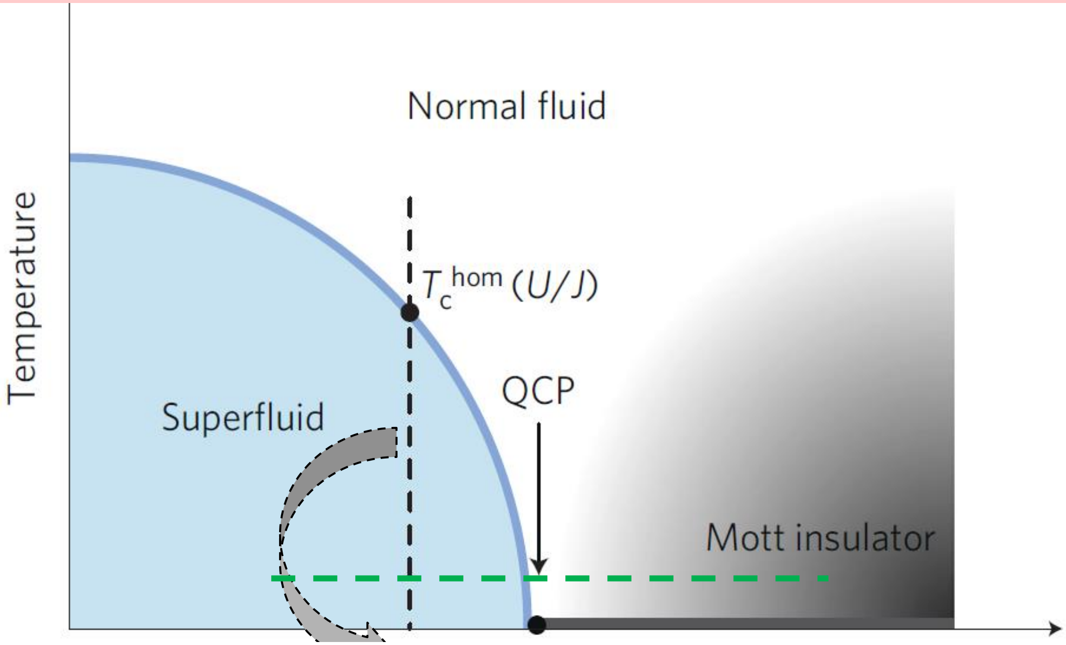
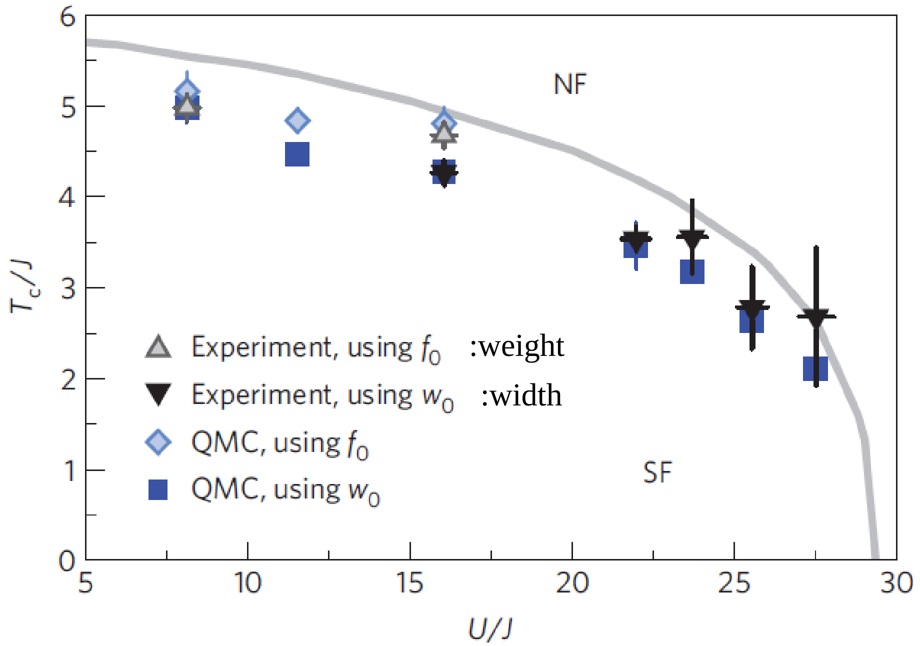
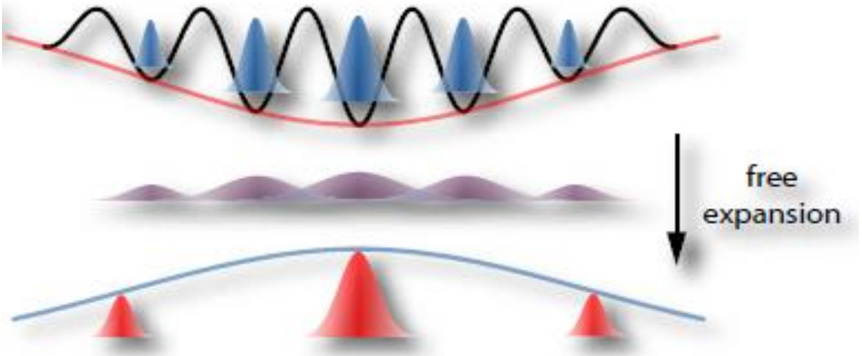


$$H = -J\sum_{<i,j>} a_i^{+} a_j + \frac{U}{2}\sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i$$



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



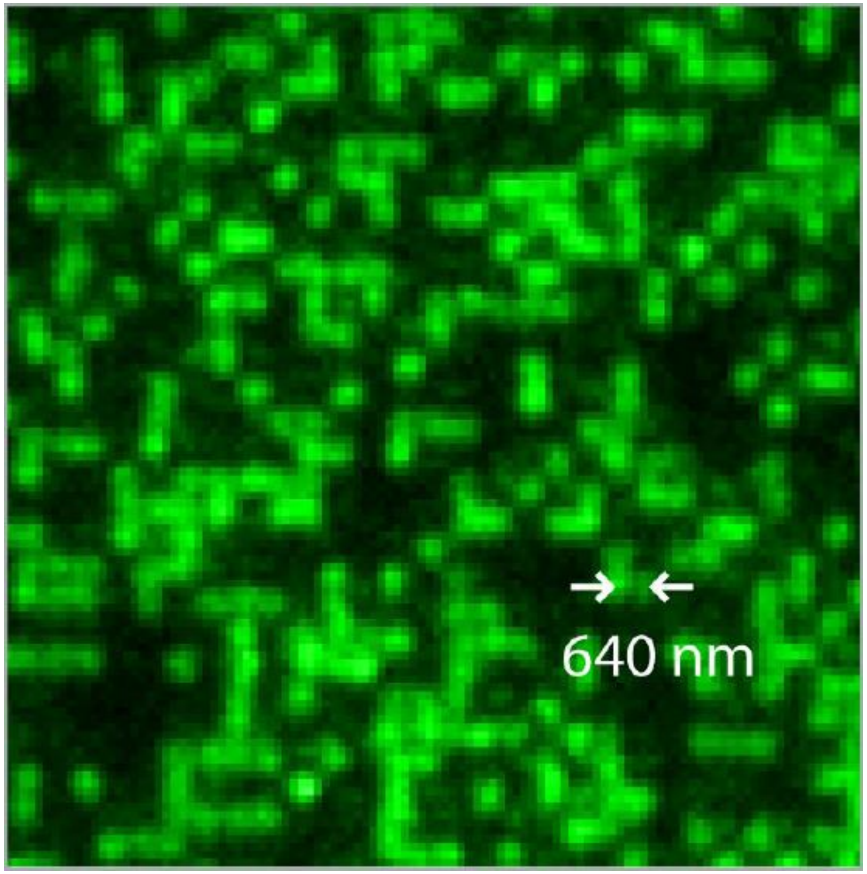
Nature Physics **6**, *998(2010)*

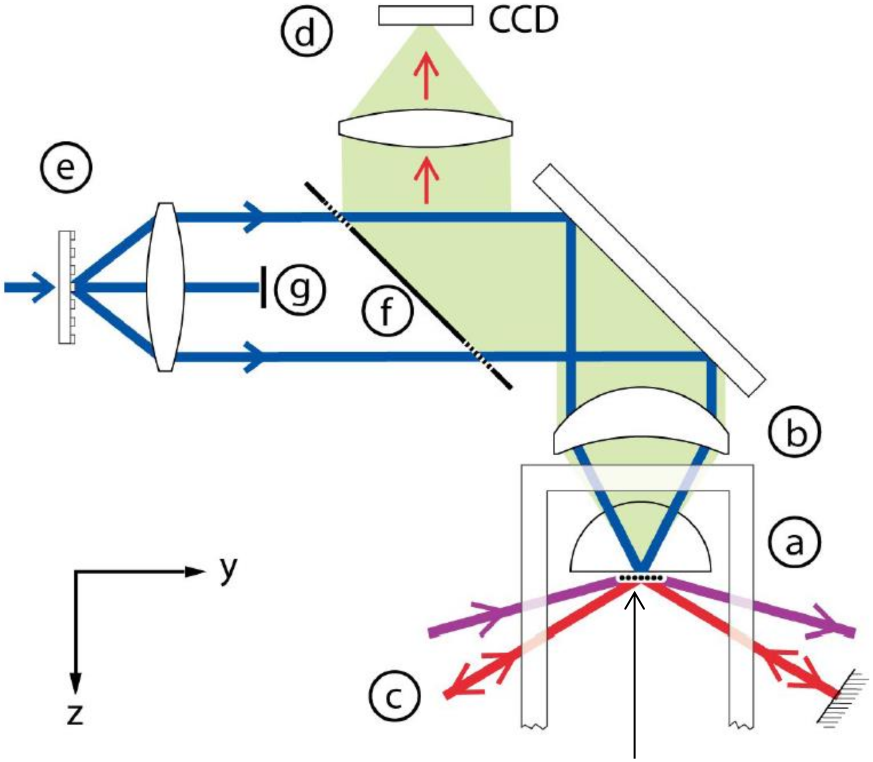
Quantum Gas Microscope

: Observation of Atom Distribution in an Optical lattice with Single Site Resolution

