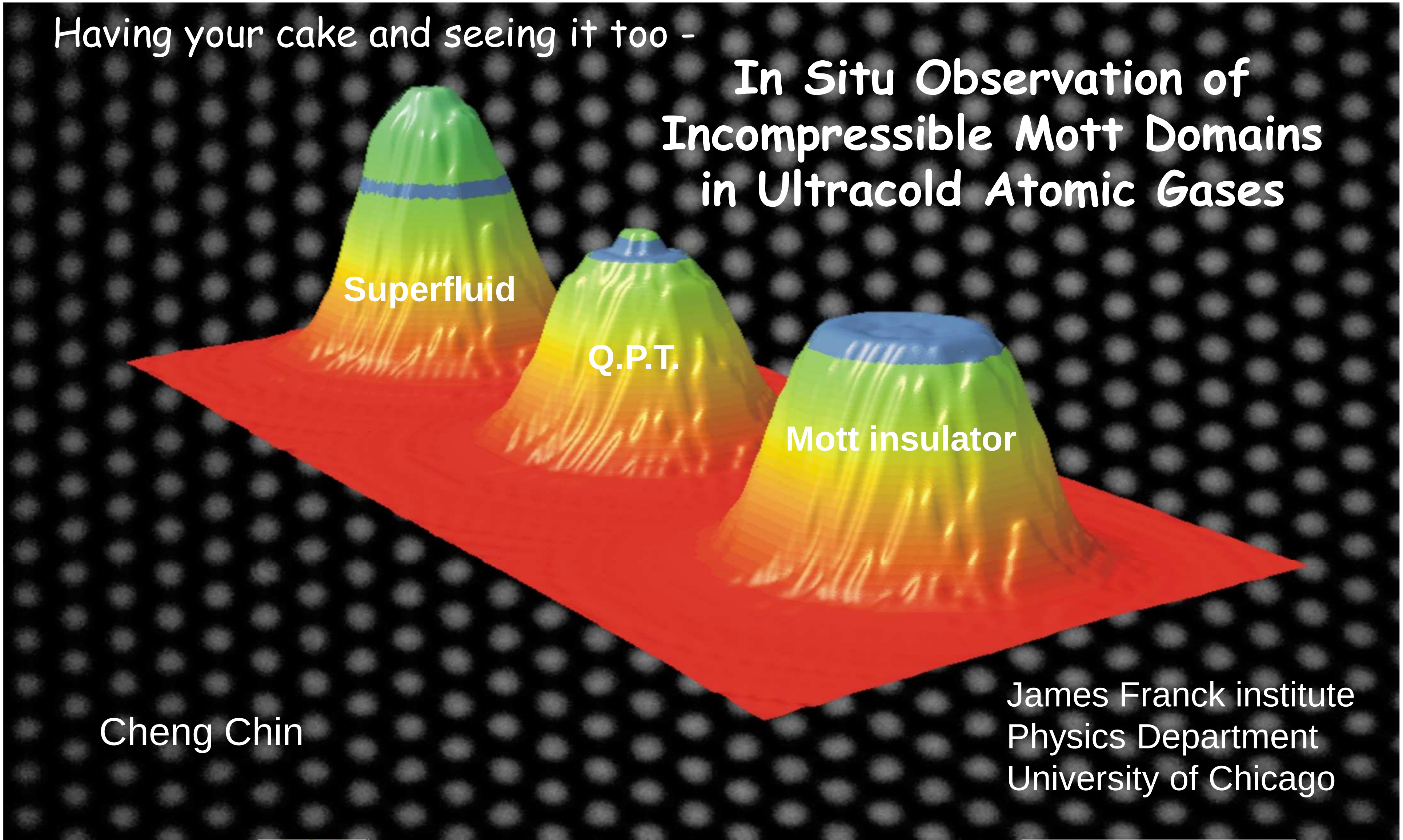
Colloquium, Physics Department at the University of Virginia, 9/02/2011

Having your cake and seeing it too -

In Situ Observation of Incompressible Mott Domains in Ultracold Atomic Gases



Cheng Chin

James Franck institute
Physics Department
University of Chicago

Funding: NSF, the David & Lucile Packard Foundation, DARPA, AFOSR Air Force Office of Scientific Research

Cake Recipe

(0th order approximation)

