Strongly Correlated "Materials" made out of Ultra Cold Atoms

Tin-Lun Ho

The Ohio State University

PSM2010
Yokohama, Japan, March 11, 2010

Ho and Zhou, PNAS 2009
(cooling scheme using band insulator)

Ho and Zhou, Nature physics 2010
(deducing bulk properties from trap data)

Zhou and Ho: universal thermometry (cond-mat/09)

Ho and Zhou: Universal cooling scheme (cond-mat/09)

Ho and Li: Quantum Hall Needles in Synthetic Gauge Fields
(to be published)

Great interests in strongly correlated soon after discovery of BEC

Systems being studied in various labs at present :

Strongly Interacting Fermi (and Bose) gases

Low D quantum Gases, disordered quantum gases

Bosonic Quantum Hall states

Optical Lattice Emulator

Expt: Munich, MIT, Rice, ETH, NIST, UIUC, Penn State

Spin-1 Boson singlet

ENS, Paris

Diploar gases

Quantum Simulation:
Most ambitious project in cold atoms ever

* To find solutions to unsolved problems/models

* As a calibration for theories.

Main Challenge in QS

Ultra low T

Very low S/N

Very small energy scales in this regime

$10^{-12} - 10^{-14} K$

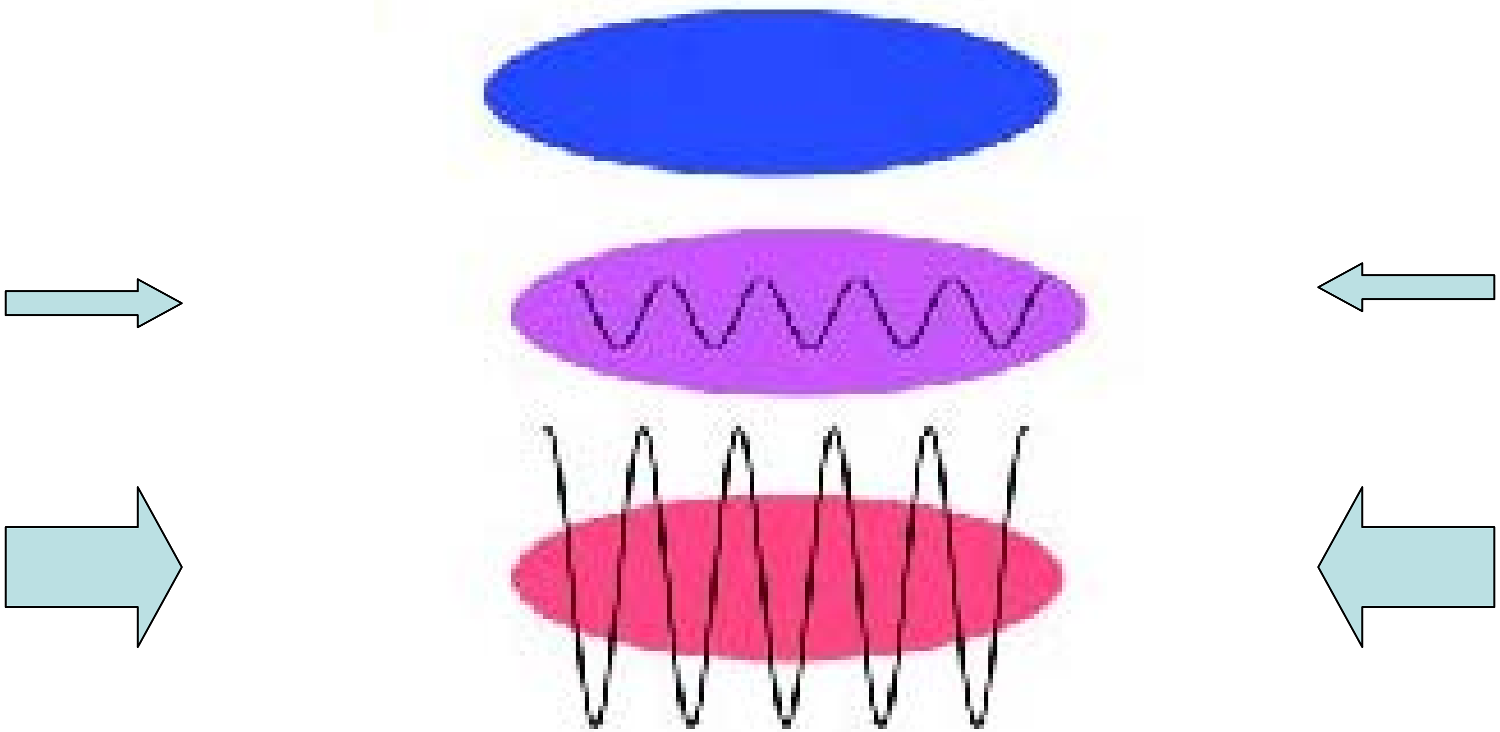
How to obtain information of bulk systems from Data of trapped gases ?

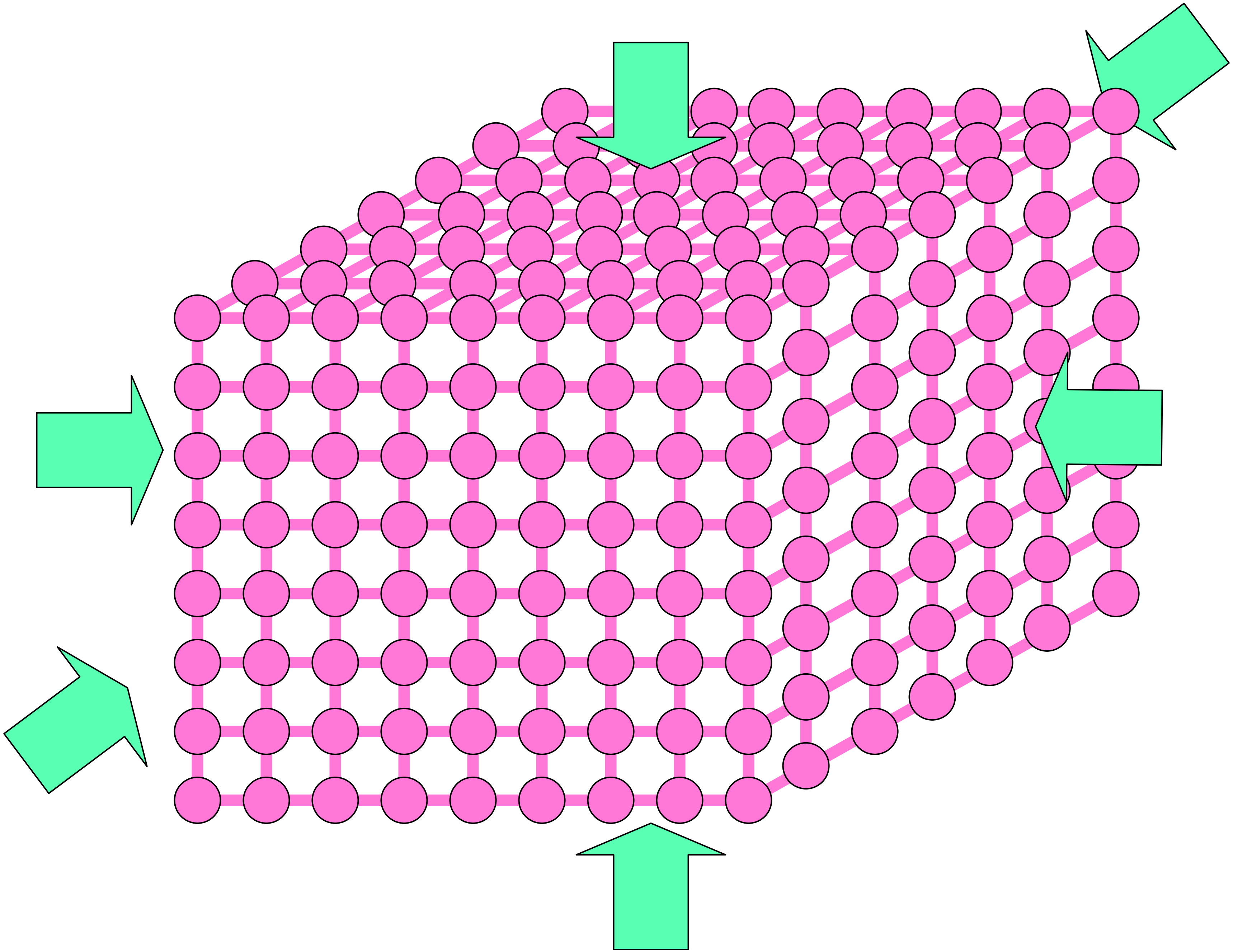
→ Quantum Many-body precision measurement

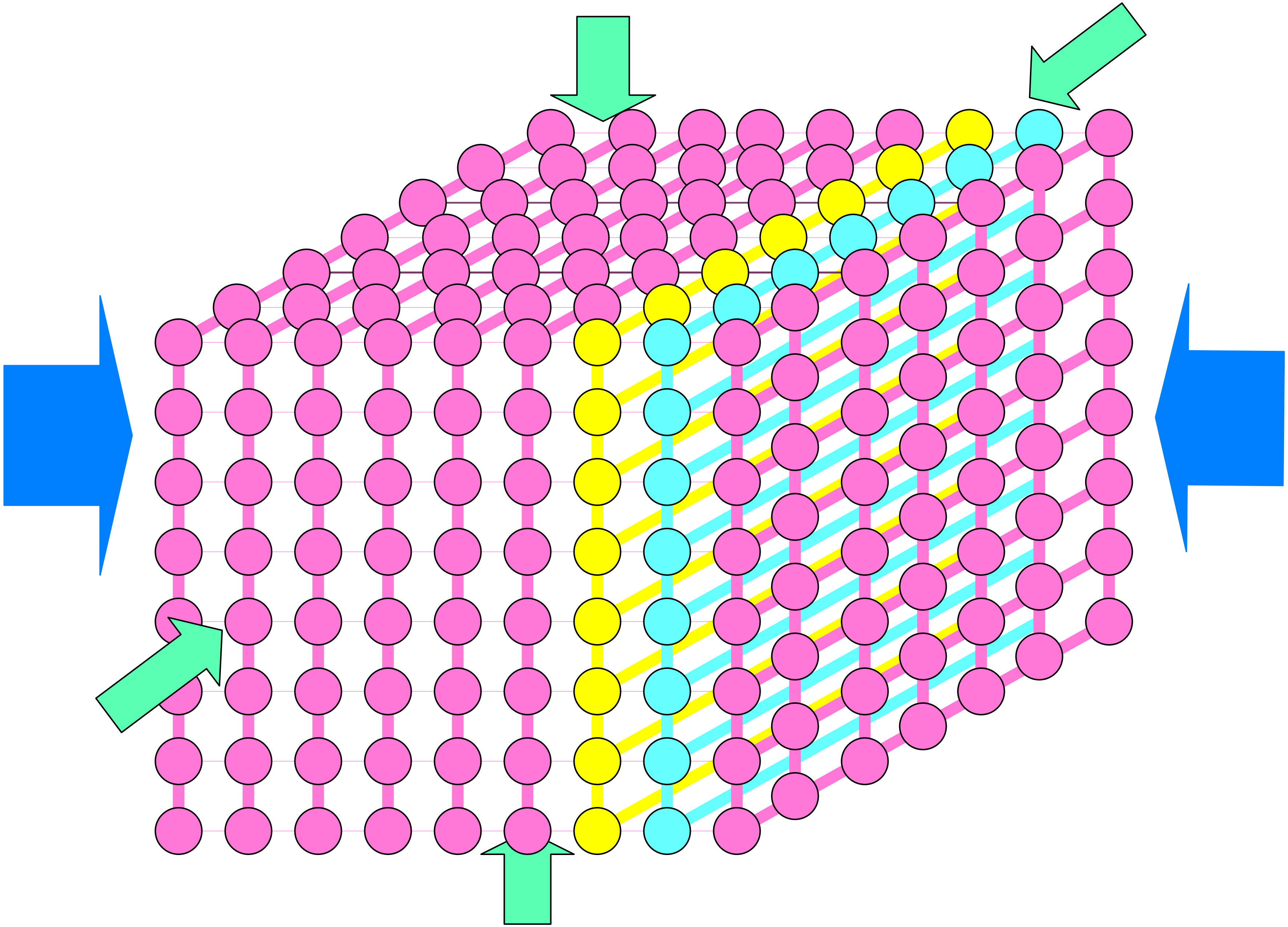
Part I: Quantum Simulation via Optical Lattice Emulator