[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 SF-MI Transition

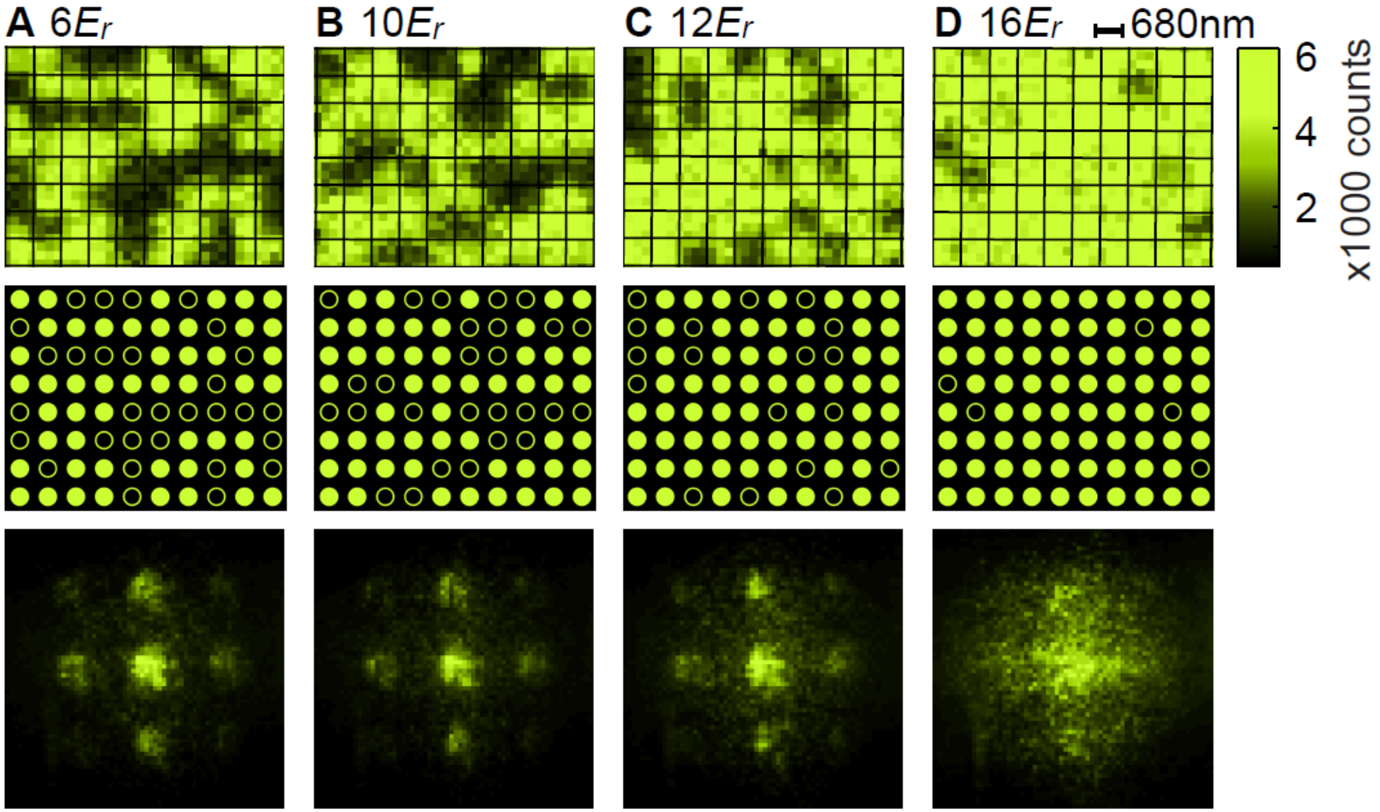
[WS Bakr, et al., Science 329, 547(2010)]

SF ⟷ MI

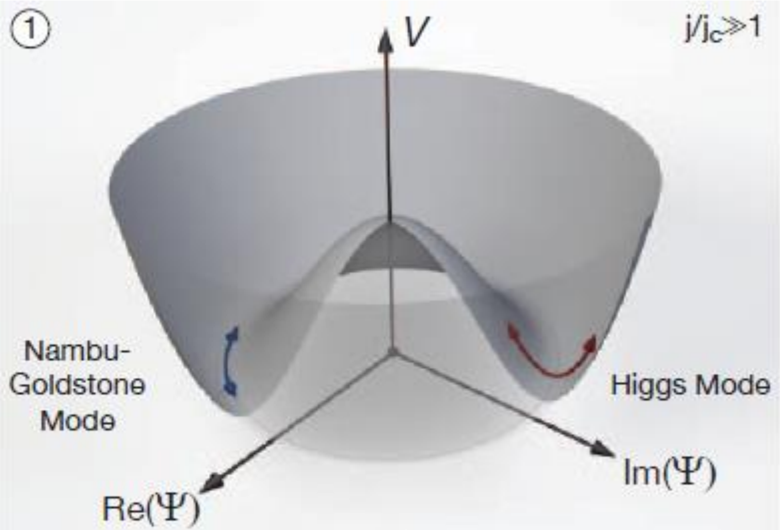
In Situ-image

after analysis

TOF-image

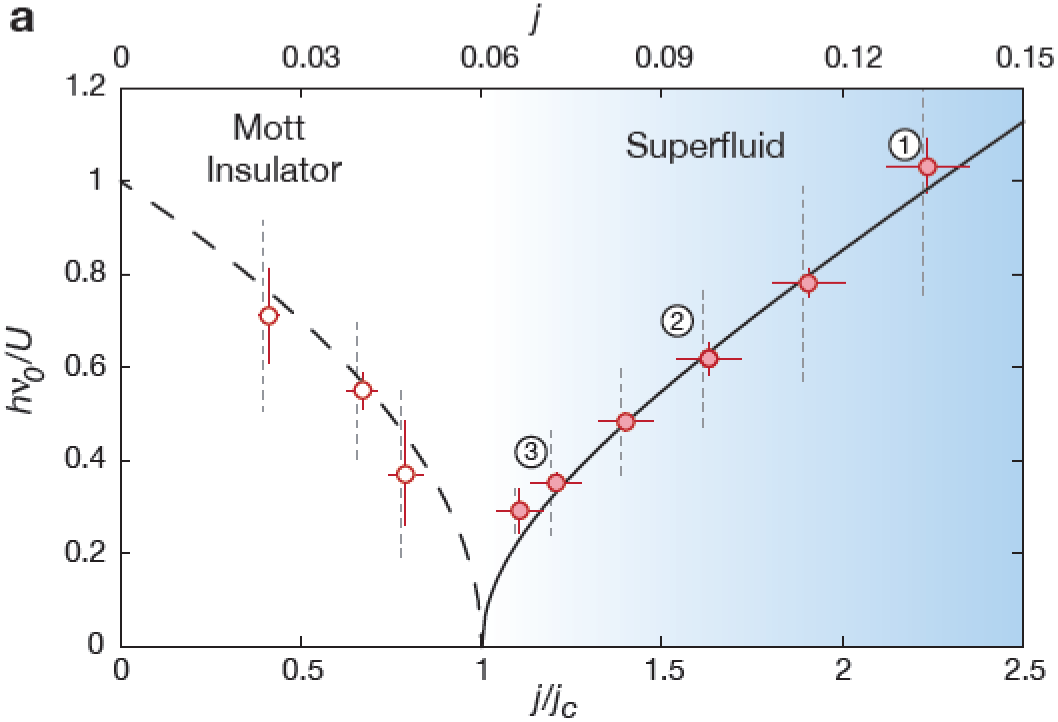


“amplitude-(Higgs-)mode”