1. Mix flour and baking powder

2. Heat it to 350 F in an oven

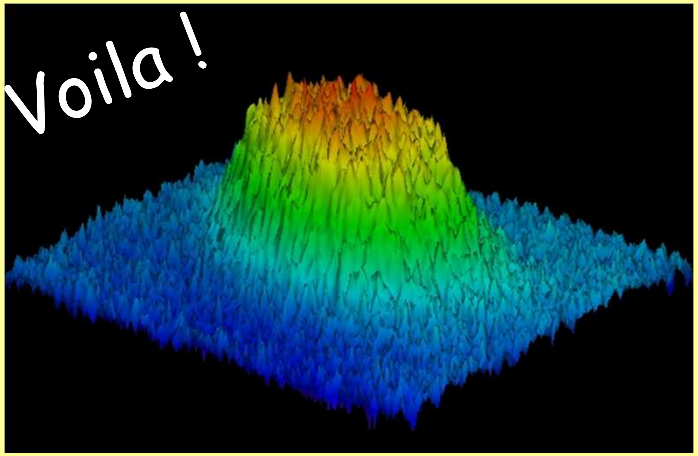
3. Bake for 30~40 minutes

Our "Ice Cream" Cake Recipe

1. Prepare some atoms in a bowl

2. Cool it to 10 nano-K

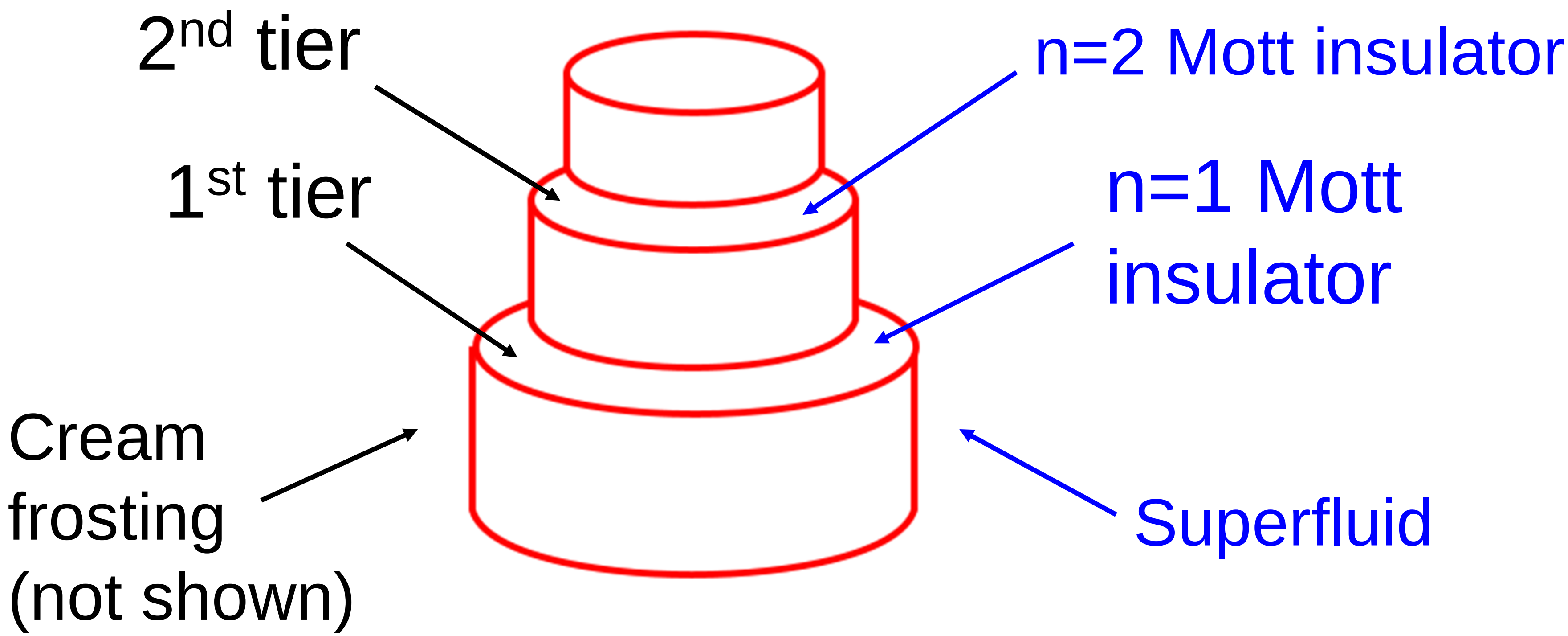
3. "Bake" for 200ms



Comments

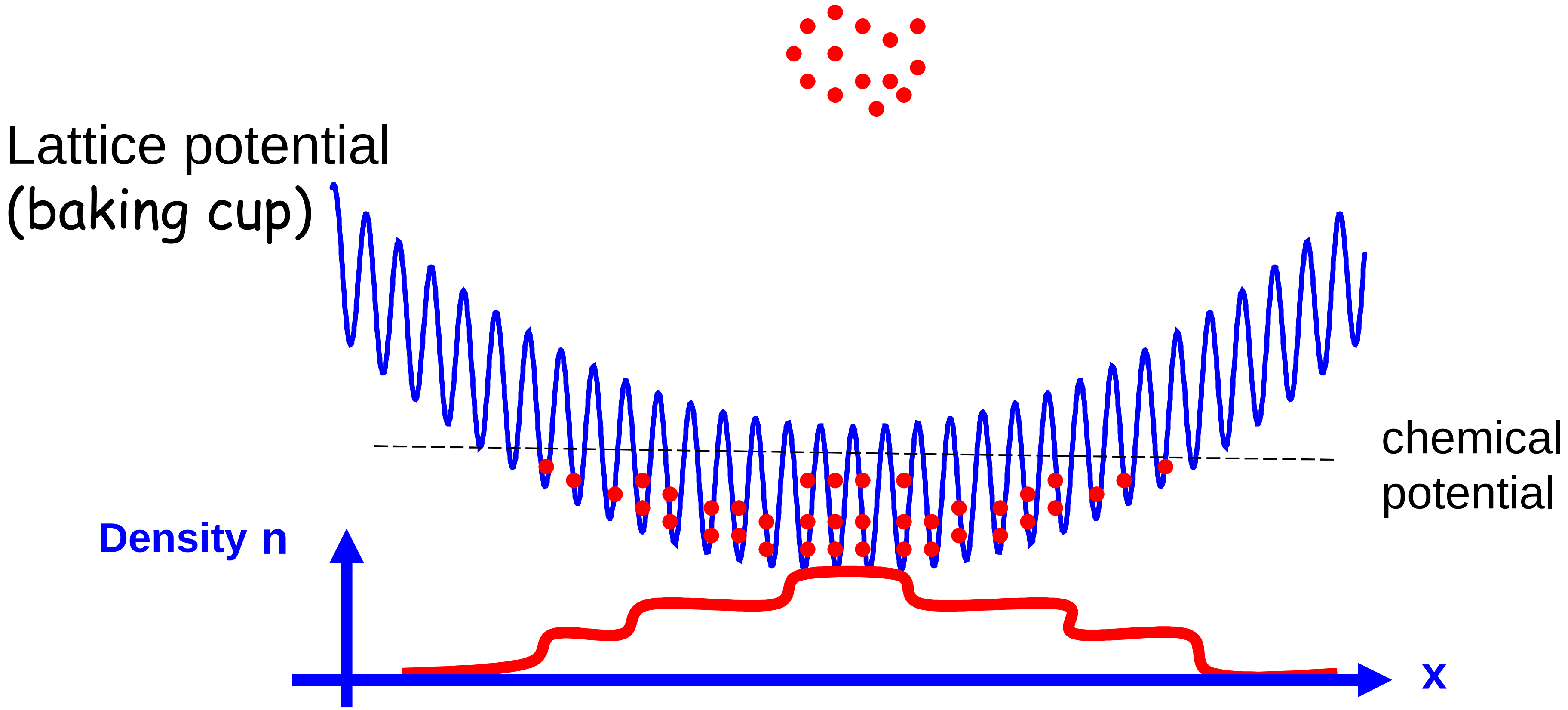
- We are not the first one to make the cake, but the first one to see it.
- We can see it because we make only one cake.
- All physics occurs in the baking.