Optical lattice

Produced by a pair of counter propagating laser







Observation of Superfluid-insulator transition

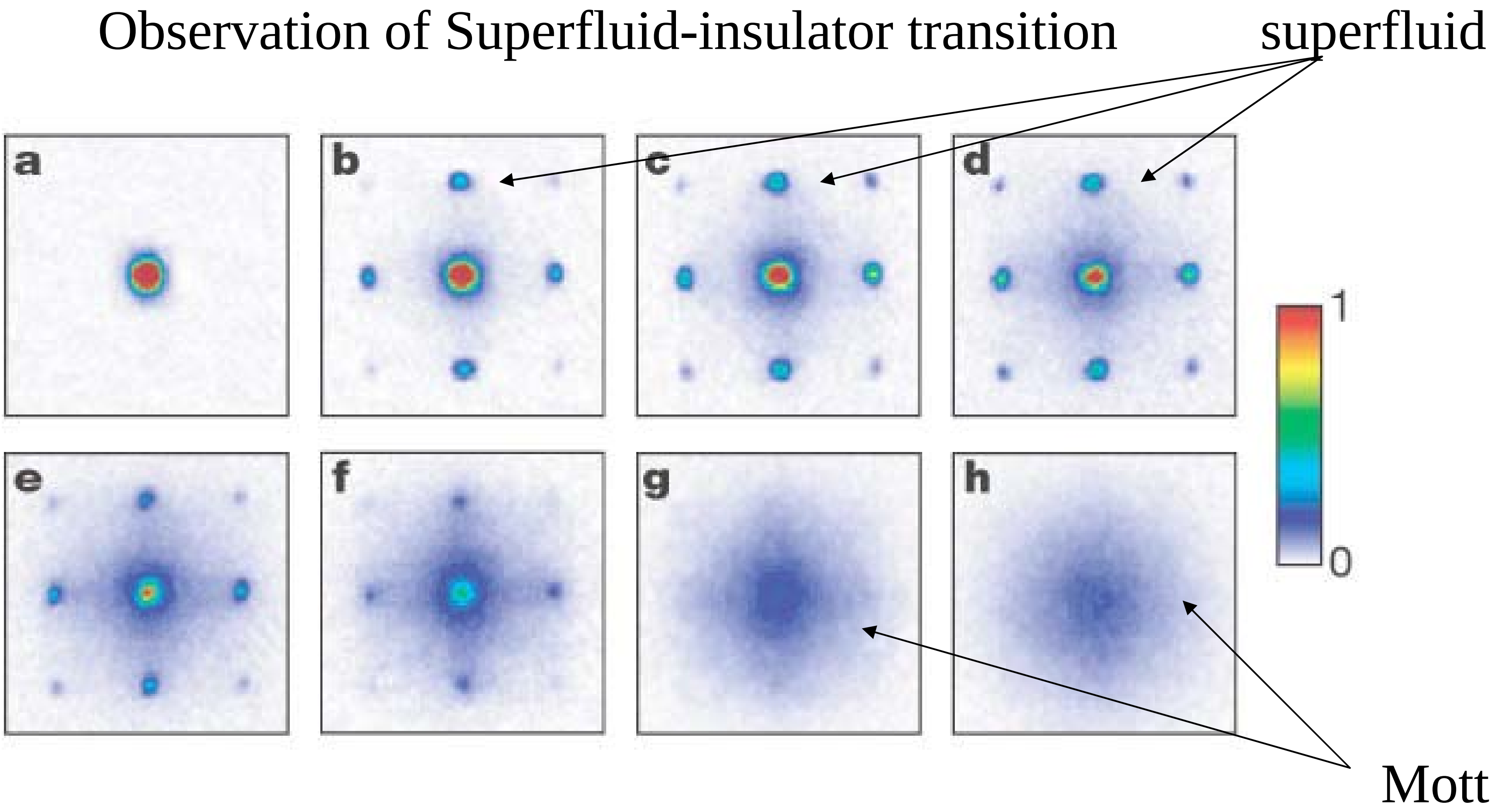
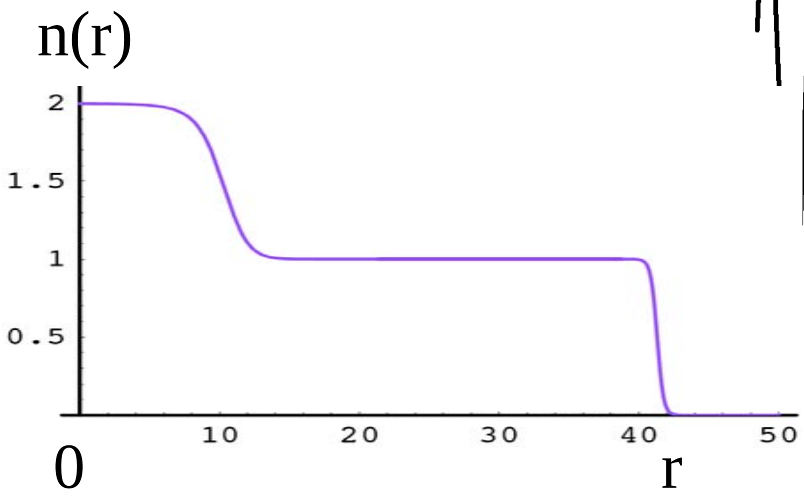
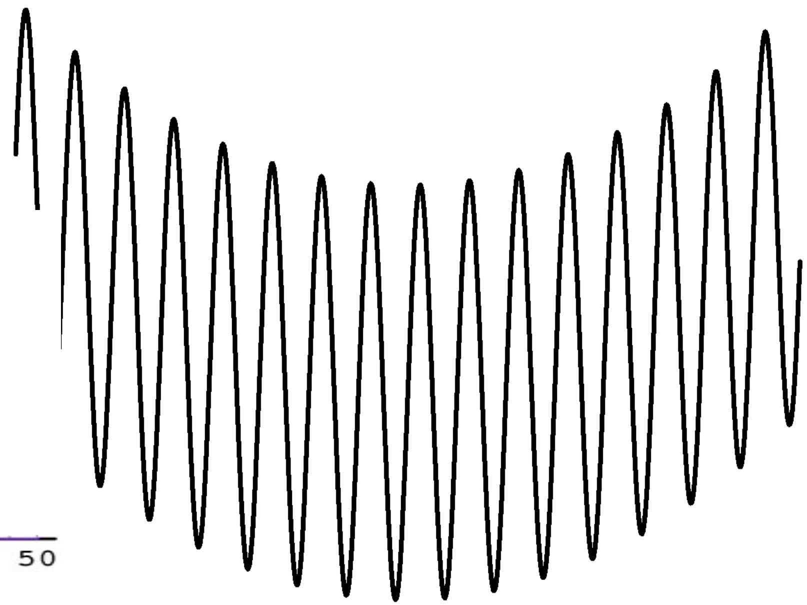


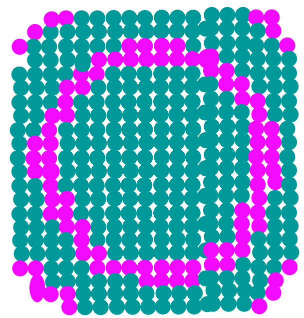
Figure 2 Absorption images of multiple matter wave interference patterns. These were obtained after suddenly releasing the atoms from an optical lattice potential with different potential depths V_0 after a time of flight of 15 ms. Values of V_0 were: **a**, 0 E_r; **b**, 3 E_r; **c**, 7 E_r; **d**, 10 E_r; **e**, 13 E_r; **f**, 14 E_r; **g**, 16 E_r; and **h**, 20 E_r.

M. Greiner et.al, Nature 415, 39 (2002)
M. Greiner, O. Mandel. Theodor, W. Hansch & I. Bloch,Nature (2002)

Typical density profile in an optical lattice :
Wedding cake structure

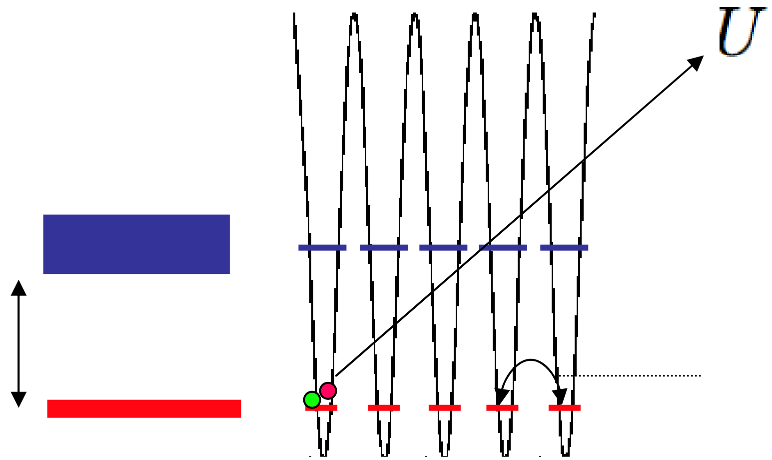






Relevant energy scales:

Band gap E_G



Hopping

Virtual hopping

$$E_G >> U >> t >> t^2/U$$

Strong correlation!

$$H = -t \sum_{\mathbf{R},\mathbf{R}'} a^\dagger_{\mathbf{R}} a_{\mathbf{R}'} + U \sum_{\mathbf{R}} n_{\mathbf{R}}(n_{\mathbf{R}} - 1)/2$$

Boson

$$H = -t \sum_{\langle \mathbf{R},\mathbf{R}' \rangle,\sigma} c^\dagger_{\mathbf{R}\sigma} c_{\mathbf{R}'\sigma} + U \sum_{\mathbf{R}} n_{\mathbf{R}\uparrow} n_{\mathbf{R}\downarrow}$$

Fermion

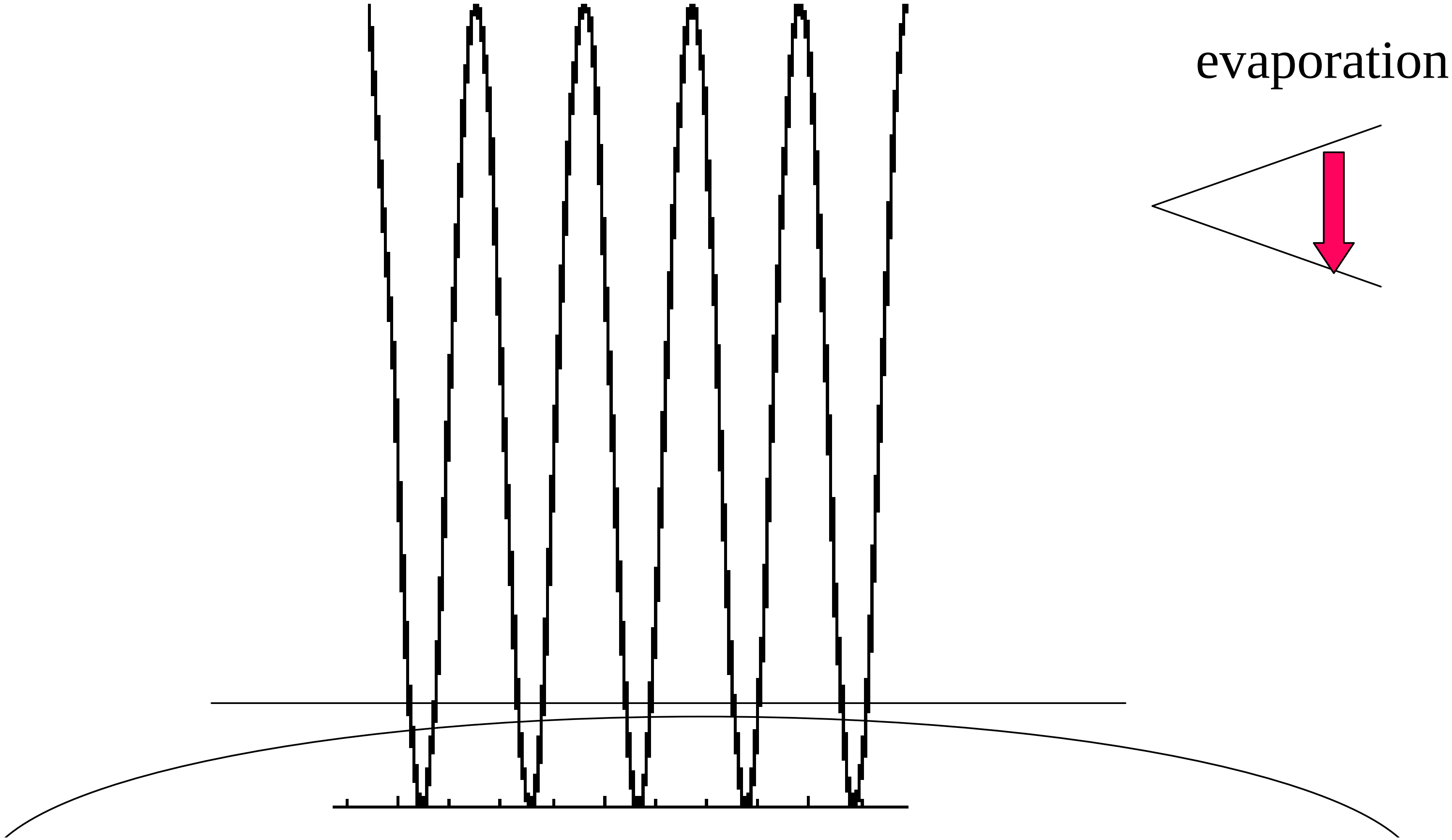
^{87}Rb $a_s = 5.45nm$ and $d = 425nm$

V_o/E_R	3	5	10	15	20
E_G (nK)	90	294	678	956	1171
U (nK)	15.5	24.2	44.6	63.7	82.0
t (nK)	17.9	10.4	3.01	1.03	0.39
t^2/U (nK)	20.66	4.45	0.20	0.0166	0.0019