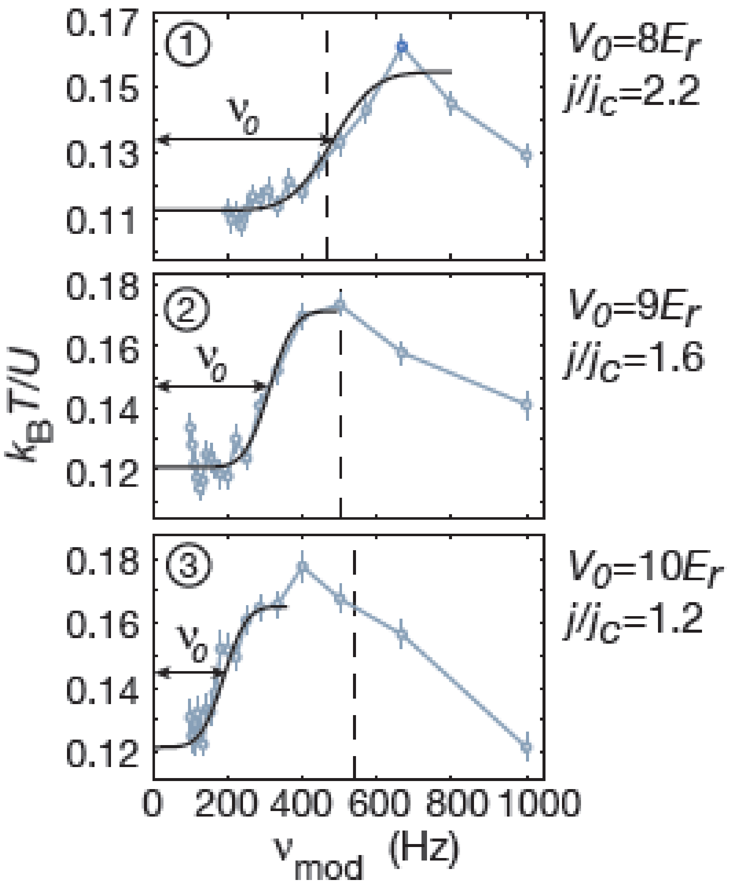


The `Higgs' Amplitude Mode at the Two-Dimensional Supefruid-Mott Insulator Transition

M. Endres *et al* (2012)



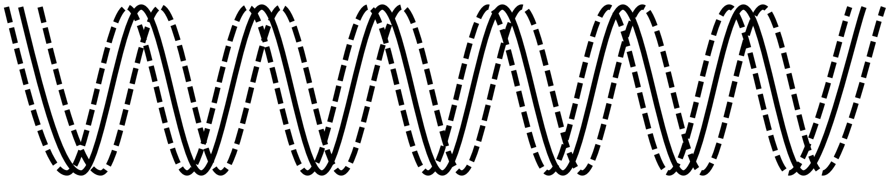
Lattice modulation spectra



Quantum Simulation of Frustrated Magnetism in a Triangular Lattice

[Sengstock Group(2011)]

Phase Modulation of Optical Lattice:

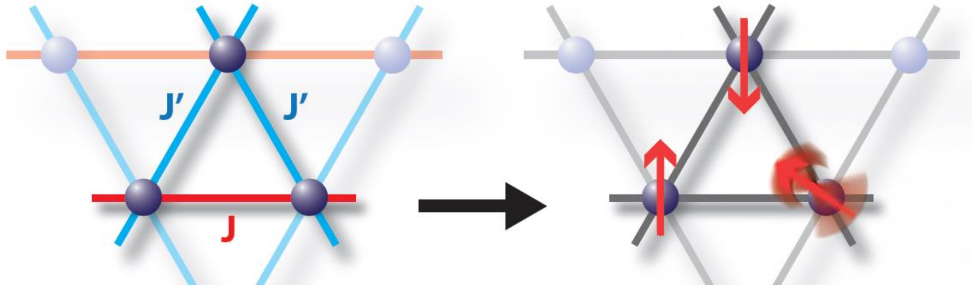


Kcos(ωt)

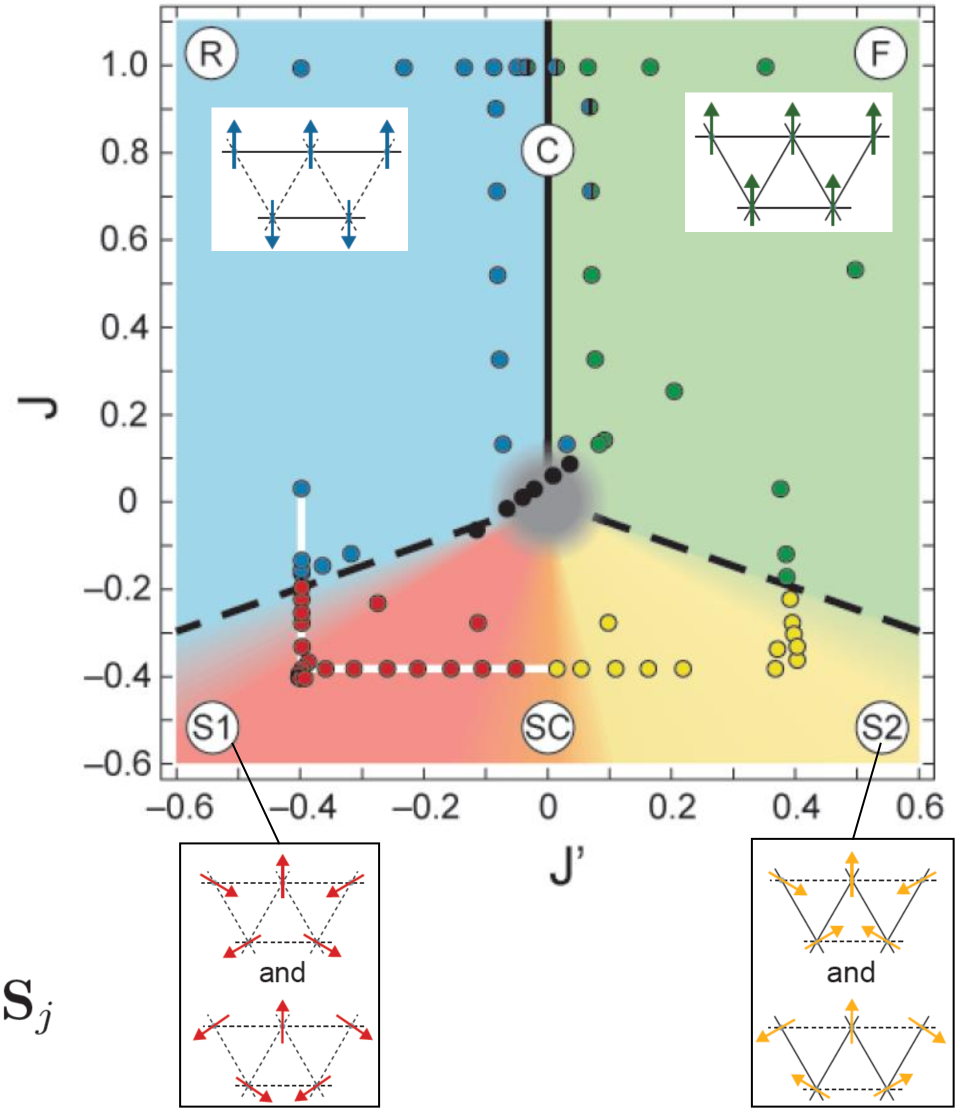
$$J \to J \times J_0(\beta)$$

:Zero-th order Bessel Function

β=K/ω



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



Outline of This Talk

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,
pre-thermalization, quantum transport

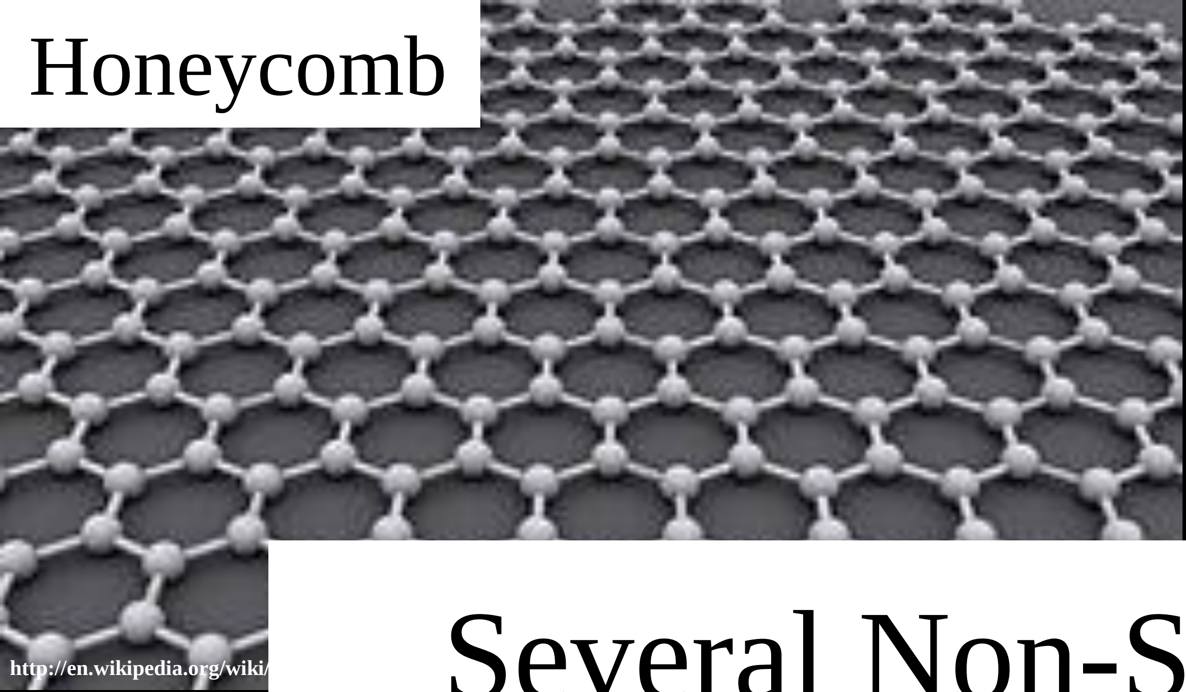
III) Ultracold Atoms in an Optical Lattice