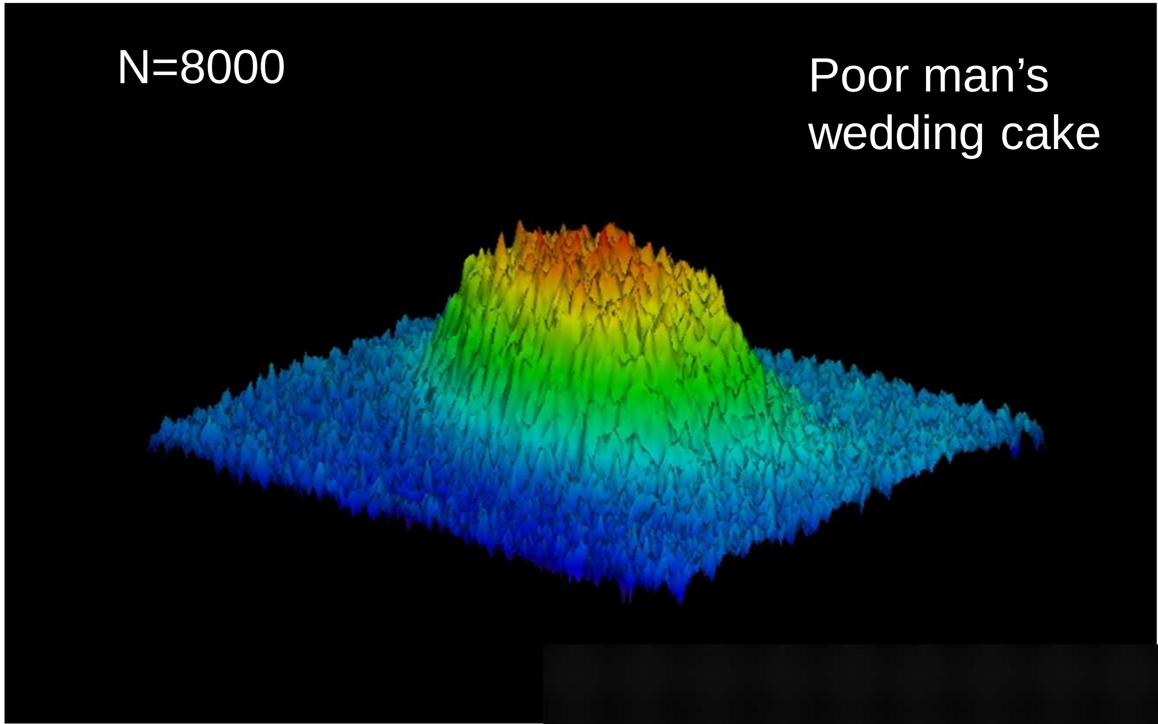
Cake Terminology

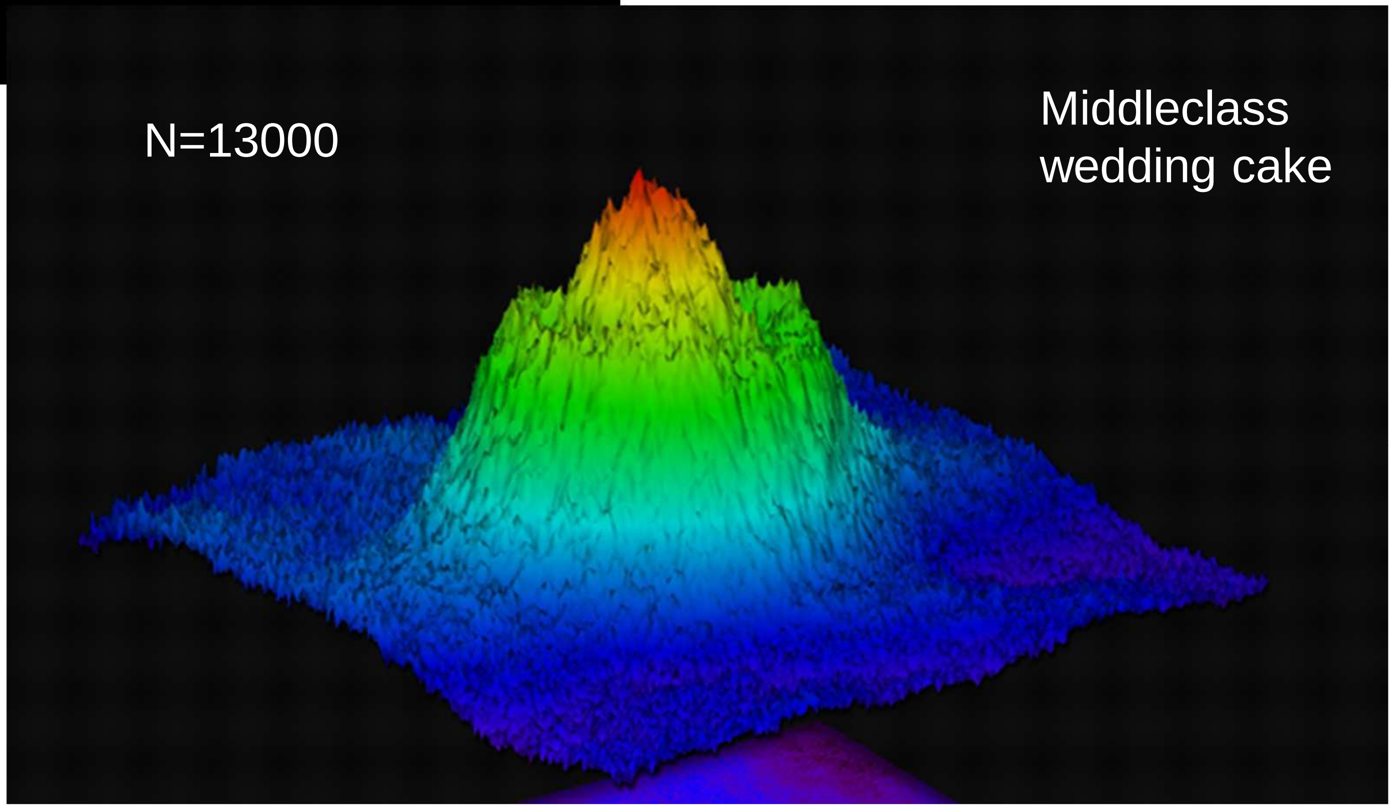


How does cake form in the lab?

(Bose-Hubbard process)




N=8000
Poor man’s
wedding cake


N=13000
Middleclass
wedding cake

Bose-Hubbard model *(Fisher et al., PRB 1989, Greiner et al., Nature 2002)*

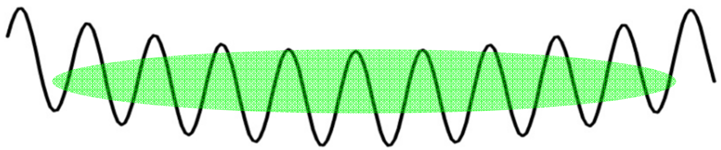
$$\hat{H} = -t\sum_{<i,j>}(\hat{b}_i^{+}\hat{b}_j + \hat{b}_j^{+}\hat{b}_i) + U\sum_{i}\frac{\hat{n}_i(\hat{n}_i - 1)}{2} - \sum_{i}\mu_i\hat{n}_i$$