^{40}K $a_s = 5.55nm$ and $d = 377.5nm$

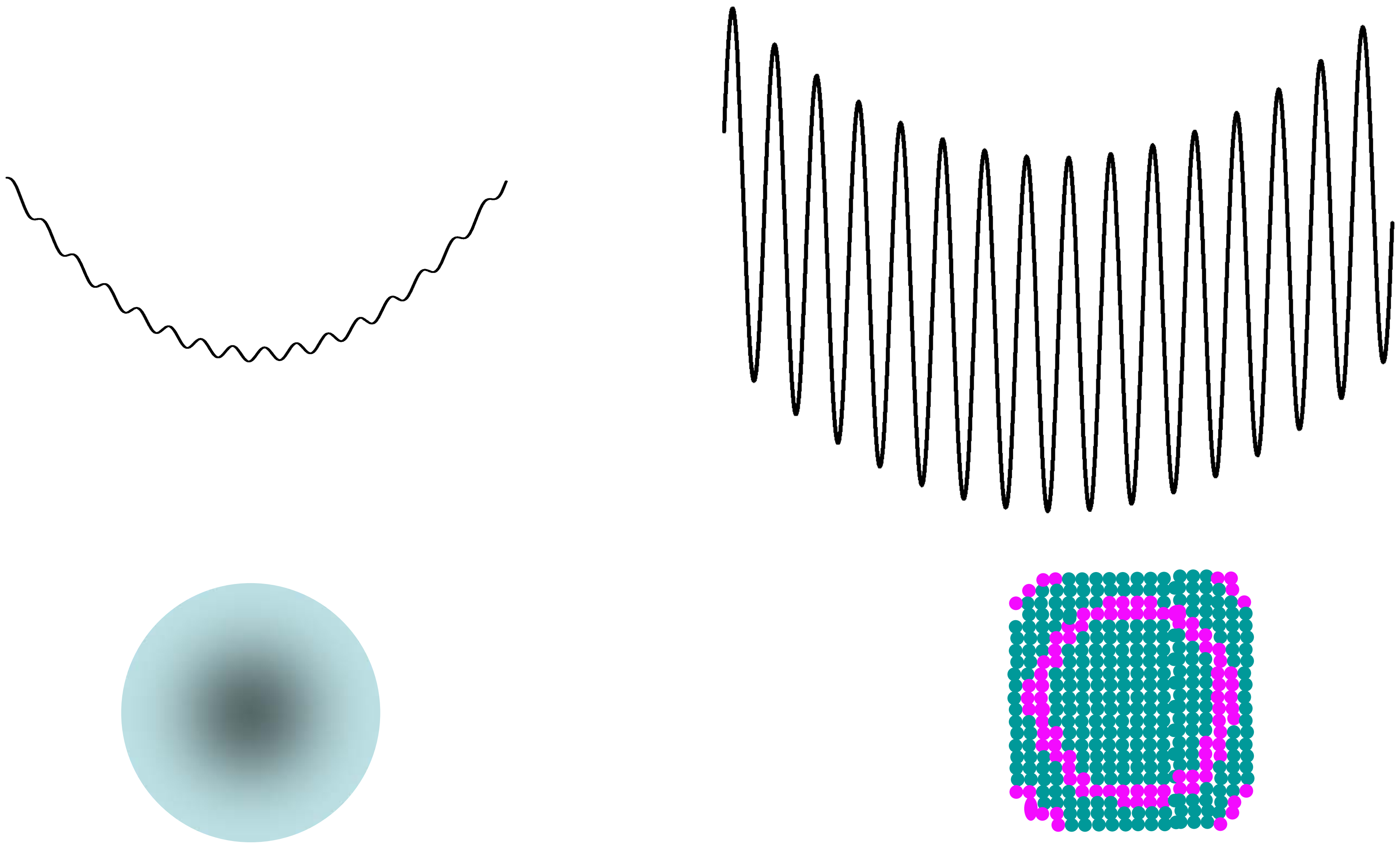
V_o/E_R	3	5	10	15	20
E_G (nK)	114	372	860	1212	1485
U (nK)	22.4	35.2	64.8	92.6	119.2
t (nK)	22.6	13.1	3.81	1.30	0.50
t^2/U (nK)	22.8	4.92	0.225	0.018	0.0021

Source of difficulty
I: Conventional evaporation fails.

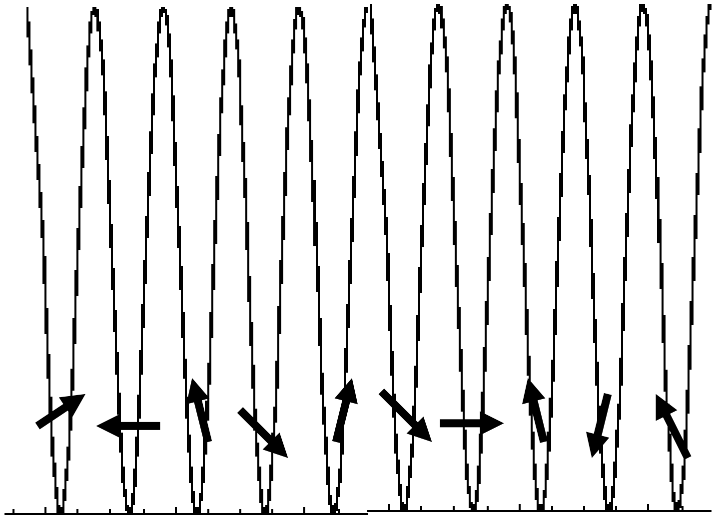


Current methods of achieving strongly correlated states:

Raising the optical lattice in a trapped gas:



Even if evaporation works, there is another difficulty.



Spin disordered Mott insulator

At $T > T_c$, spin is disordered.
Entropy per site is ln2.
This entropy per site can not be changed by evaporation.

In addition, there will be entropy regeneration near the surface.

Much more serious is that the intrinsic heating due to spontaneous emission : $1k_B$ /sec

Part I : To realize the full power of quantum simulation

Bulk thermodynamic properties of interest:

Equation of state $n = n(\mu, T)$ ➔ phase boundary

Entropy density $s = s(\mu, T)$

Superfluid density $\rho_s = \rho_s(\mu, T)$

Compressibility $\kappa_T(\mu, T) = \dfrac{\partial n(\mu, T)}{\partial \mu}$

Spin susceptibility

Staggered magnetization $\tilde{m} = \tilde{m}(\mu, T)$

Simplest example: Equation of state $n = n(\mu, T)$

Local density approximation (LDA) : $Q(\vec{r}) = Q(\mu - V(\vec{r}))$

•LDA is valid for N>50 in typical traps

If LDA works, then the experimental data $n(\vec{r})$ immediately gives $n(\mu, T)$

$$n(\vec{r}) = n(\mu(\vec{r}), T) = n_o(\mu - V(\vec{r}), T)$$

Density of trapped gas   Density of homogenous system

Presence of phase transition: boundary:

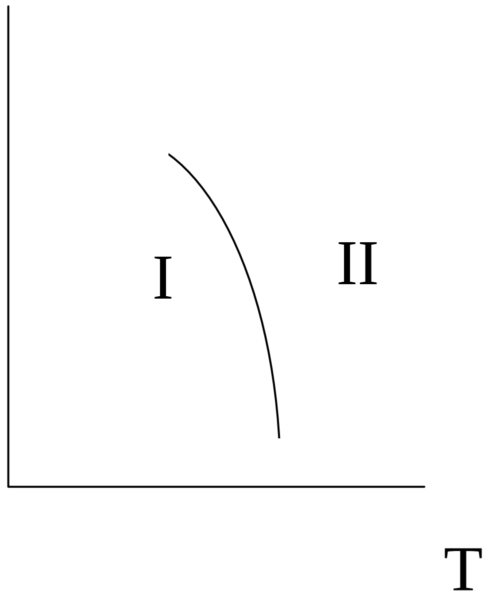
$$P_I(\mu,T) = P_{II}(\mu,T)$$

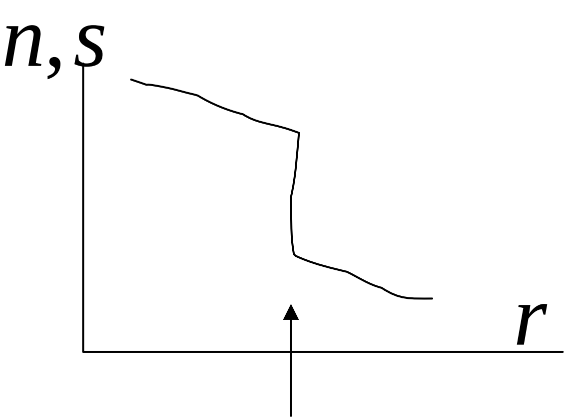
$$dP = n d\mu + s dT$$

First order transition: n , s discontinuous

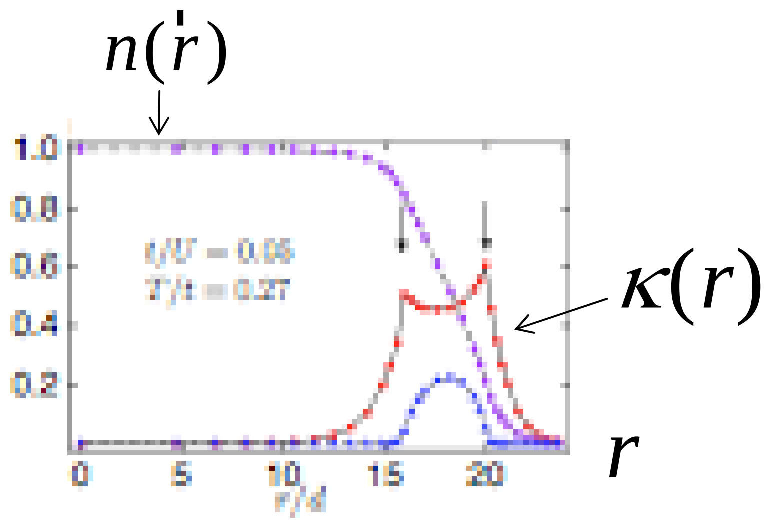
Continuous transition: change of slope in

$$\frac{\partial n}{\partial \mu}, \frac{\partial s}{\partial \mu}$$





1^{st} order



Continuous transitions

Essential step of this procedure :

- high quality density data
- Accurate determination of T and μ

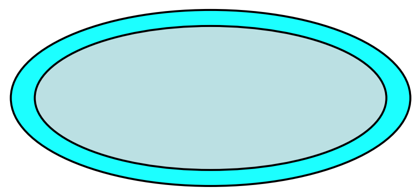
Use the tail of the density or number fluctuation