Superfluid-Mott insulator transition, quantum-gas-microscope, Higgs mode,
frustrated magnetism

IV) (our recent work) Ultraold Atoms in a Flat Band

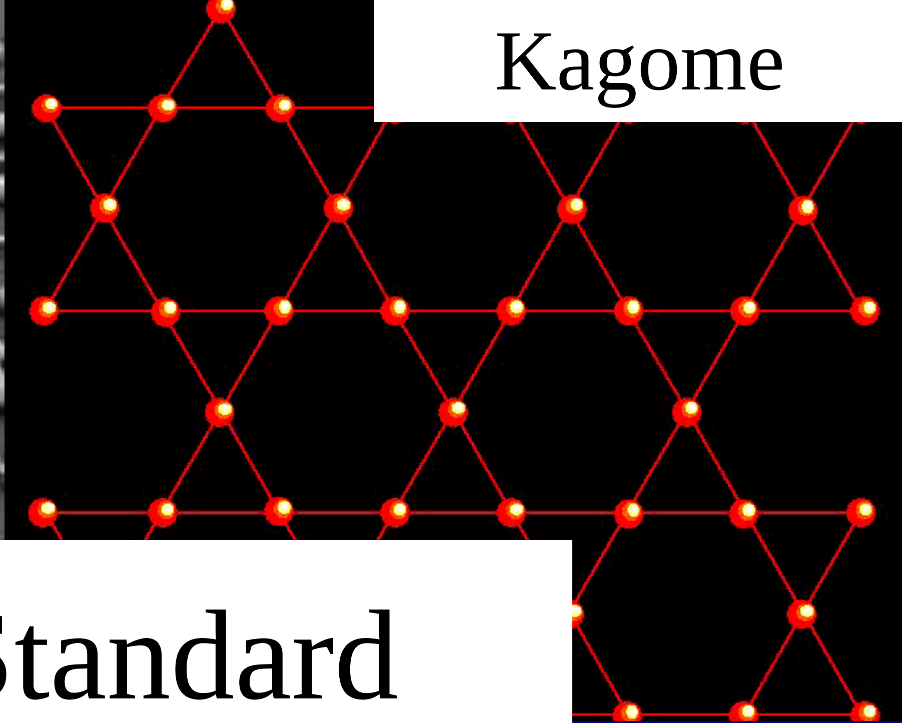
localization/delocalization on flat band

Several Non-Standard Optical Lattices are realized

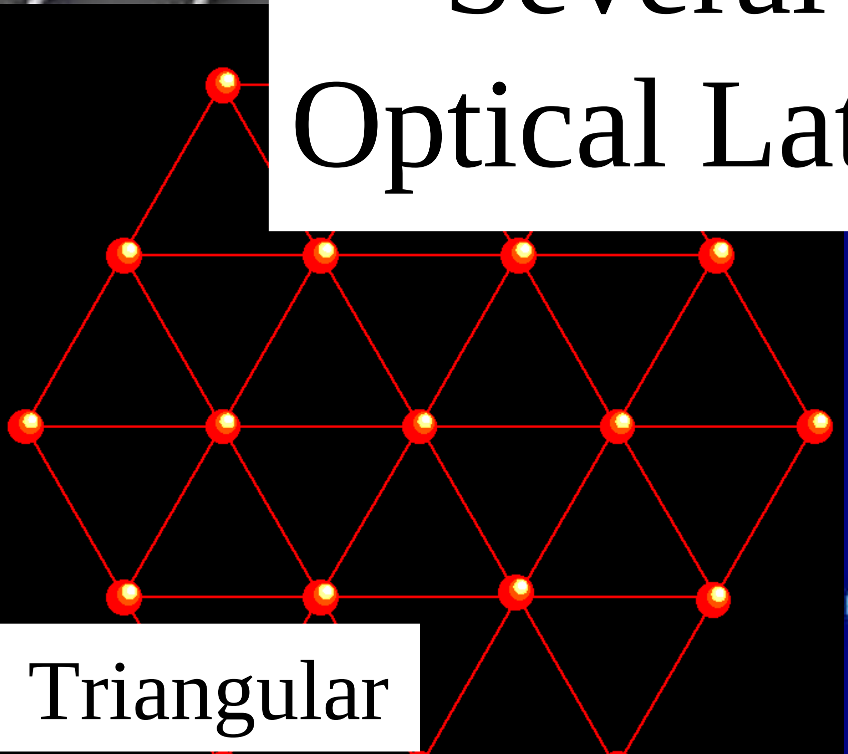


Honeycomb

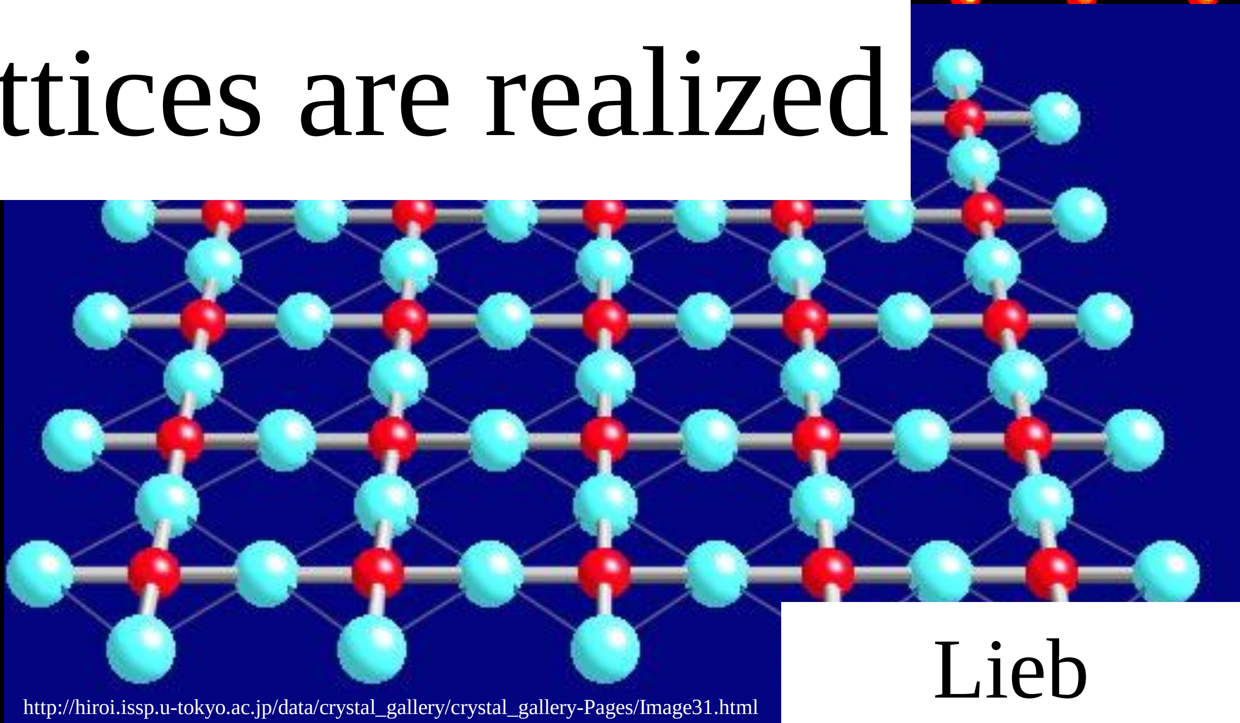
http://en.wikipedia.org/wiki/



Kagome



Triangular



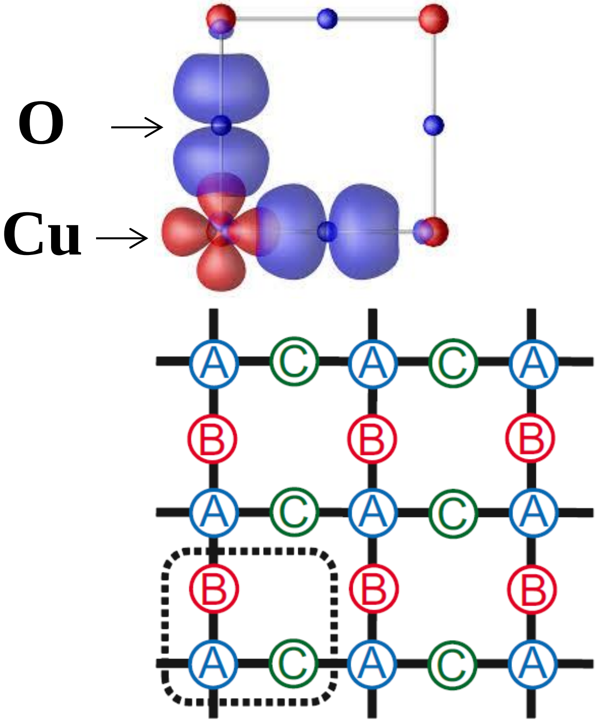
Lieb

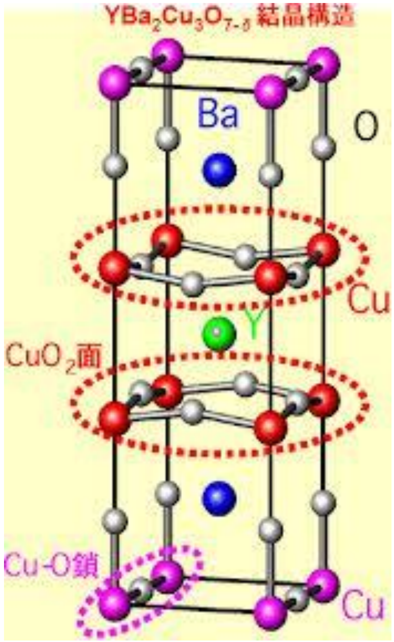
http://hiroi.issp.u-tokyo.ac.jp/data/crystal_gallery/crystal_gallery-Pages/Image31.html