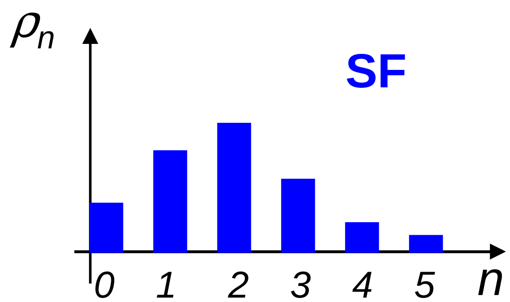
Tunneling Interaction Trap potential

Density distribution

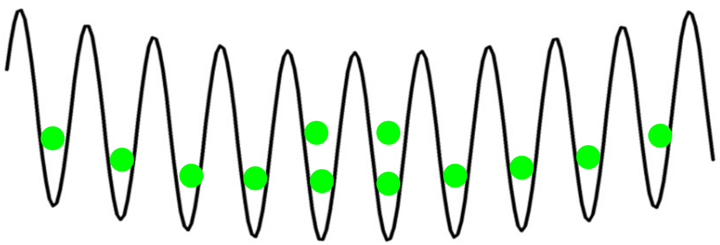
Number statistics

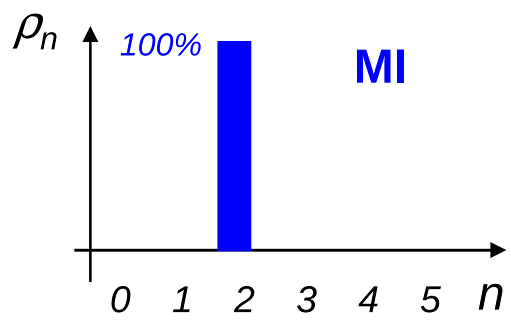
t >> U
Superfluid
compressible



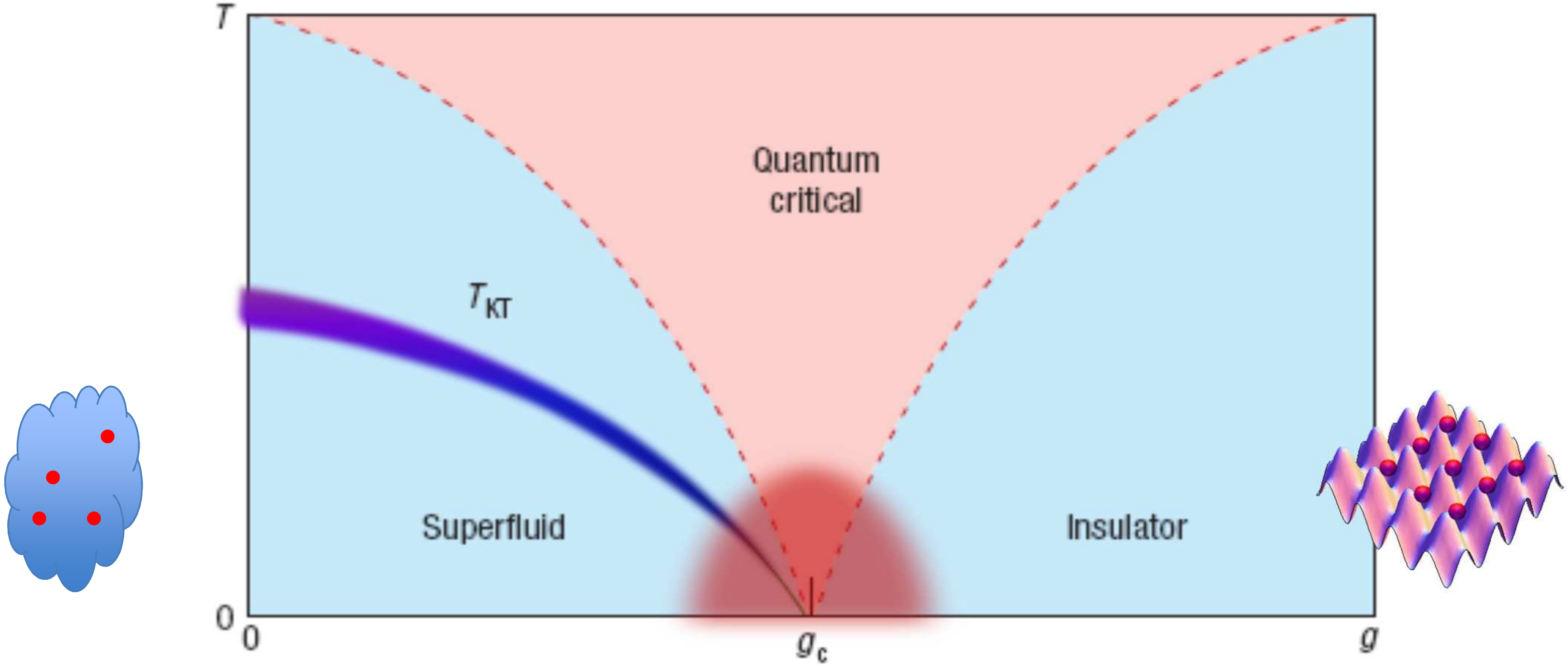


U >> t
Mott insulator
incompressible





Phase transition and quantum phase transition



Phase diagram and AdS4-CFT3 duality: Sachdev, Nature physics (2007)

Synopsis

How do we see the wedding cake?

Science Project 1:

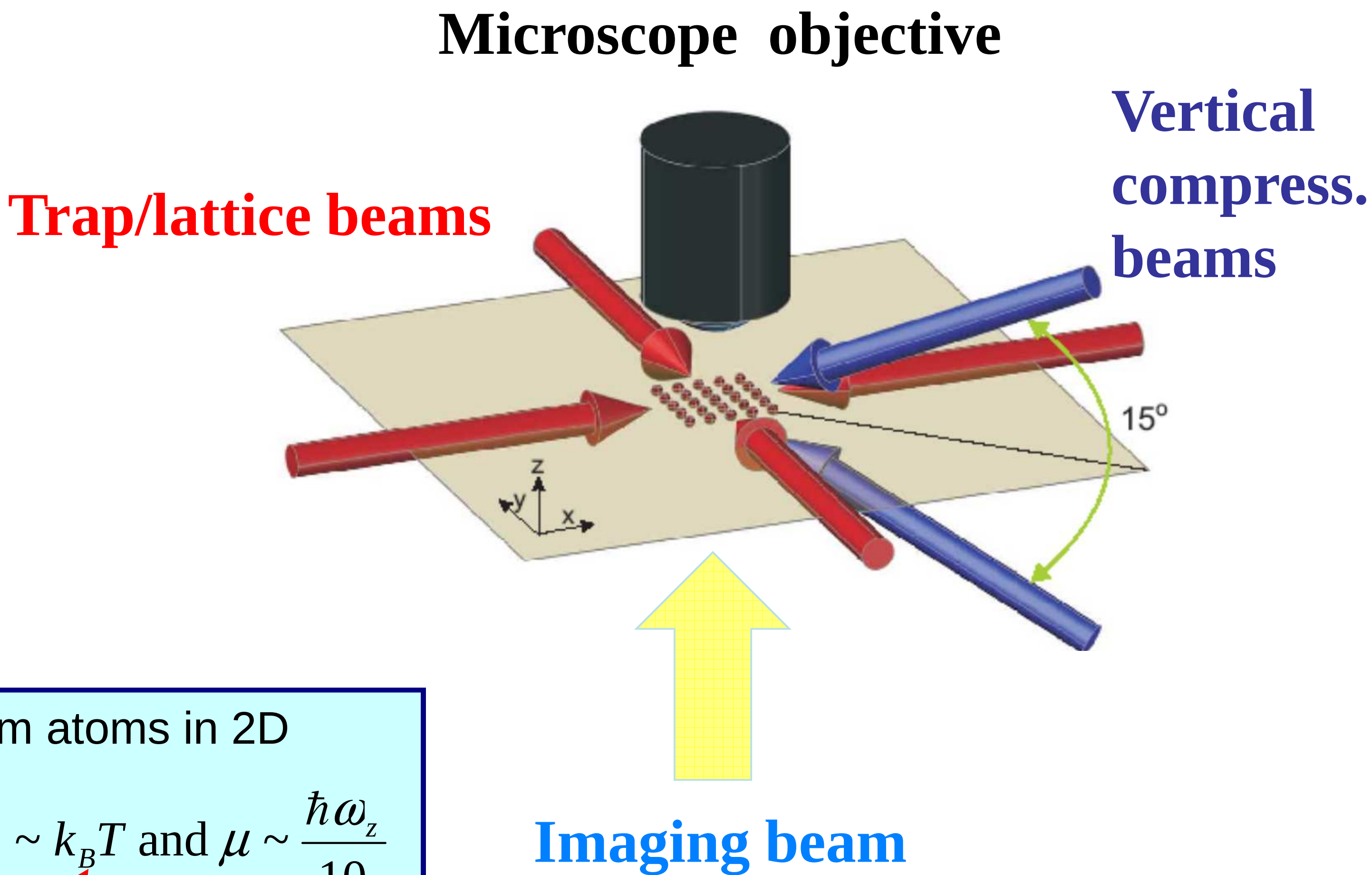
Properties of SF and Mott insulator

Quantum phase transition

Science Project 2:

Quantum microscopy and quantum information

In situ Imaging a single layer of 2D gas



Cesium atoms in 2D

$$15\hbar\omega_r \sim k_B T \text{ and } \mu \sim \frac{\hbar\omega_z}{10}$$

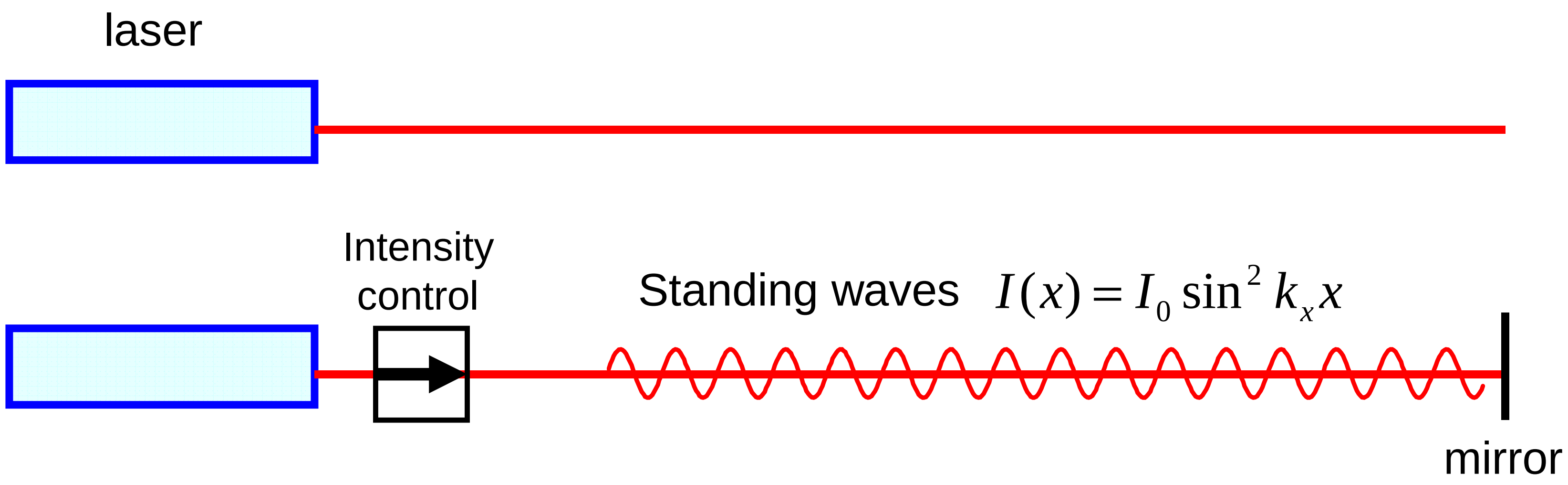
Determined from the density profile.

N.D. Gemelke et al., Nature 460 (2009)

See also: (Harvard) W.S. Bakr et al., Nature 462 (2009)

(MPQ) J.F. Sherson et al., Nature 467 (2010)

What is an optical lattice?



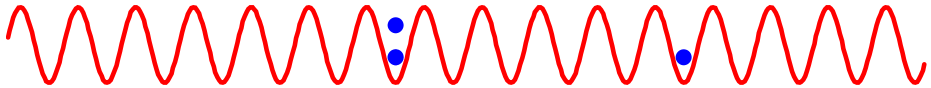
Atomic polarization $\quad P = \varepsilon\, E$

Atom-photon interaction $\quad V = -\int P \cdot dE = -\tfrac{1}{2}\varepsilon\, E^2 = -\tfrac{1}{2}\alpha_{AC} I$