At the surface, density is low, can do fugacity expansion

$$n(\vec{x}) = \alpha e^{(\mu - V(\vec{x}))/T} / \lambda^3$$

$$\tilde{n}(x,y) = \alpha \left(\frac{T}{\hbar\omega}\right) \frac{e^{(\mu - V(\vec{r}))/T}}{\lambda^2}$$

column density



III. Entropy Density

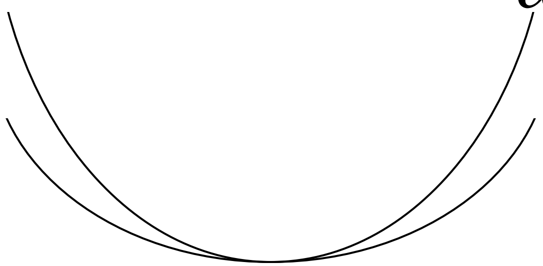
$s = s(\mu, T)$ $\qquad$ $s = s(\vec{r})$

$$s = \left(\frac{\partial P}{\partial T} \right)_{\mu}$$

Need two configurations of different T

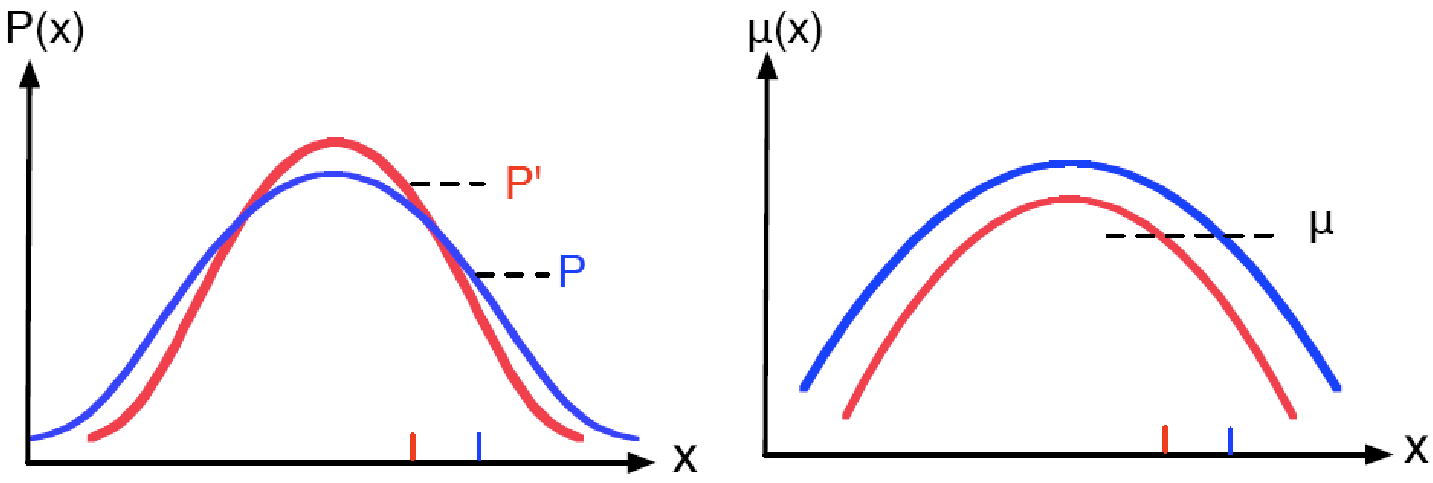
Compare them at the same μ

$$dP = n d\mu + s dT \qquad dP = \int n d\mu$$



$\omega' \longrightarrow T' \quad \mu'$ $\qquad$ $P'(x,0,0) = P(\mu'(x), T')$

$\omega \longrightarrow T \quad \mu$ $\qquad$ $P(x,0,0) = P(\mu(x), T)$



$$s(x,0,0)=\frac{P'(x',0,0)-P(x,0,0)}{T'-T}$$

$$\mu'(x')=\mu(x)$$

$$\mu(x)\equiv\mu-\frac{1}{2}M\omega^2x^2=\mu'-\frac{1}{2}M\omega'^2x'^2\equiv\mu'(x')$$

Superfluid density: n_s

For a superfluid $P = P(T, \mu_o, \vec{w})$ $\vec{w} = \vec{v}_s - \vec{v}_n$

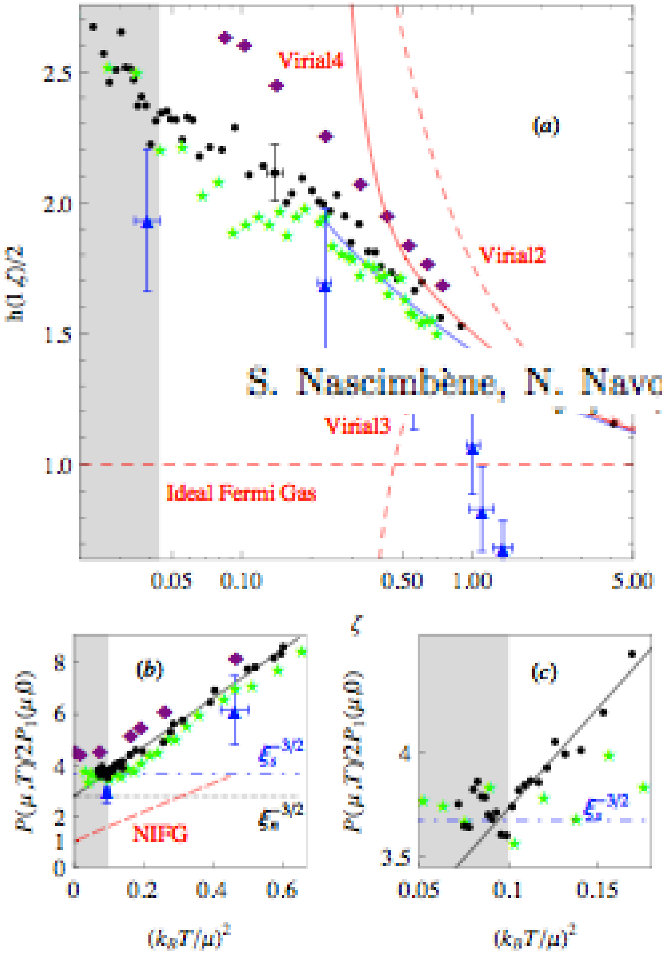
$$dP = n d\mu_o + s dT - M n_s \vec{w} \cdot d\vec{w}$$ $$\vec{v}_n = \Omega \hat{z} \times \vec{x}$$

$$\left(\frac{\partial n}{\partial w^2}\right)_{\mu_o, T} = -\frac{M}{2}\left(\frac{\partial n_s}{\partial \mu_o}\right)_{w^2, T}$$

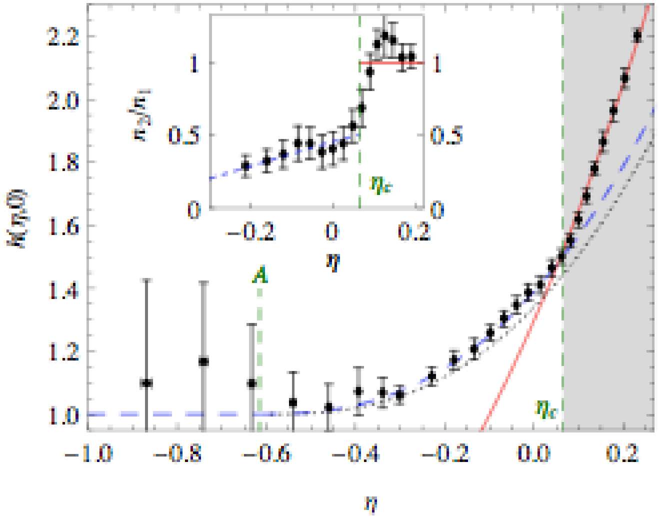
Spatial changes in n_s ←→ changes in n with respect to rotation

Exploring the thermodynamics of a universal Fermi gas
S. Nascimbene, N. Navon, K. Jiang, F. Chevy, C. Salomon
arXiv: 0911.0747

3D Fermi gas (infinite Scattering length)



Apply the algorithm of Ho and Zhou



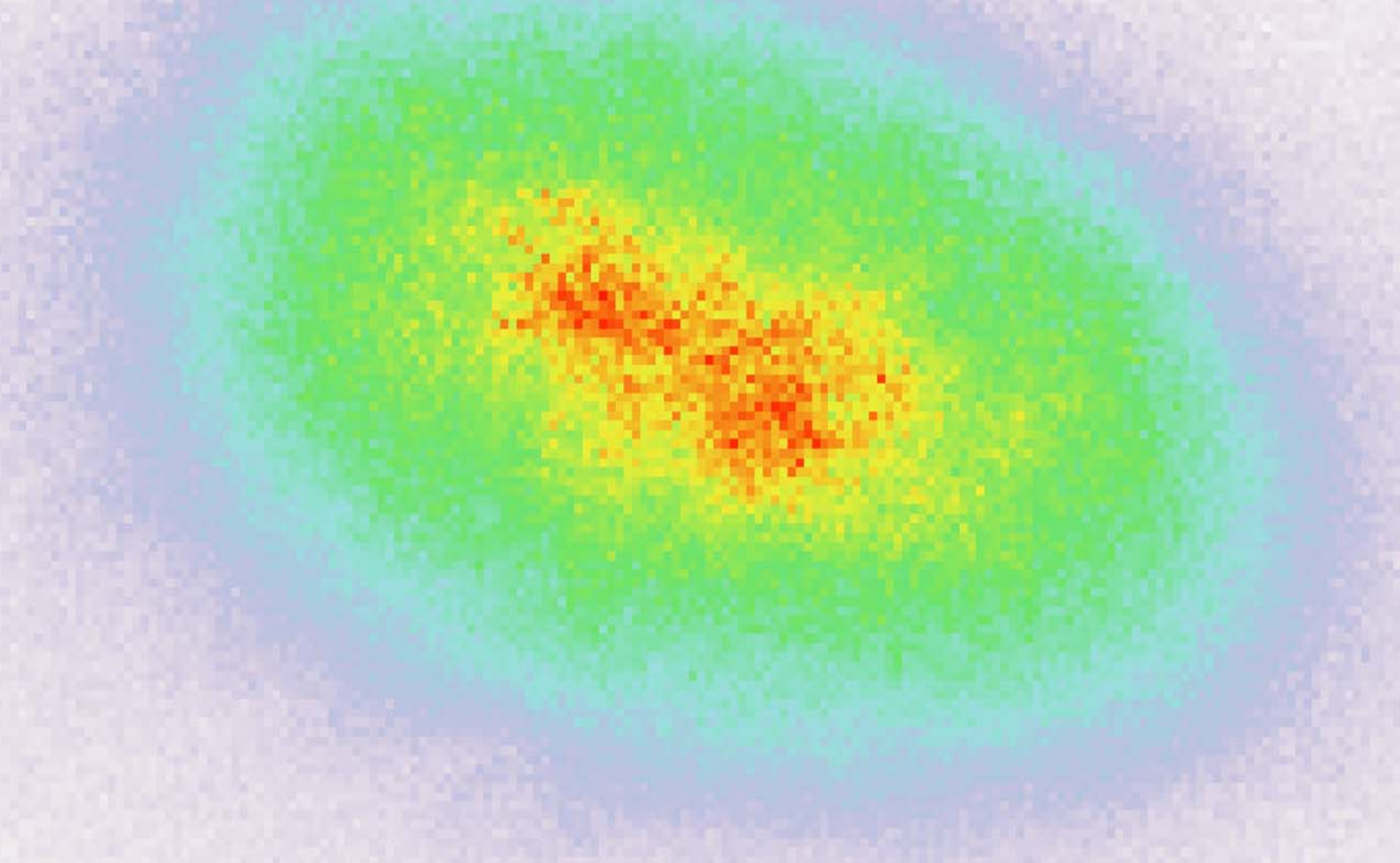
Measurement of Universal Thermodynamic Functions for a Unitary Fermi Gas,
Munekazu Horikoshi,1* Shuta Nakajima,2 Masahito Ueda,1,2 Takashi Mukaiyama1,3

Science, 442, vol 327, (2010)

In-situ Observation of Incompressible Mott-Insulating Domains of Ultracold Atomic Gases

Nathan Gemelke, Xibo Zhang, Chen-Lung Hung, and Cheng Chin

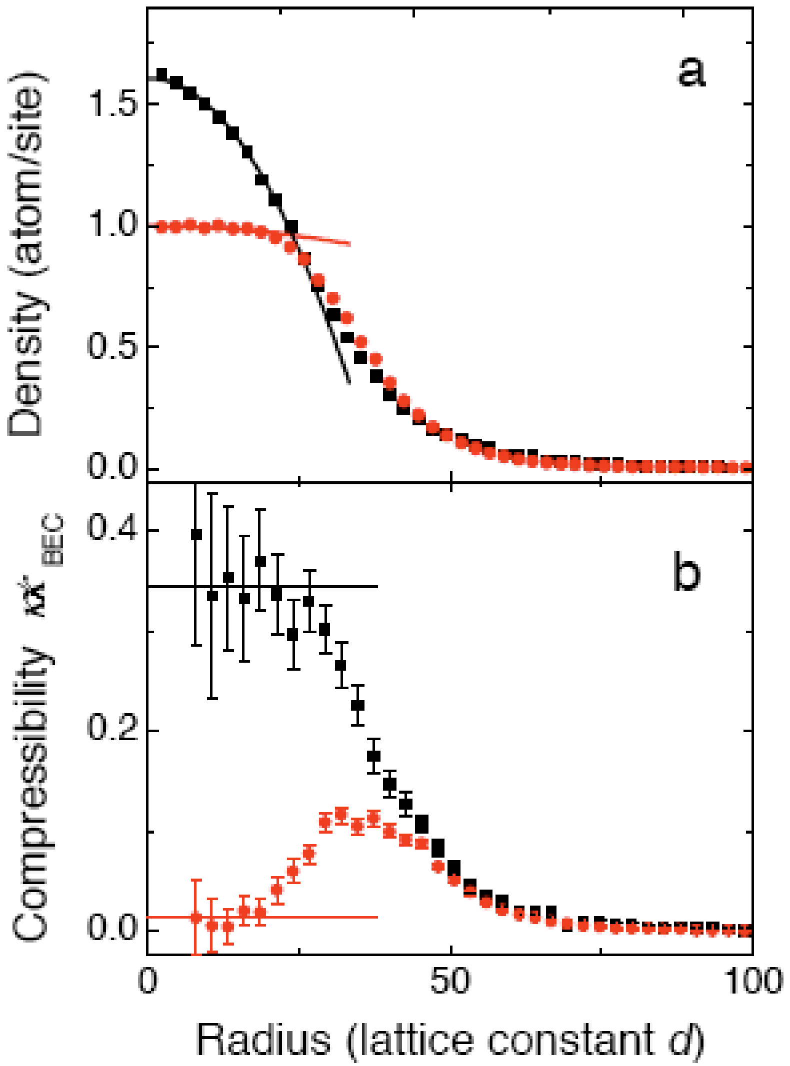
Nature 460, 995 (2009)