Study of Hubbard Model with Lieb Lattice

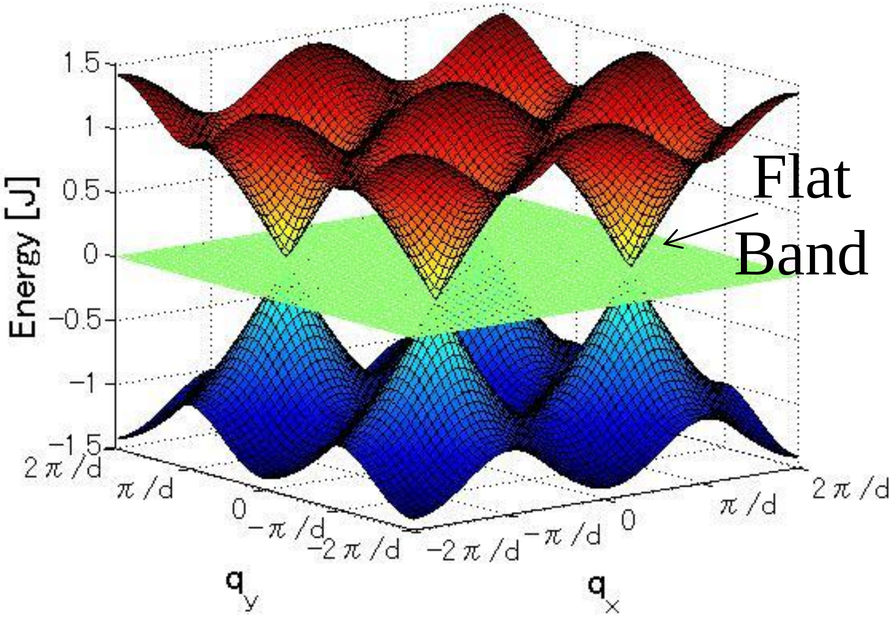
More realistic lattice model of High-Tc Cuprate
than square lattice :
d-p Model(=Lieb lattice)

“CuO$_2$ plane (d-p model)”





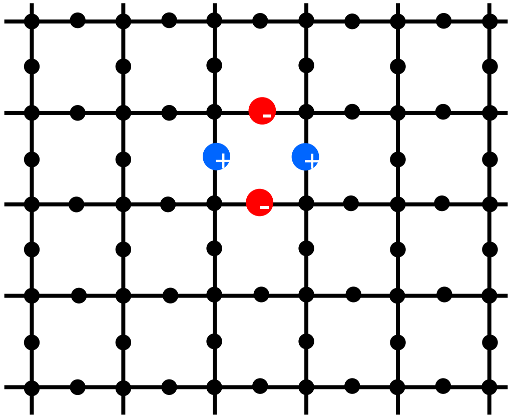
Flat band and Dirac Cone



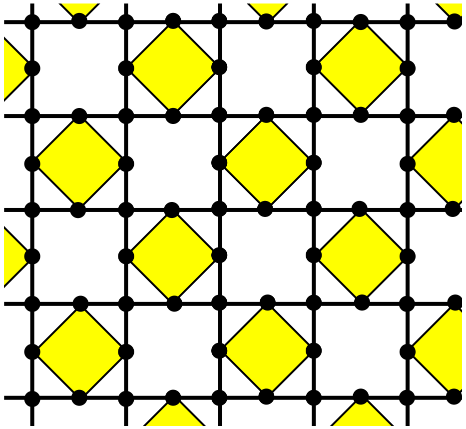
“Boson in a flat band”

(case of Lieb lattice)

“plaquette”:
“localized eigenstate”



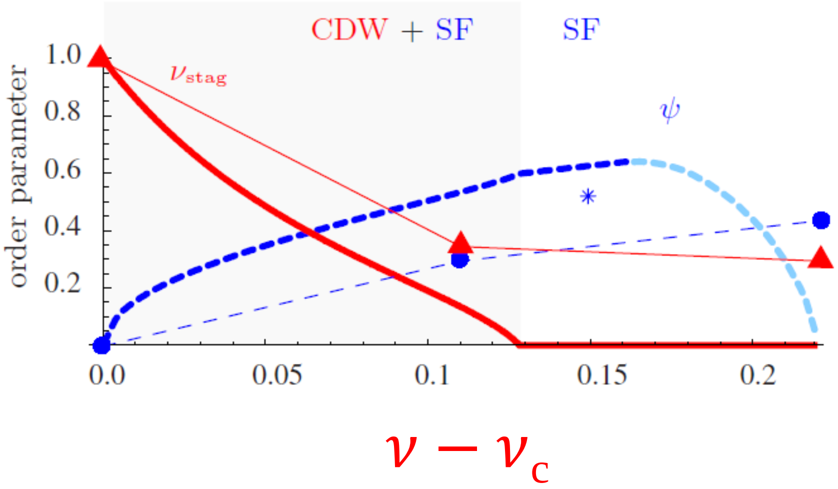
closed packing
at ν_c=1/6



$\nu > \nu_c$

Exotic strongly correlated state:
Super-Solid !?

[discussion with S. Furukawa]



Prediction of super-solid for Kagome lattice

Huber & Altman PRB 82, 184502 (2010)

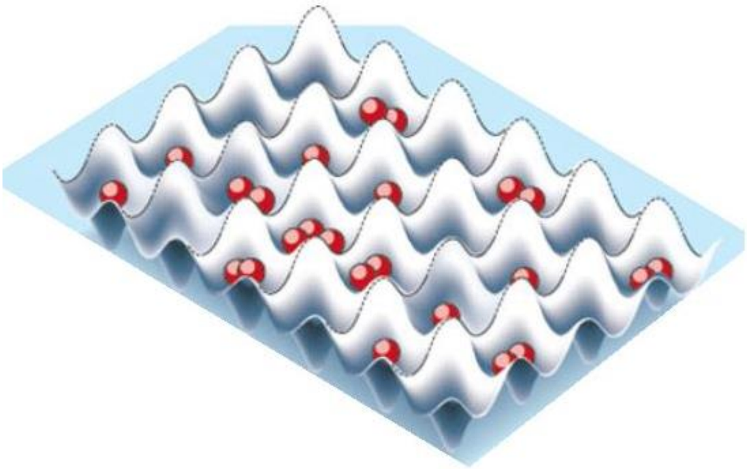
What is Super-Solid ?

“superfluid”

(Off-Diagonal Long-Range Order)

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

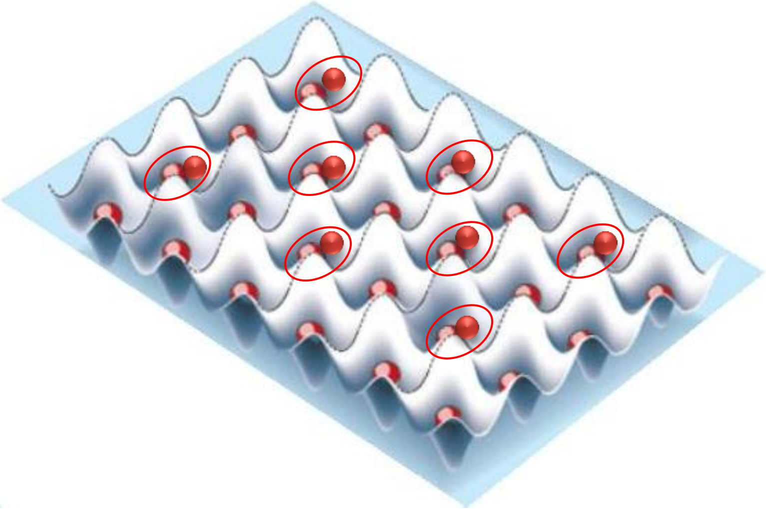
$$\rightarrow n_0$$



“Solid order”

(Diagonal Long-Range Order
/ density wave)