α_{AC} : AC polarizability

Optical lattice potential $\quad V(x) = V_0 \sin^2 k_x x$

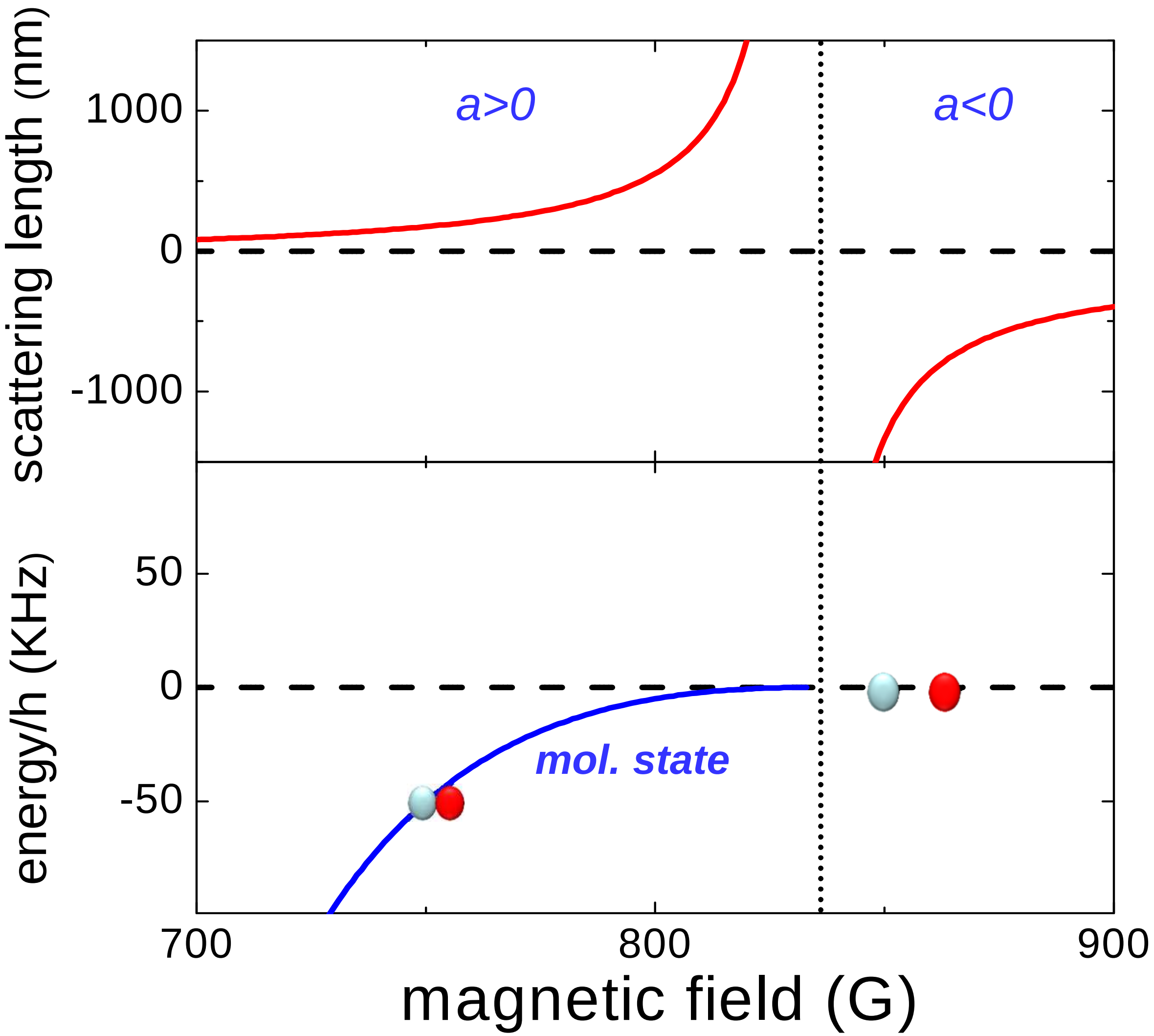
Optical lattice toolbox



Site index i-1 i i+1 …

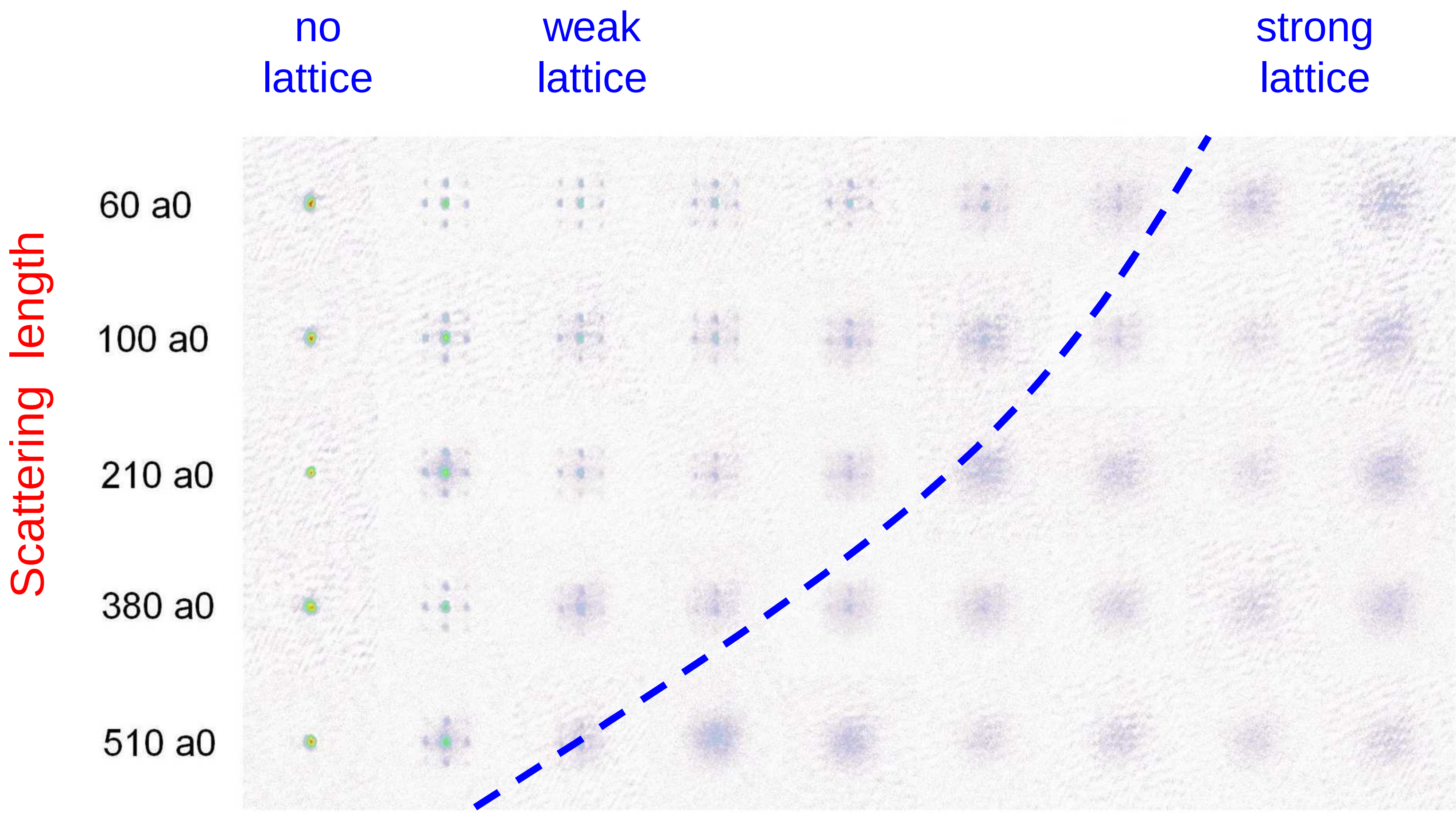
		Controlled by
Hopping	$-t\sum_{<i,j>}(\psi_i^+\psi_j+\psi_j^+\psi_i)$	Lattice potential
Interaction	$\frac{U}{2}\sum_i n_i(n_i-1)$	Feshbach tuning
Trapping potential	$-\sum_i n_i(\mu-V_i)$	Trap potential

Feshbach resonance in ultracold gases



Chin, Grimm, Julienne and Tiesinga, Rev. Mod. Phys. (2010)

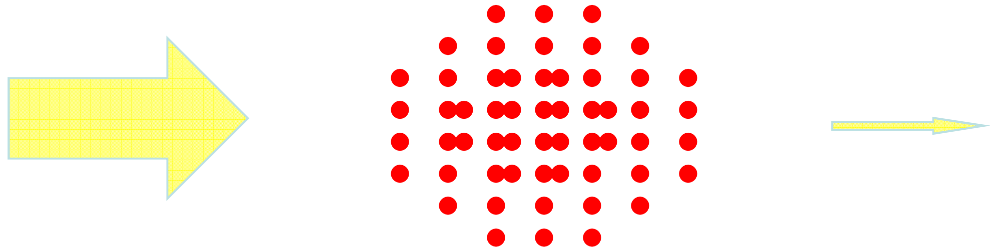
SF-MI transition in a single layer of 2D lattice



Why is it difficult to see the cake?