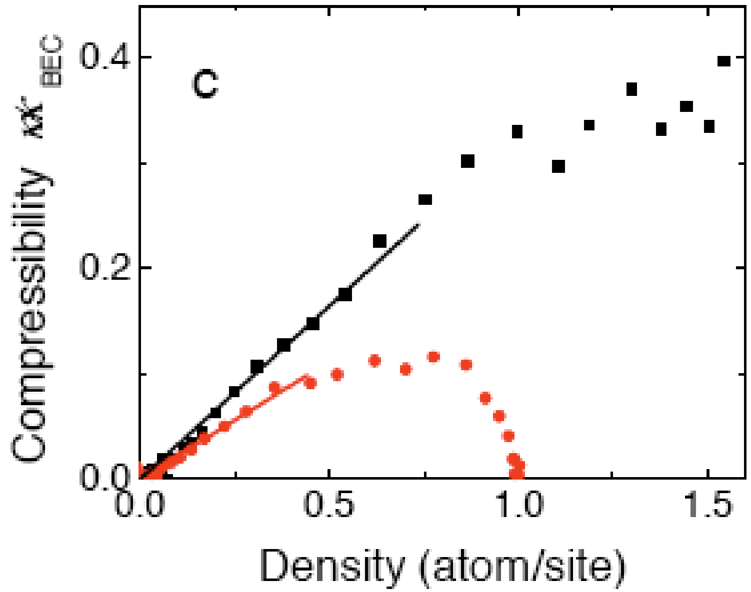


Advantage of Cs in 2D lattice : low lattice depth, large lattice constant

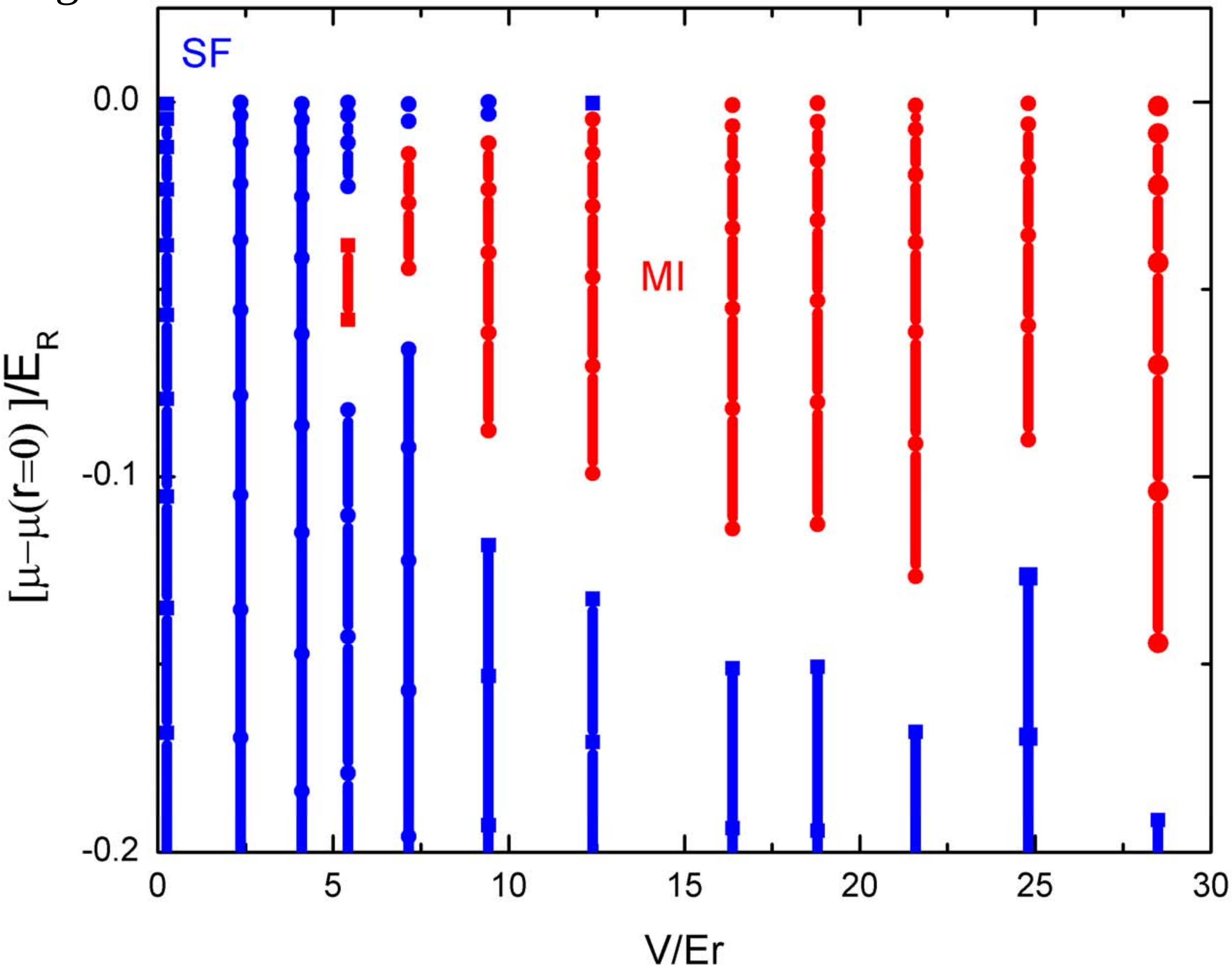
Estimate of T based on number fluctuation, and Determination of phase diagram

$$T\frac{\partial N}{\partial \mu} = \langle N^2 \rangle - \langle N \rangle^2$$

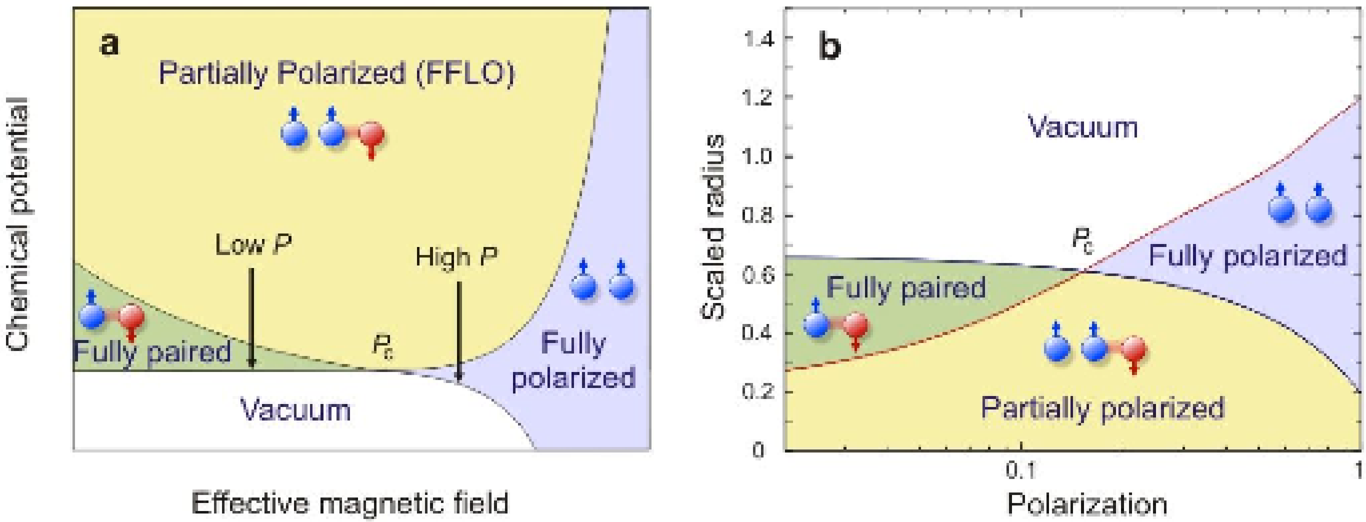


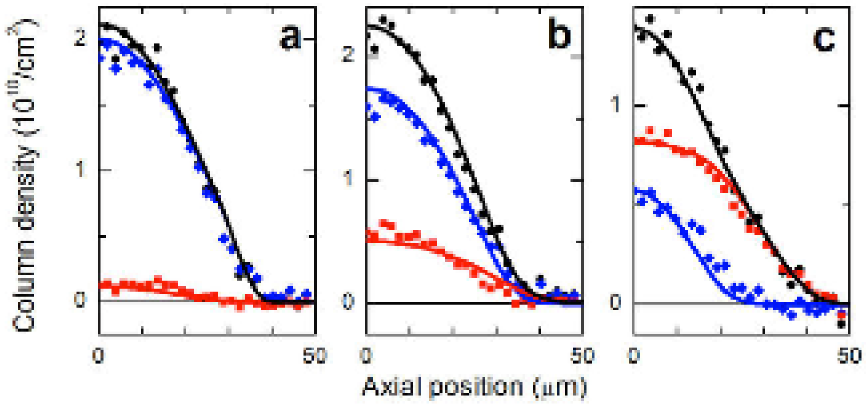


Cheng Chin et.al



Spin-Imbalance in a One-Dimensional Fermi Gas,
Yean-an Liao, Ann Sophie C. Rittner, Tobias Paprotta, Wenhui Li, Guthrie B. Partridge, Randall G. Hulet, Stefan K. Baur & Erich J. Mueller   arXiv.0912.0092

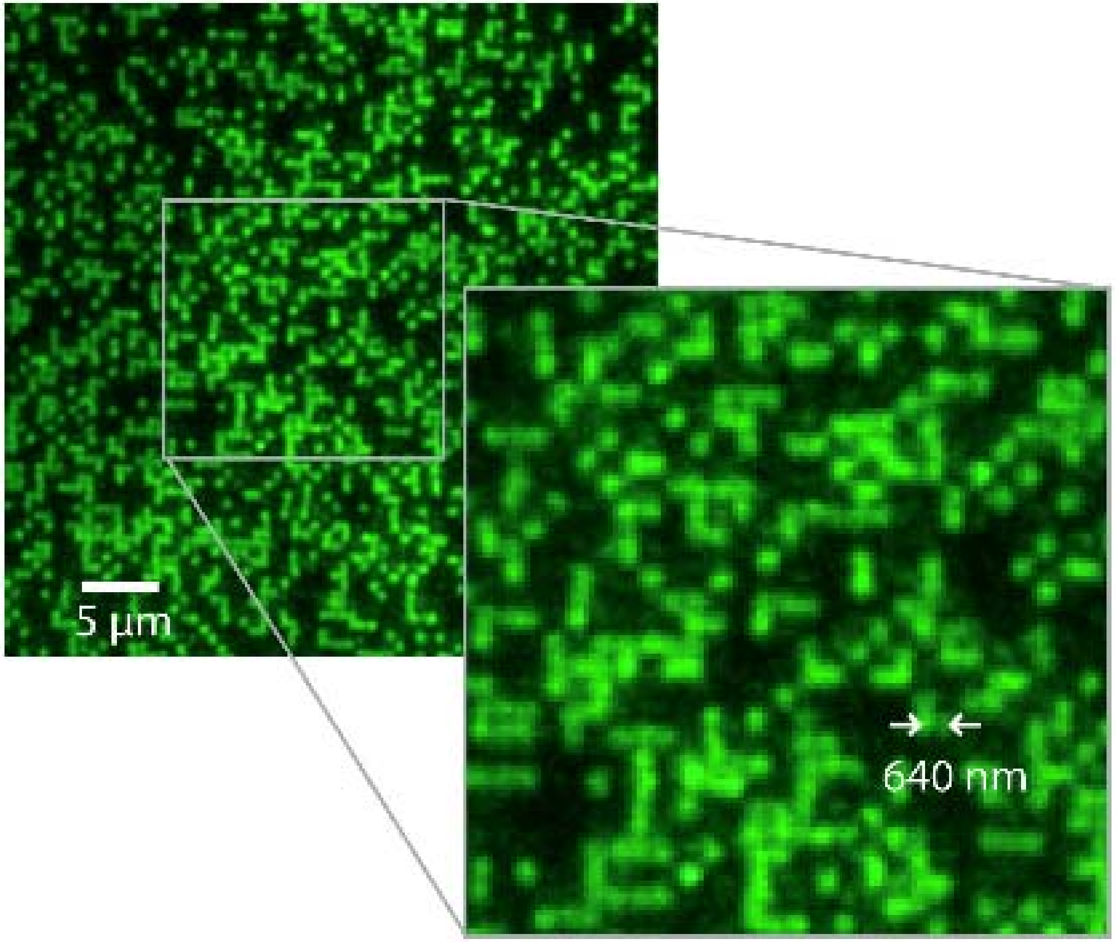




A quantum gas microscope – detecting single atoms in a Hubbard regime optical lattice

arXiv: 0908.0174

Waseem S. Bakr, Jonathon I. Gillen, Amy Peng, Simon Fölling, Markus Greiner



High-resolution scanning electron microscopy of an ultracold quantum gas

TATJANA GERICKE, PETER WÜRTZ, DANIEL REITZ, TIM LANGEN AND HERWIG OTT*
Institut für Physik, Johannes Gutenberg-Universität, 55099 Mainz, Germany