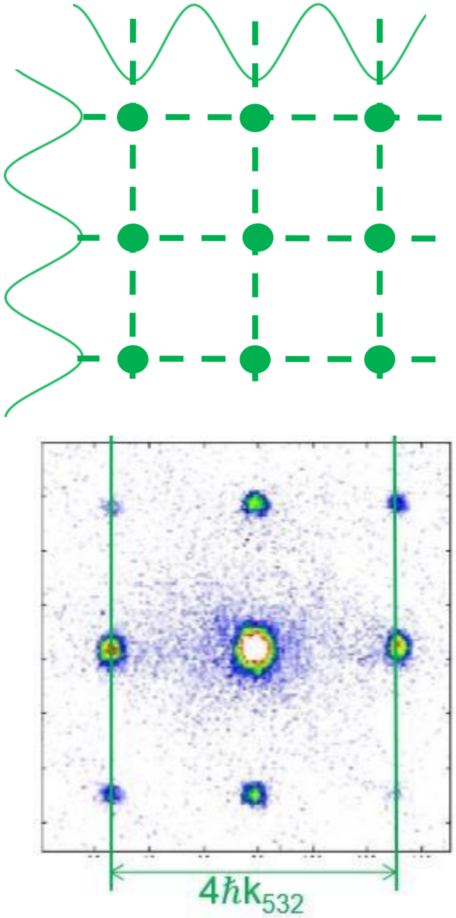
$$\langle n(\mathbf{x})n(\mathbf{x}')\rangle \neq 0$$



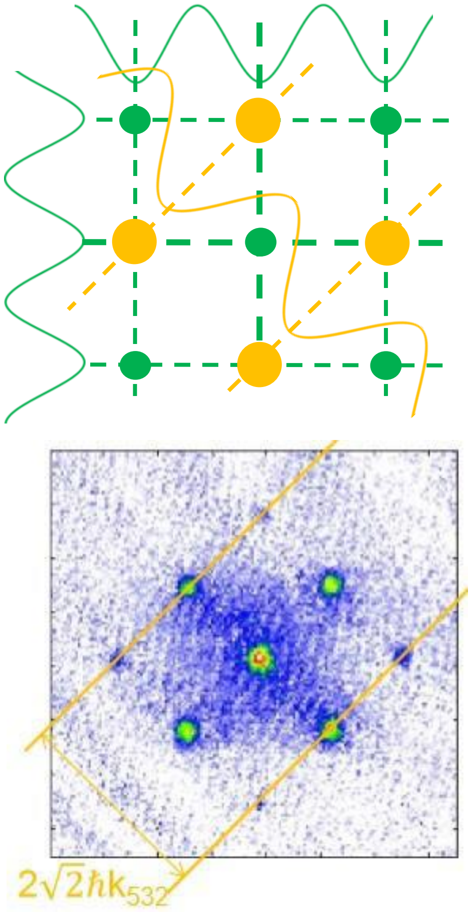
Optical Lieb Lattice

“Laser Configuration”

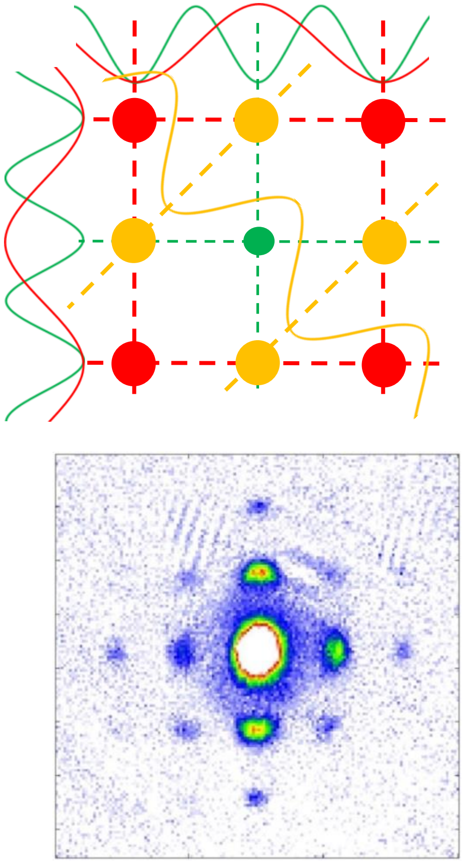
(I) 532 nm square lattice (V_{532})



(I) + (II) 532 nm diagonal lattice (V_{diag})



(I)+ (II) + (III)1064 nm square lattice (V_{1064})



Ultracold Atoms in a Flat Band

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

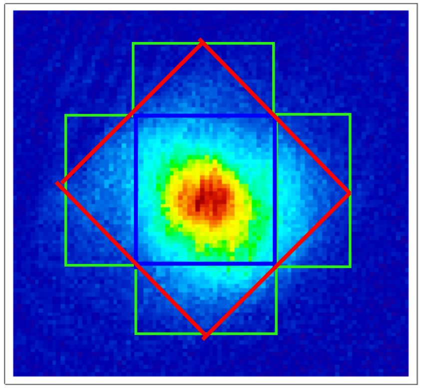
flat band: **|B⟩ − |C⟩ (q=0)**

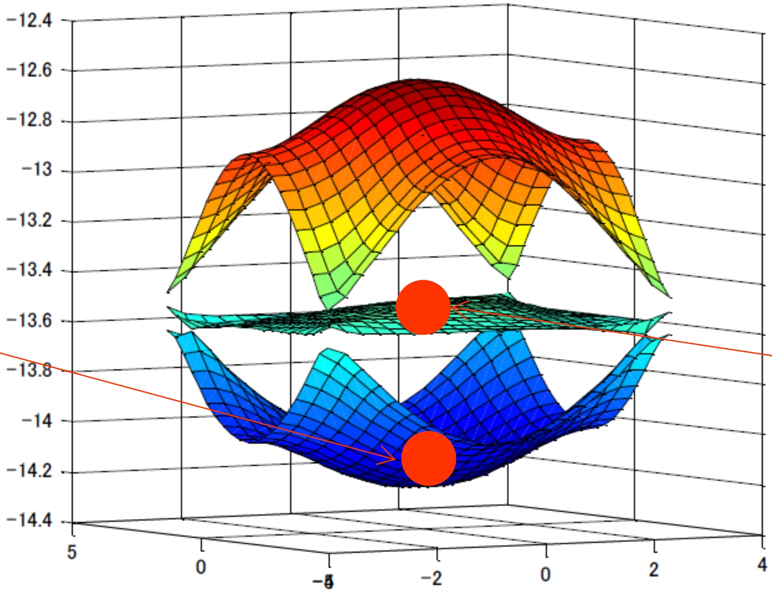
$$|\boldsymbol{q}, X\rangle = \frac{1}{\sqrt{N}} \sum_{i\in X} e^{i\boldsymbol{q}\cdot\boldsymbol{x}_i} c_i^\dagger |0\rangle$$

X=A, B, C

initially

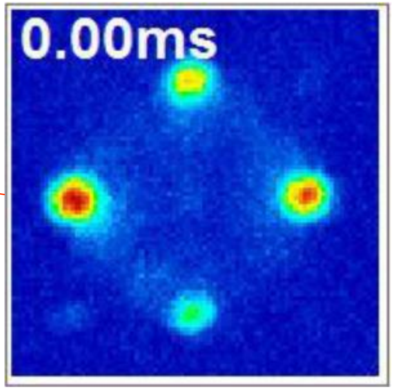
|B⟩ + |C⟩ (q=0)

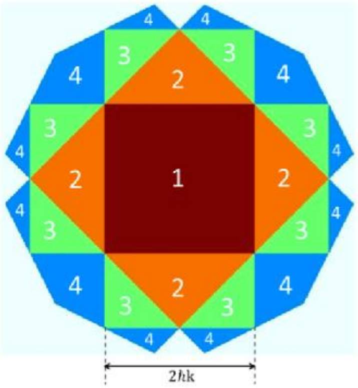




after Phase Imprinting

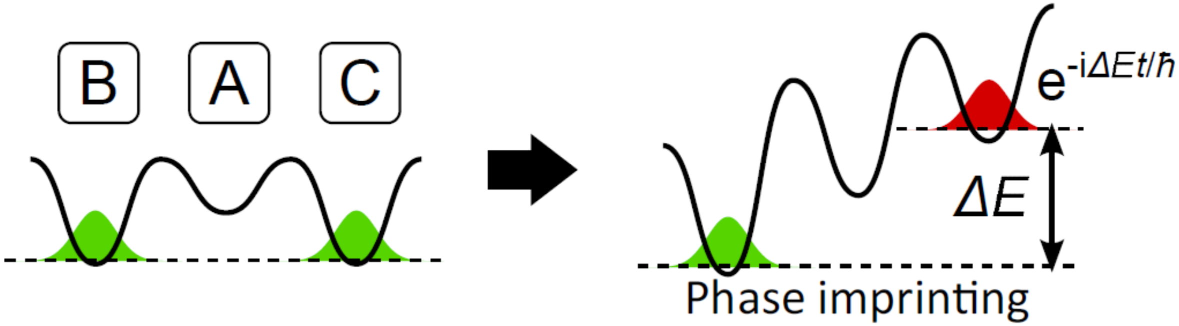
|B⟩ − |C⟩ (q=0)