Conventional approach: 3D cake

CCD camera

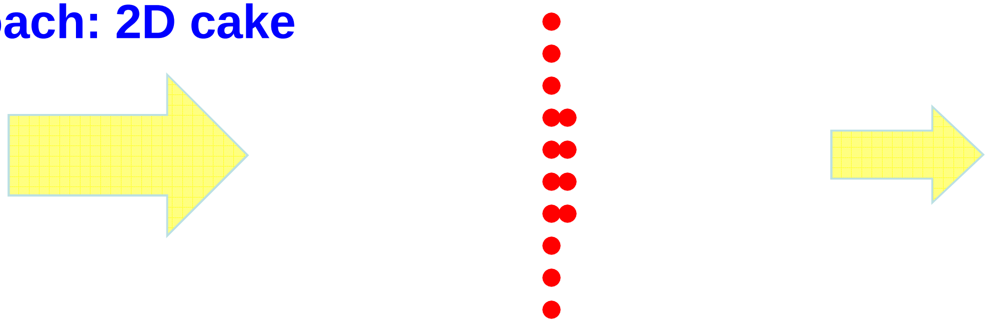


Light Intensity I

Transmission $T(x,y) << 1$

~ 30 cakes of different sizes

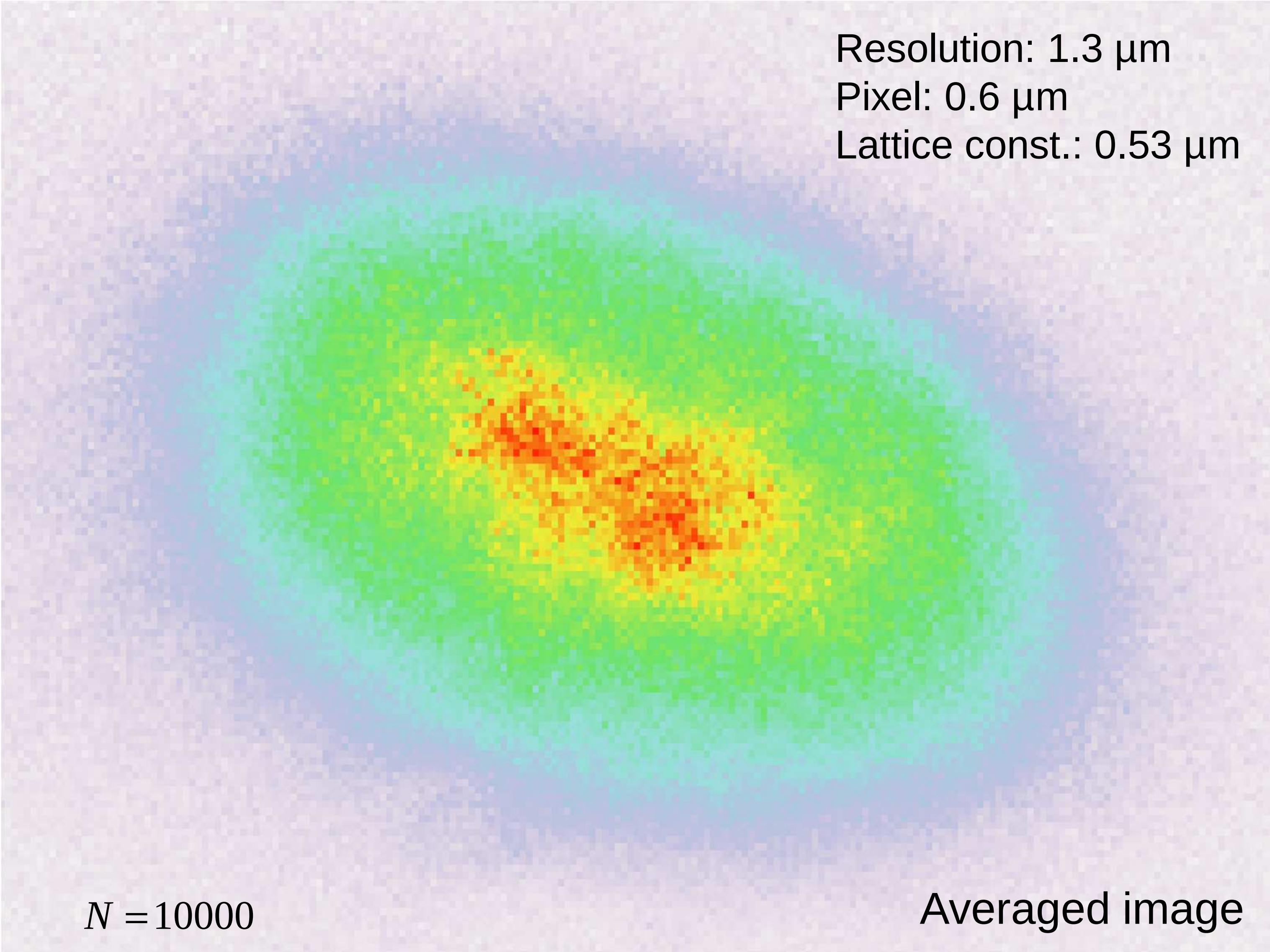
Our approach: 2D cake



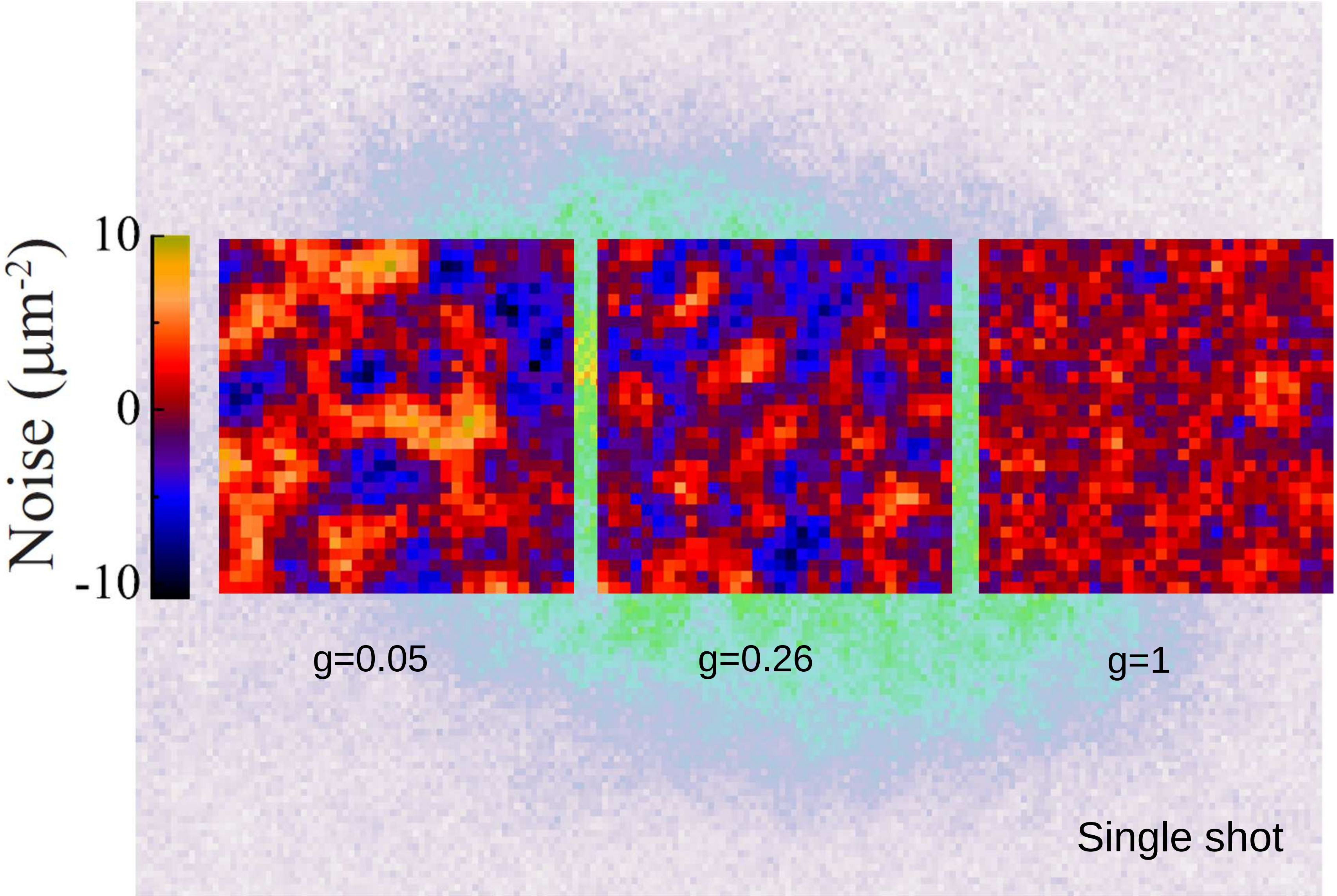
Light Intensity I

Transmission $T(x,y) \sim 0.5$

A closer cook…

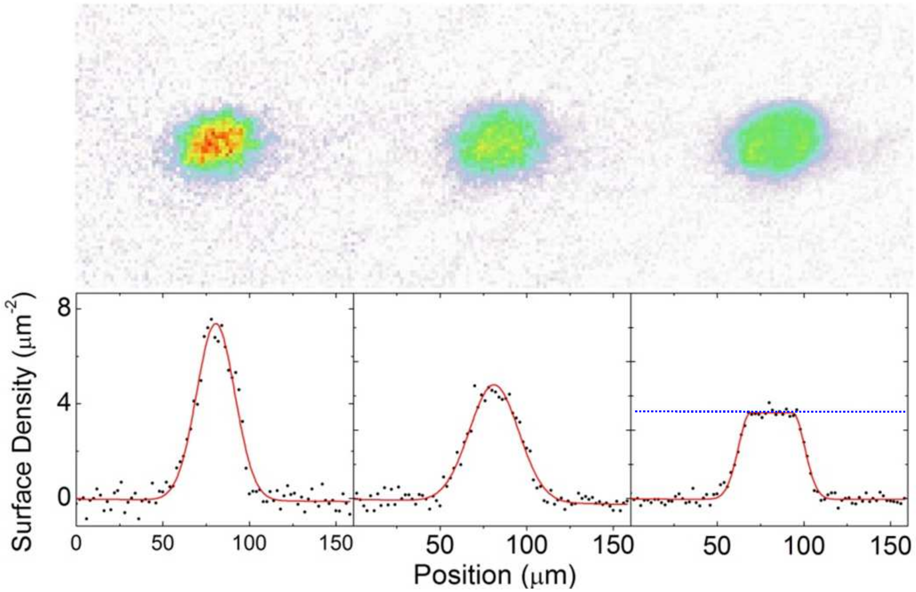


Density fluctuations and correlations

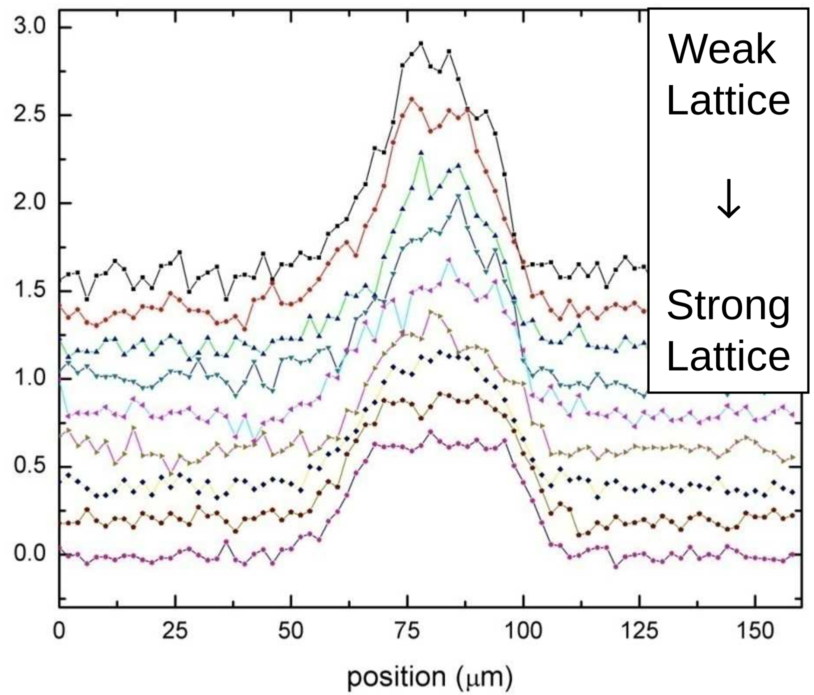


Noise of A ≡ A - <A>