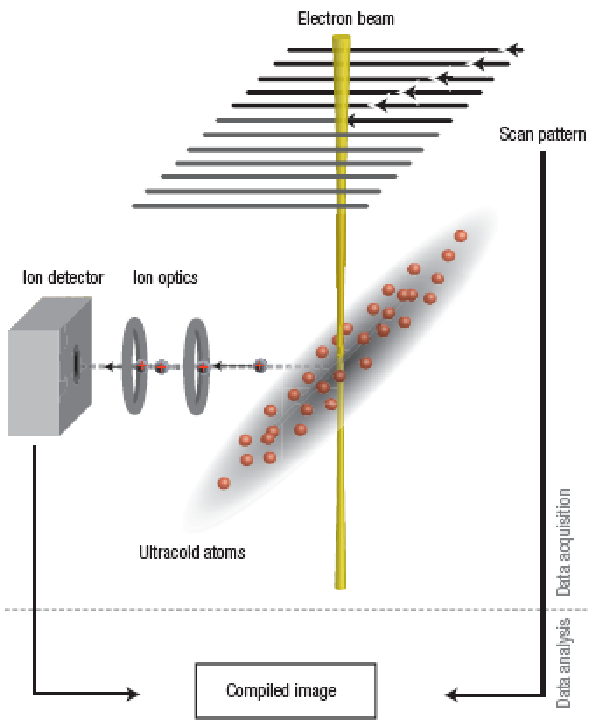
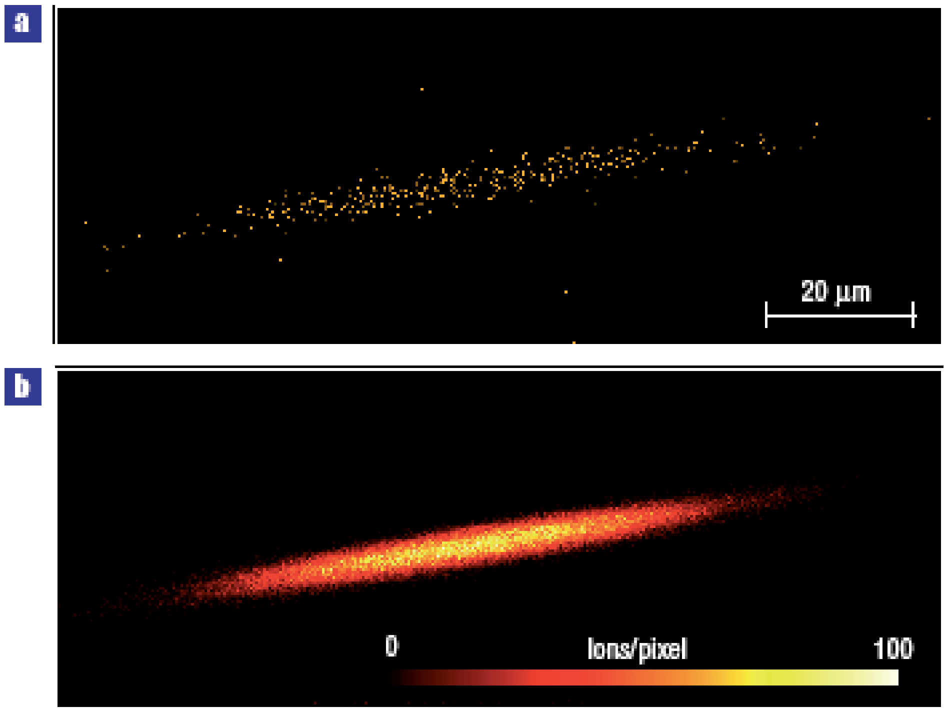
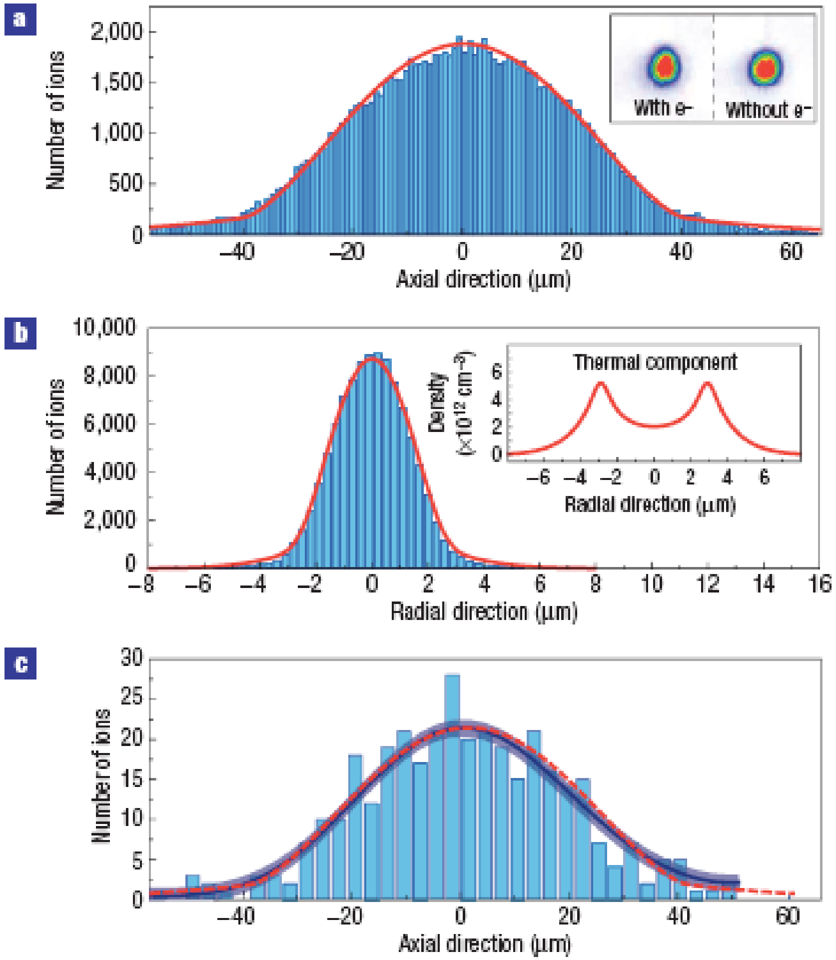
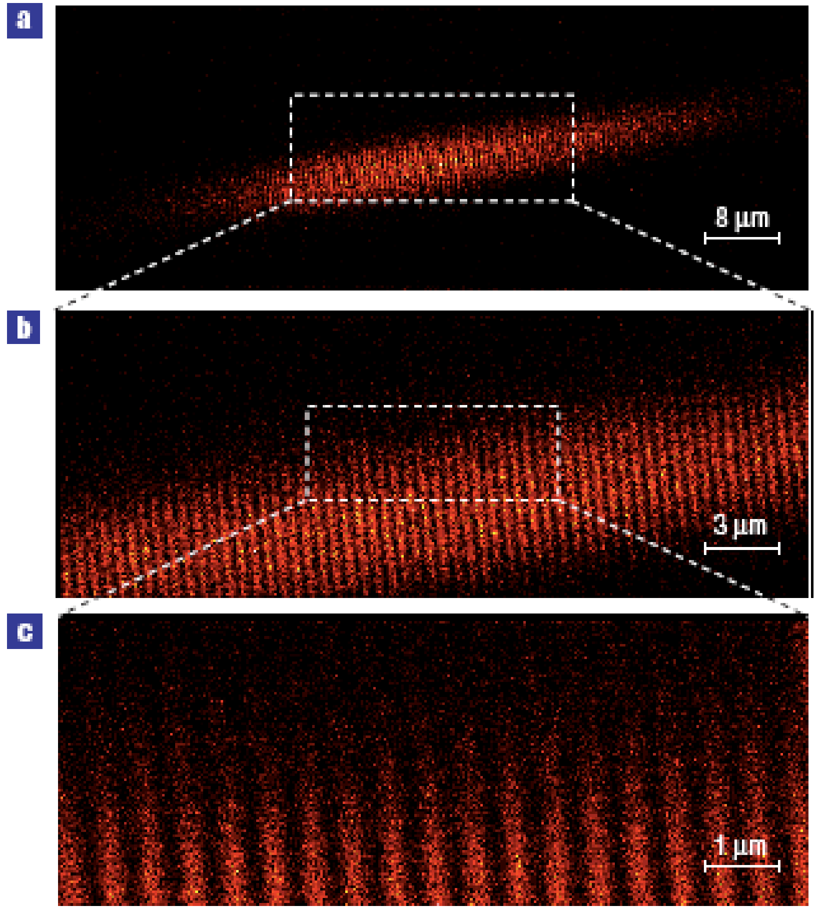
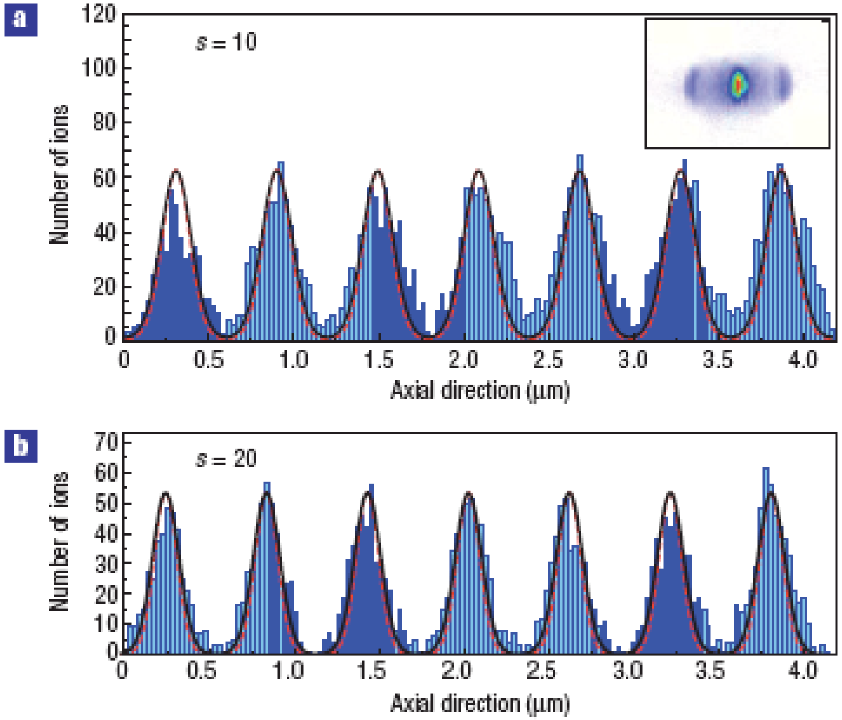