Brillouin Zones

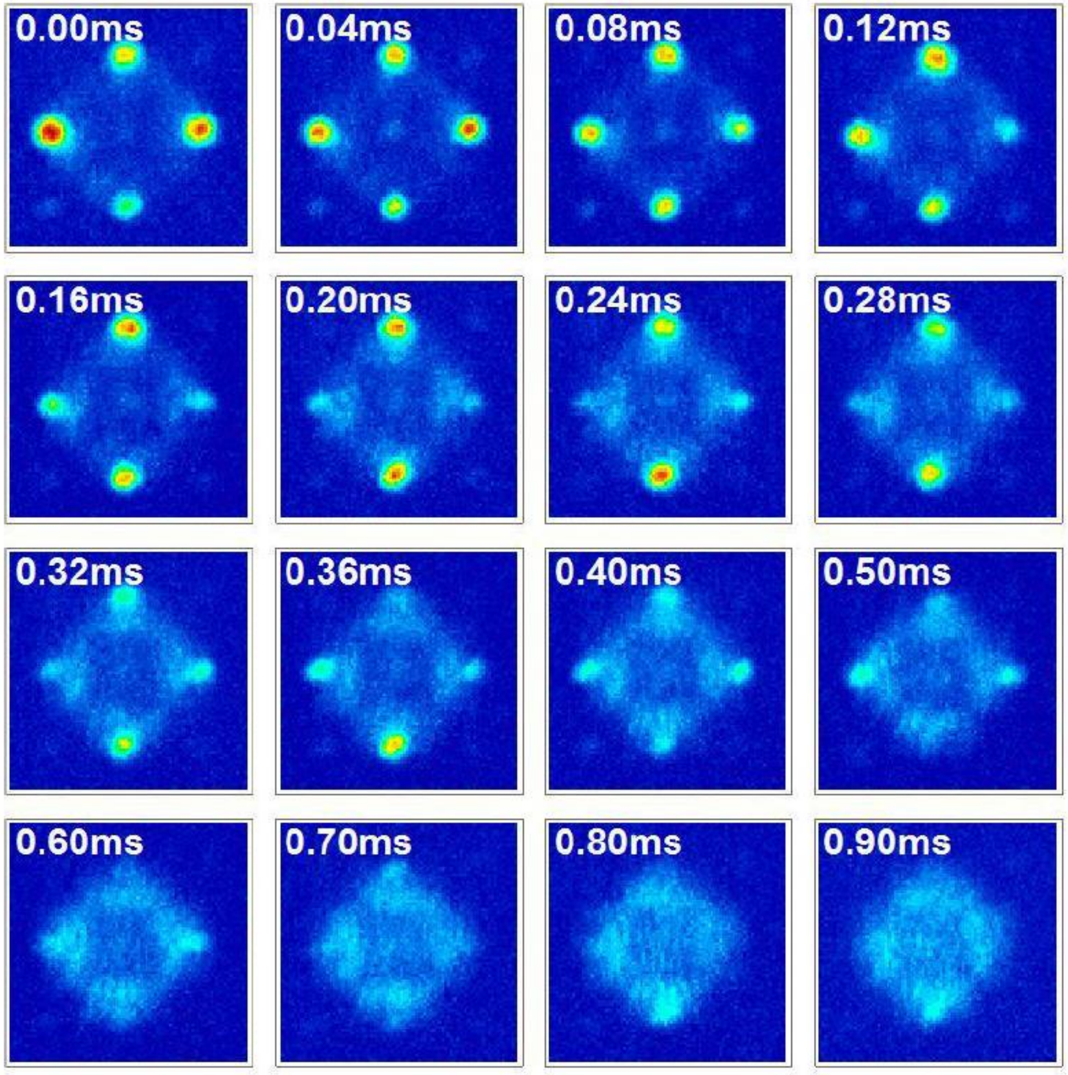
"Phase Imprinting Method"

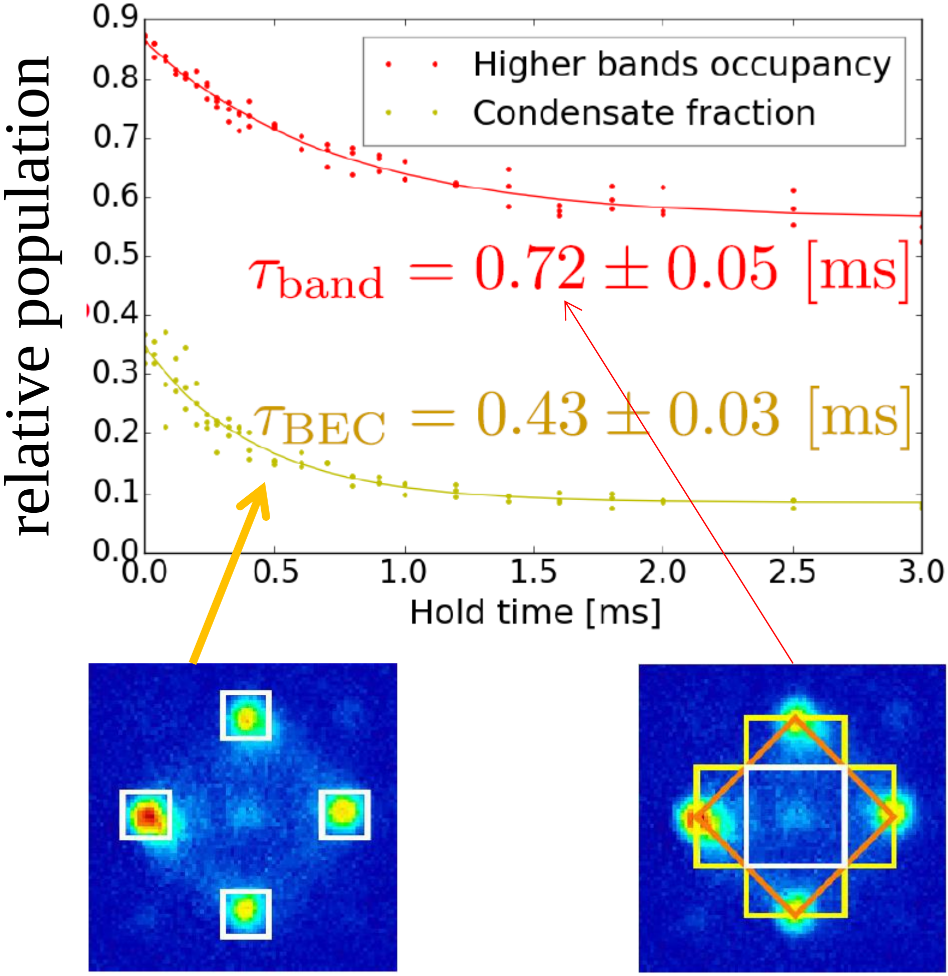


Ultracold Atoms in a Flat Band

“Non-equilibrium Dynamics after Loading into Flat Band”

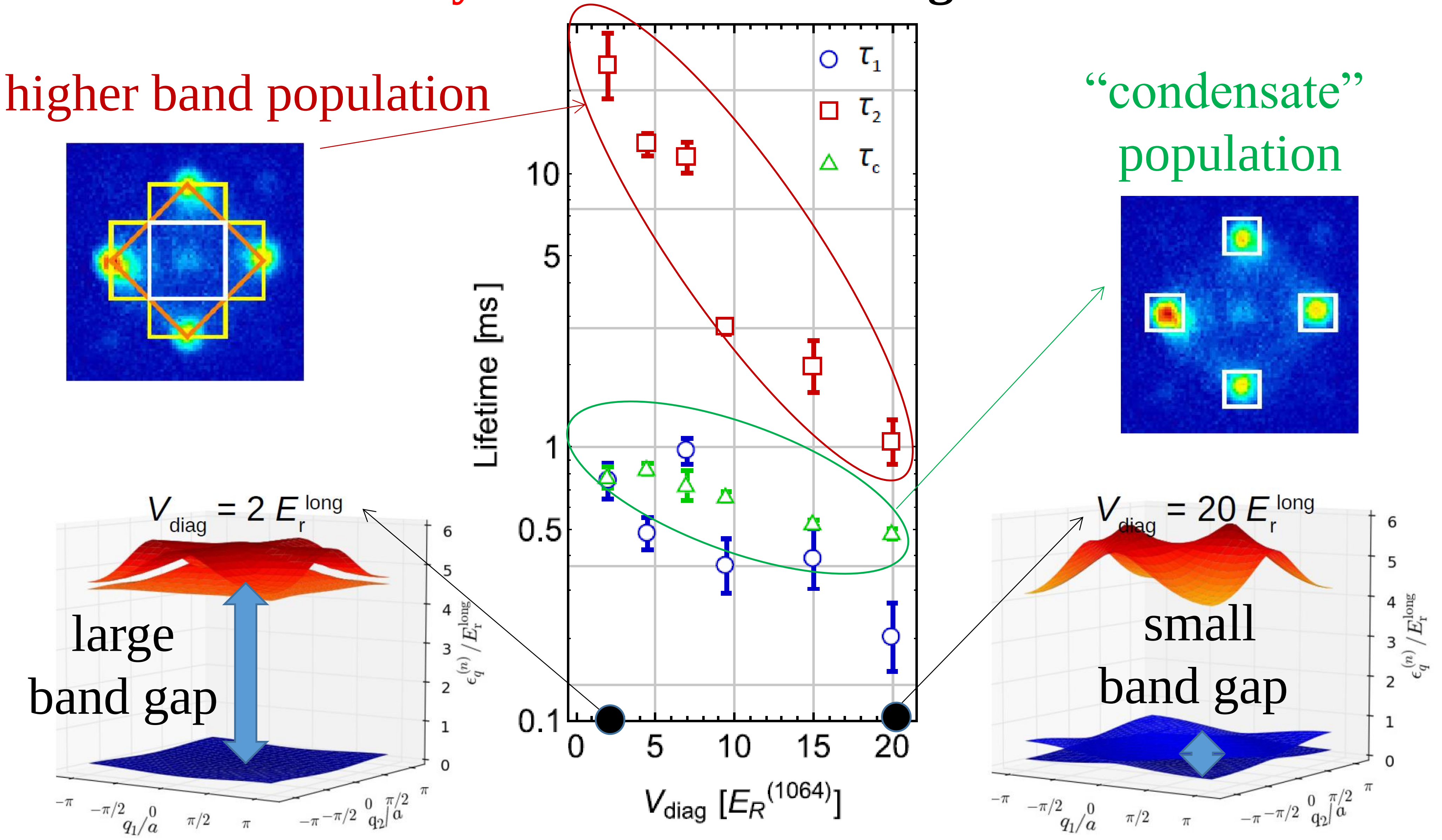
Hold time “quasi-momentum distribution”