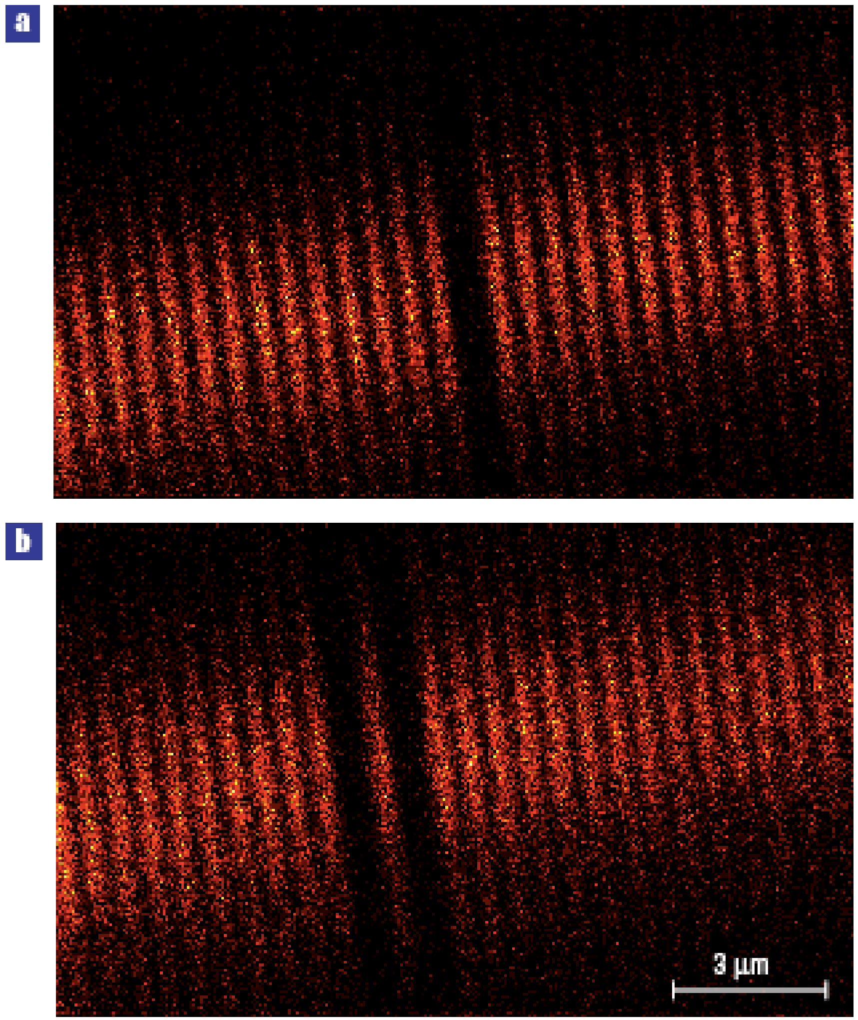
Figure 1 Working principle. The atomic ensemble is prepared in an optical dipole trap. An electron beam with variable beam current and diameter is scanned across the cloud. Electron impact ionization produces ions, which are guided with an ion optical system towards a channeltron detector. The ion signal together with the scan pattern is used to compile the image.




a
Number of ions
2,000
1,500
1,000
500
0
–40
–20
0
20
40
60
Axial direction (µm)
With e–
Without e–
b
Number of ions
10,000
8,000
6,000
4,000
2,000
0
–8
–6
–4
–2
0
2
4
6
8
10
12
14
16
Radial direction (µm)
Thermal component
Density (×10^12 cm^–3)
Radial direction (µm)
c
Number of ions
30
25
20
15
10
5
0
–40
–20
0
20
40
60
Axial direction (µm)


a
8 µm
b
3 µm
c
1 µm

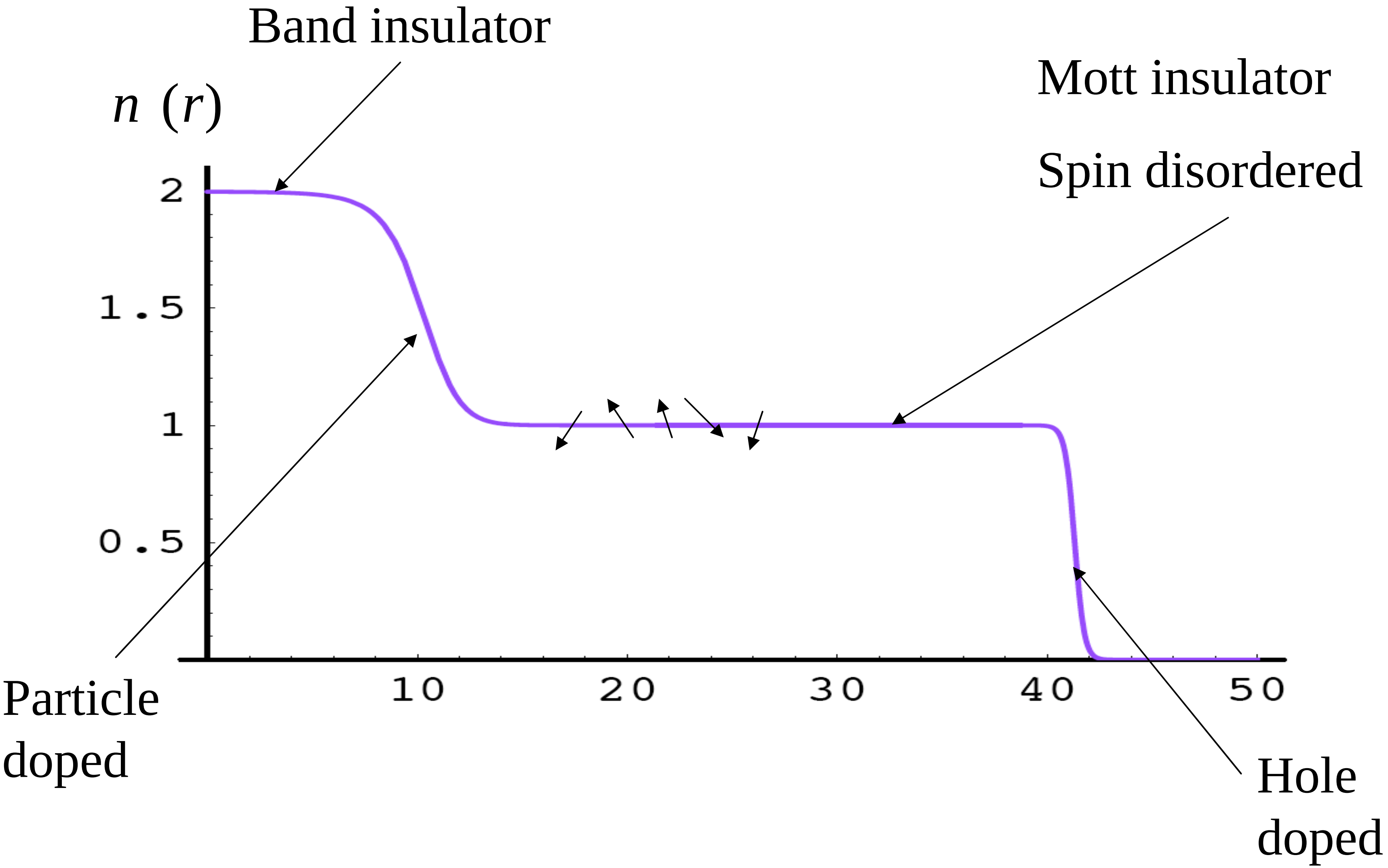

a
s = 10
Number of ions
0
20
40
60
80
100
120
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Axial direction (µm)
b
s = 20
Number of ions
0
10
20
30
40
50
60
70
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Axial direction (µm)


a
b
3 µm

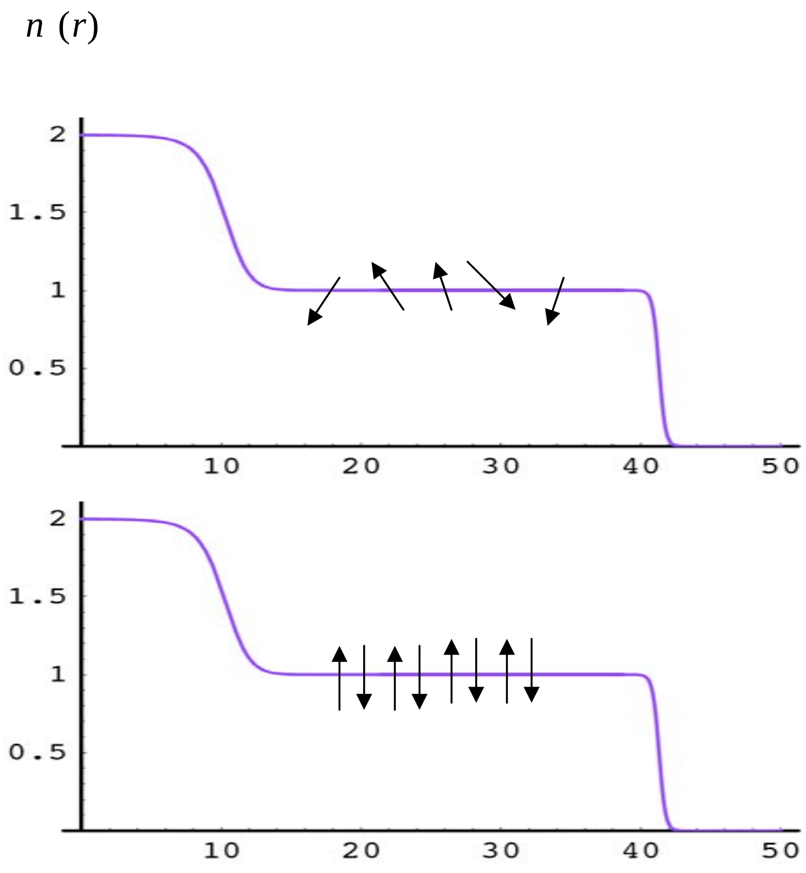
Part II : Entropy removal

Typical configurations of Lattice Fermions in a trap

$$U > T > J \qquad T = 100nK$$



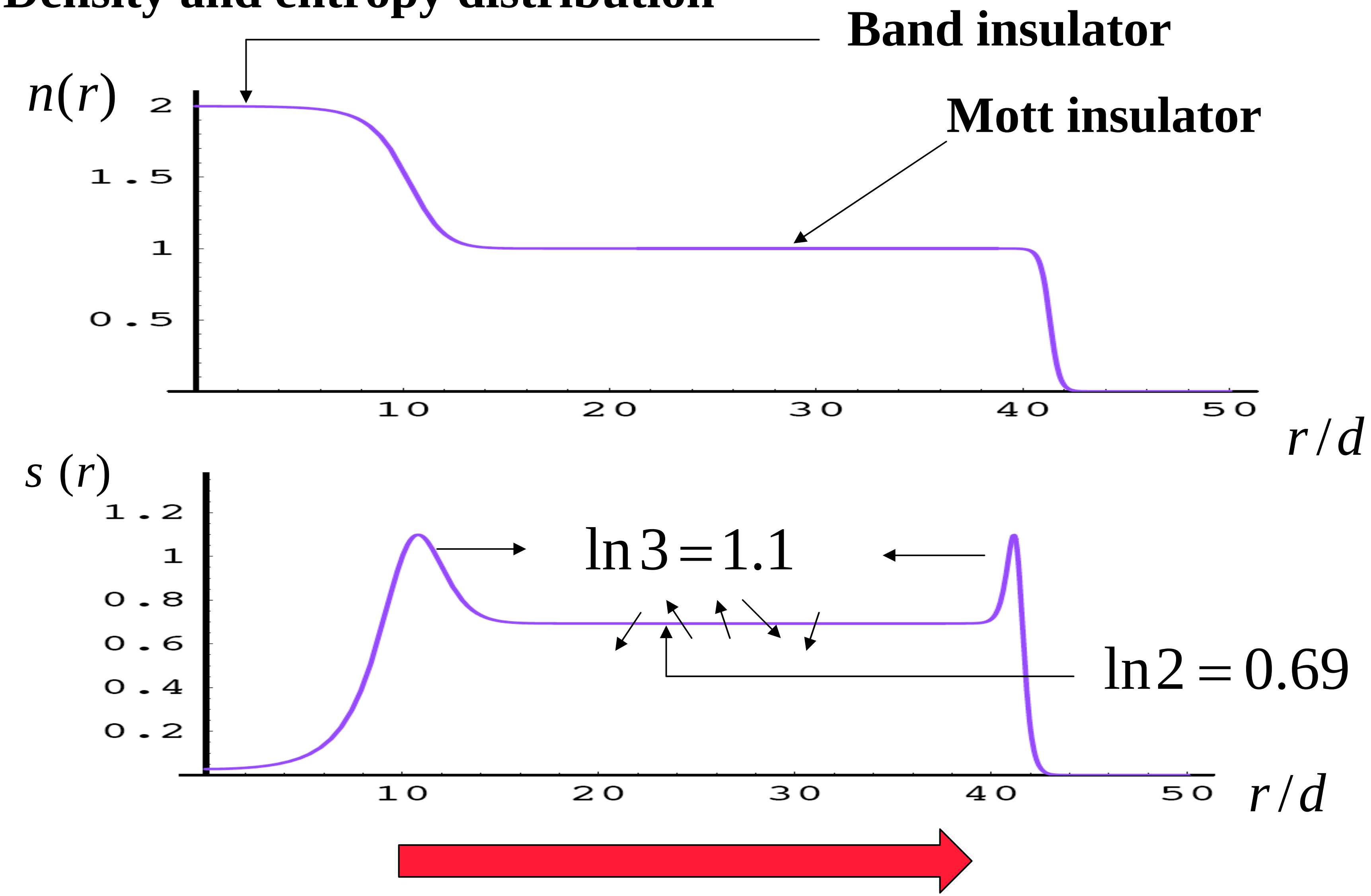
Esslinger, et.al, 2008 Science
Bloch, et.al 2008



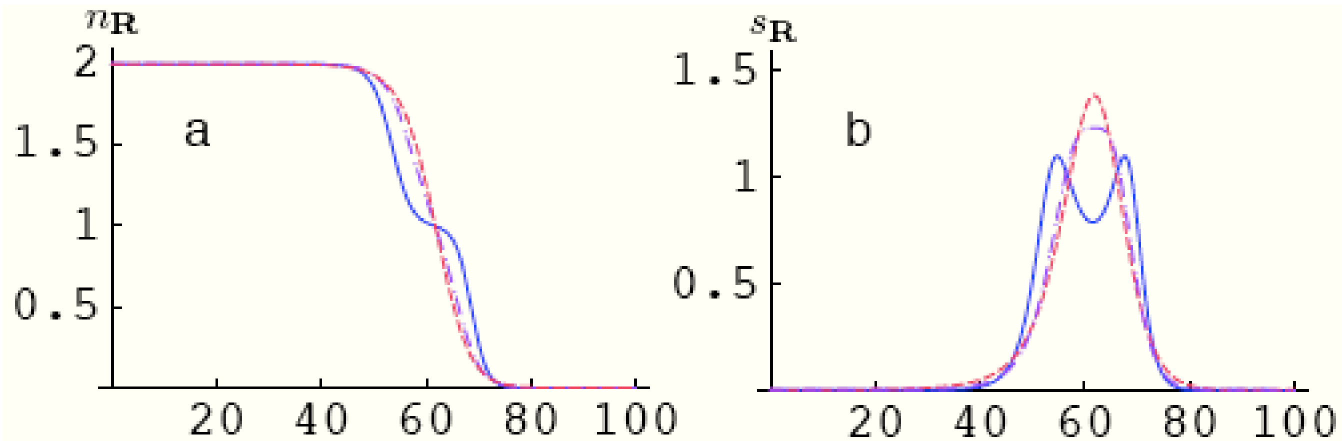
$T \gtrsim t > t^2/U$

$t^2/U \gtrsim T$

Density and entropy distribution



(spin-1, ln3)



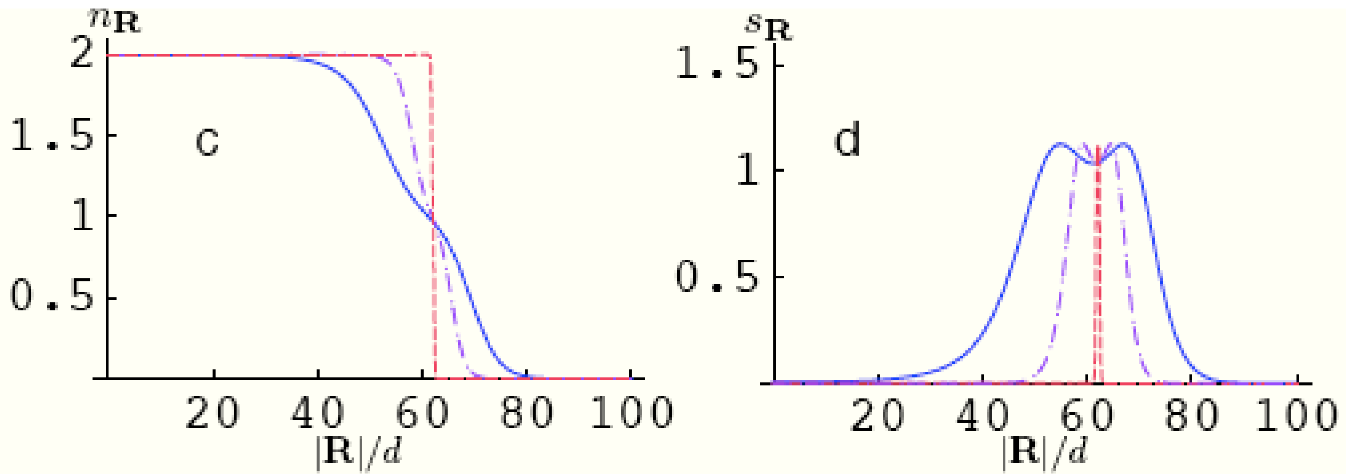
Compression of trap ⟶ Squeezing entropy to surfact

Adiabaticity ⟶ Temperature increase

Isothermal compression => Entropy reduction

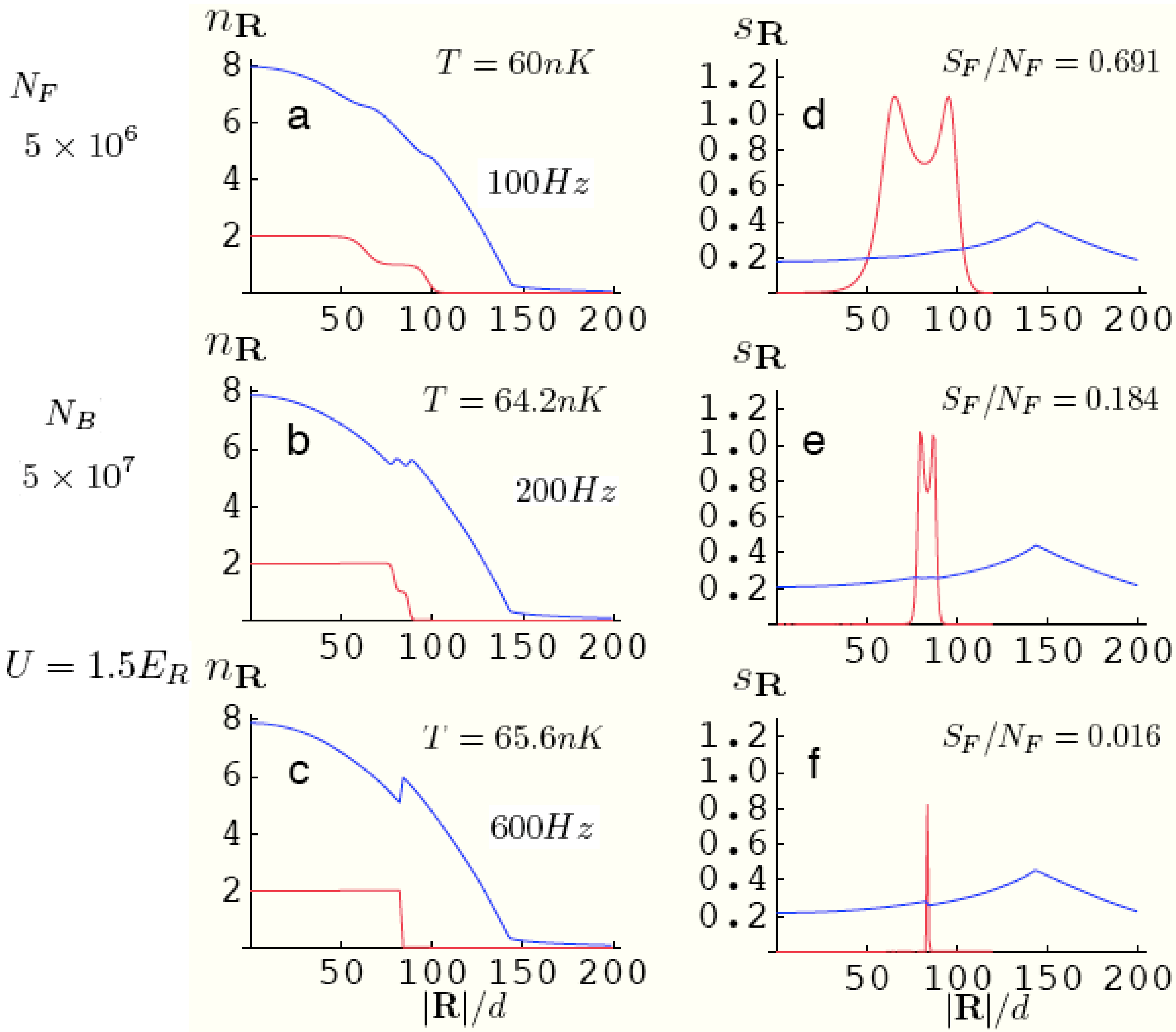
$(T = 50\text{nK})$

100Hz (blue) 150Hz (purple) 600Hz (red)



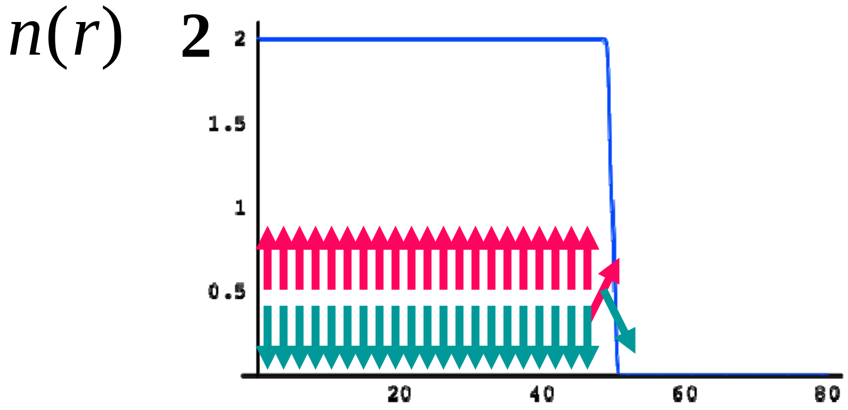
0.732 (blue) 0.333 (purple) 0.021 (red)

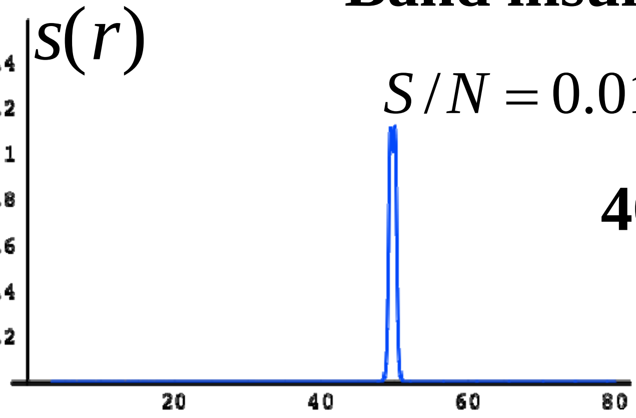
4% of the lowest value attainable today



N_F
5×10^6
N_B
5×10^7
$U = 1.5E_R$
$n_{\mathbf{R}}$
$T = 60nK$
a
100Hz
$T = 64.2nK$
b
200Hz
$T = 65.6nK$
c
600Hz
$s_{\mathbf{R}}$
$S_F/N_F = 0.691$
d
$S_F/N_F = 0.184$
e
$S_F/N_F = 0.016$
f
$|\mathbf{R}|/d$

From Band insulator to Mott insulator: Turn down the lattice adiabatically

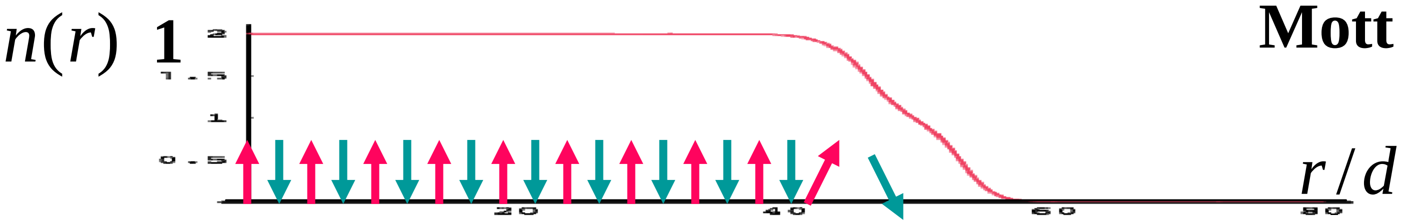




Band insulator

$S/N = 0.016$

40nK



Mott insulator

T<<40nK

Summary of our Cooling Strategy:

1. Can use a gapful phase of the system to push out the entropy out from the bulk

2. Remove the entropy by pushing it into a BEC
   Or by evaporation.. But

3. Always tighten the trap immediately to stop entropy regeneration

Basic Concept : knowing where the entropy is, and what causes it.

Summary:

Quantum Simulation Program =>

Lowest temperature regime ever achieved

Quantum Many-body precision Measurement