Ultracold Atoms in a Flat Band

“Relaxation Dynamics after Loading into Flat Band”



higher band population

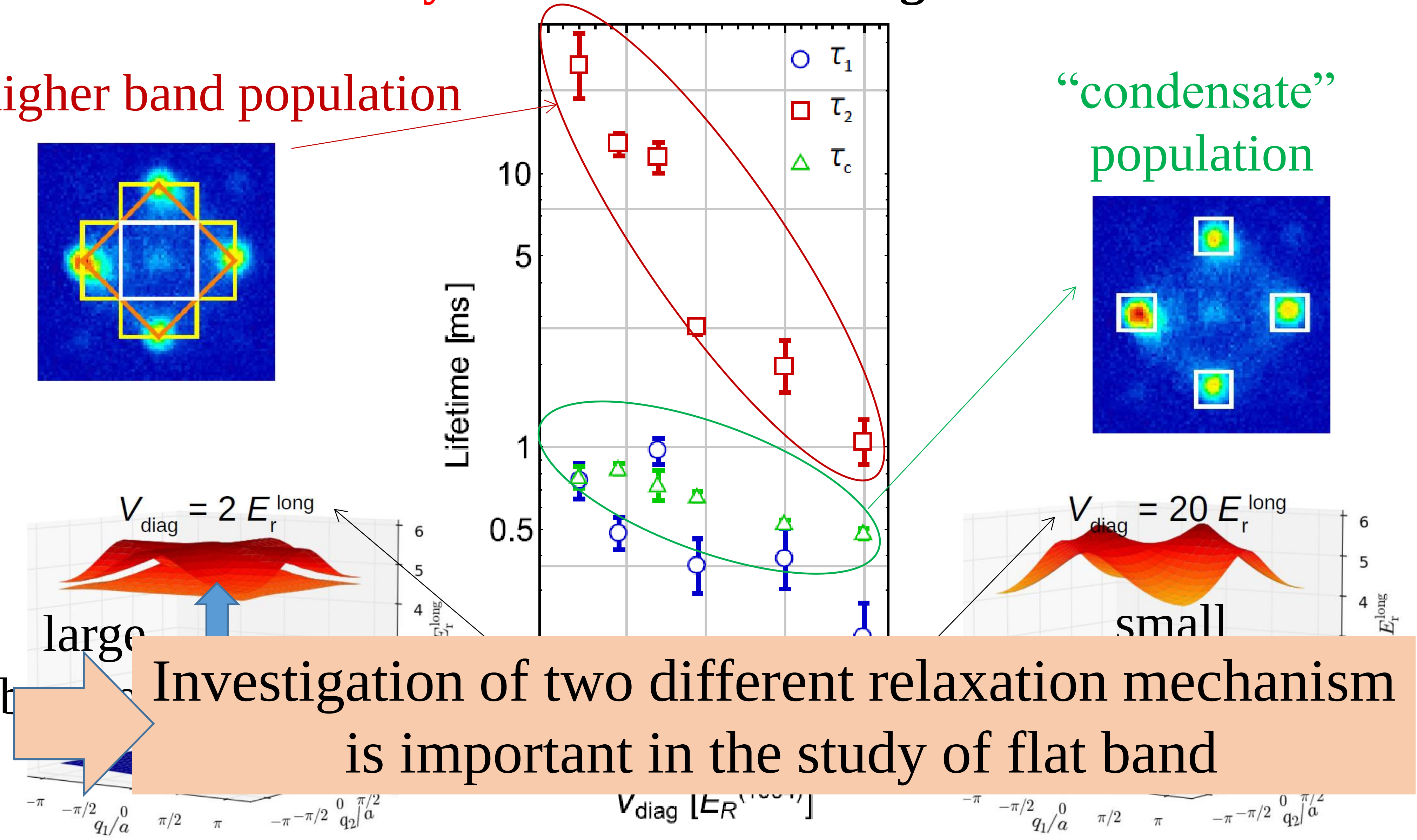
“condensate” population

large band gap

small band gap

Ultracold Atoms in a Flat Band

“Relaxation Dynamics after Loading into Flat Band”



higher band population

“condensate” population

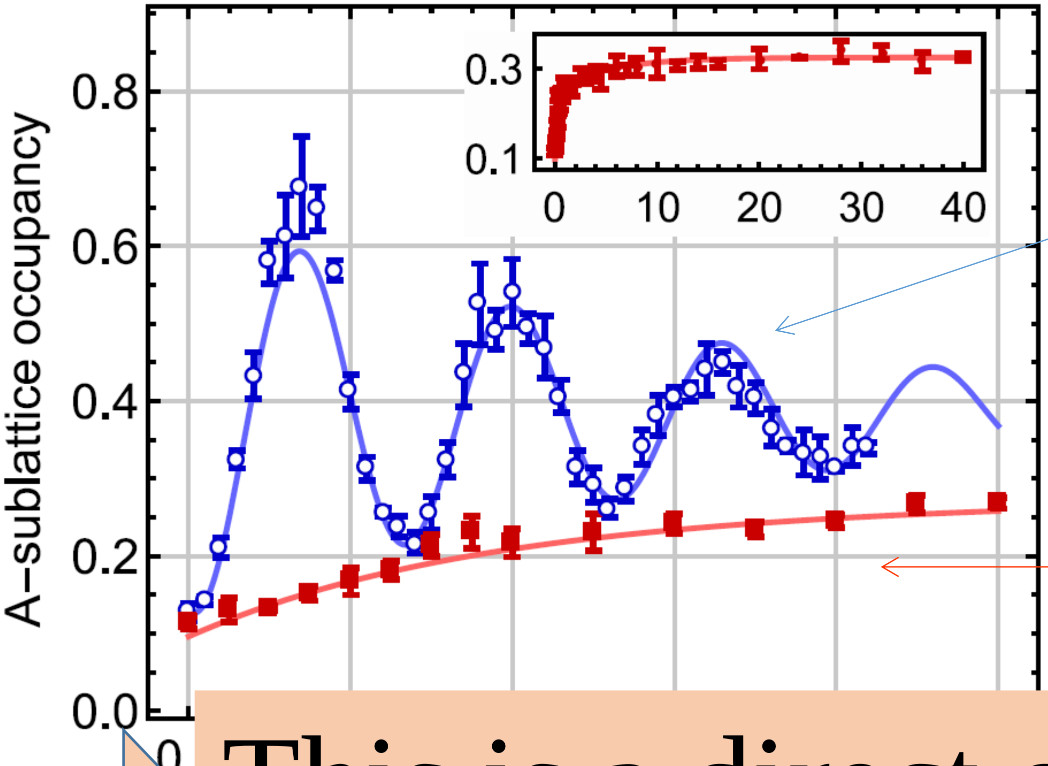
large

small

Investigation of two different relaxation mechanism is important in the study of flat band

Ultracold Atoms in a Flat Band

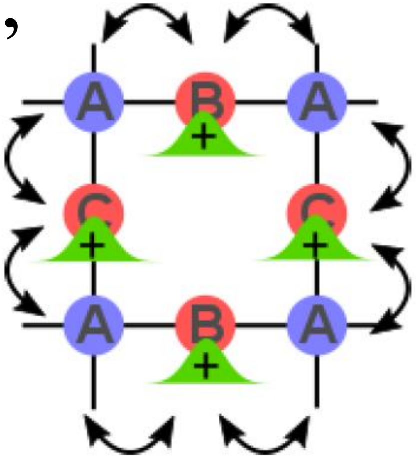
We could observe **Unique Dynamics** in
Flat band by measuring A-site population.



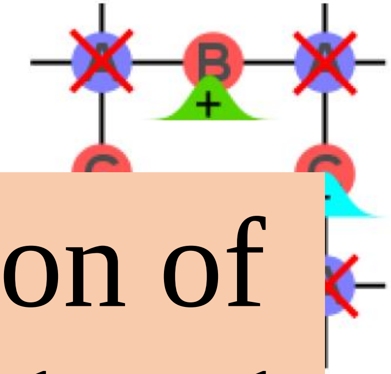
“Usual band”

|B⟩ + |C⟩

(q=0)



“Flat band”



This is a direct confirmation of
“localized state” in a flat band

Group Members

Summary

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Thank you very much for attention

16 August   Mount Daimonji at Kyoto