Observation of the Mott domain (single tier cake)



Emerging of Mott plateau

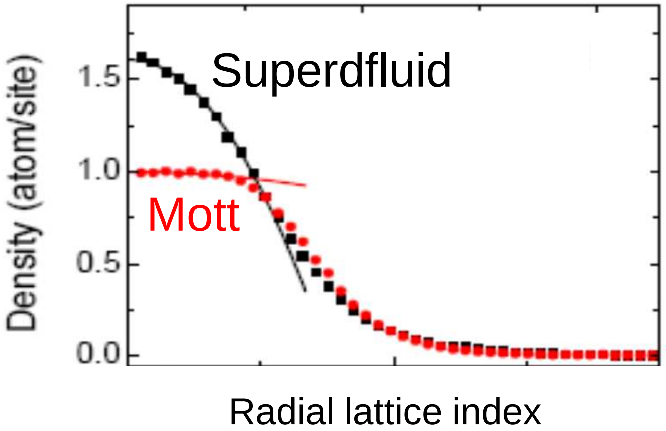


Plateau density:

Theory: $1/d^2 = 3.53$ /um^2

Experiment: 3.5(3) /um^2

Compressibility κ

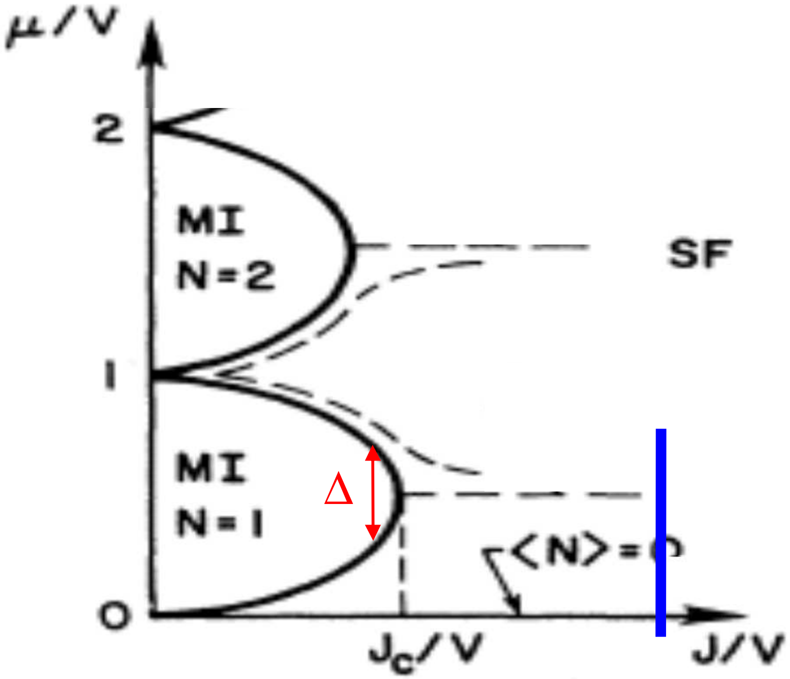


Definition

$$\kappa = \frac{\partial n}{\partial \mu} = \frac{1}{m\omega_r^2}\frac{n'(r)}{r}$$

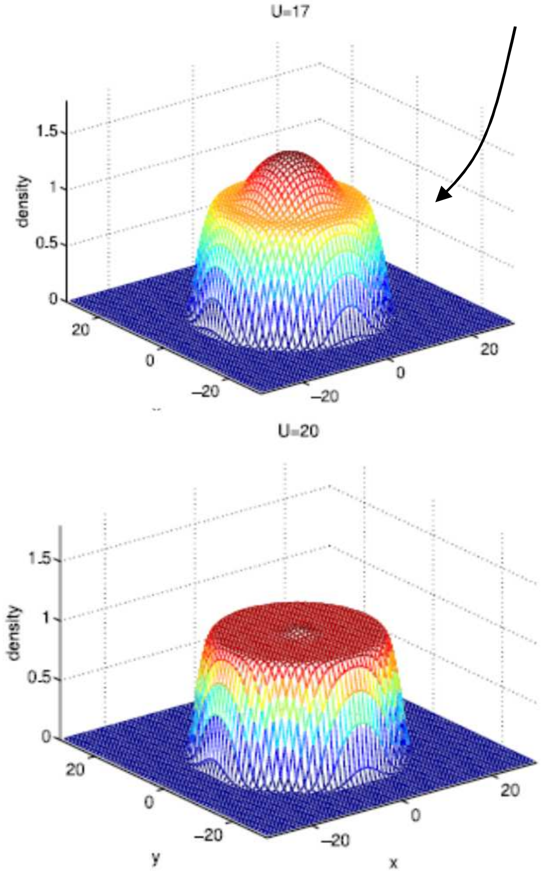
Origin of the cake structure

Phase diagram at T=0



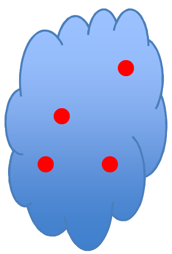
Fisher et al., PRB 40, 546 (1989)

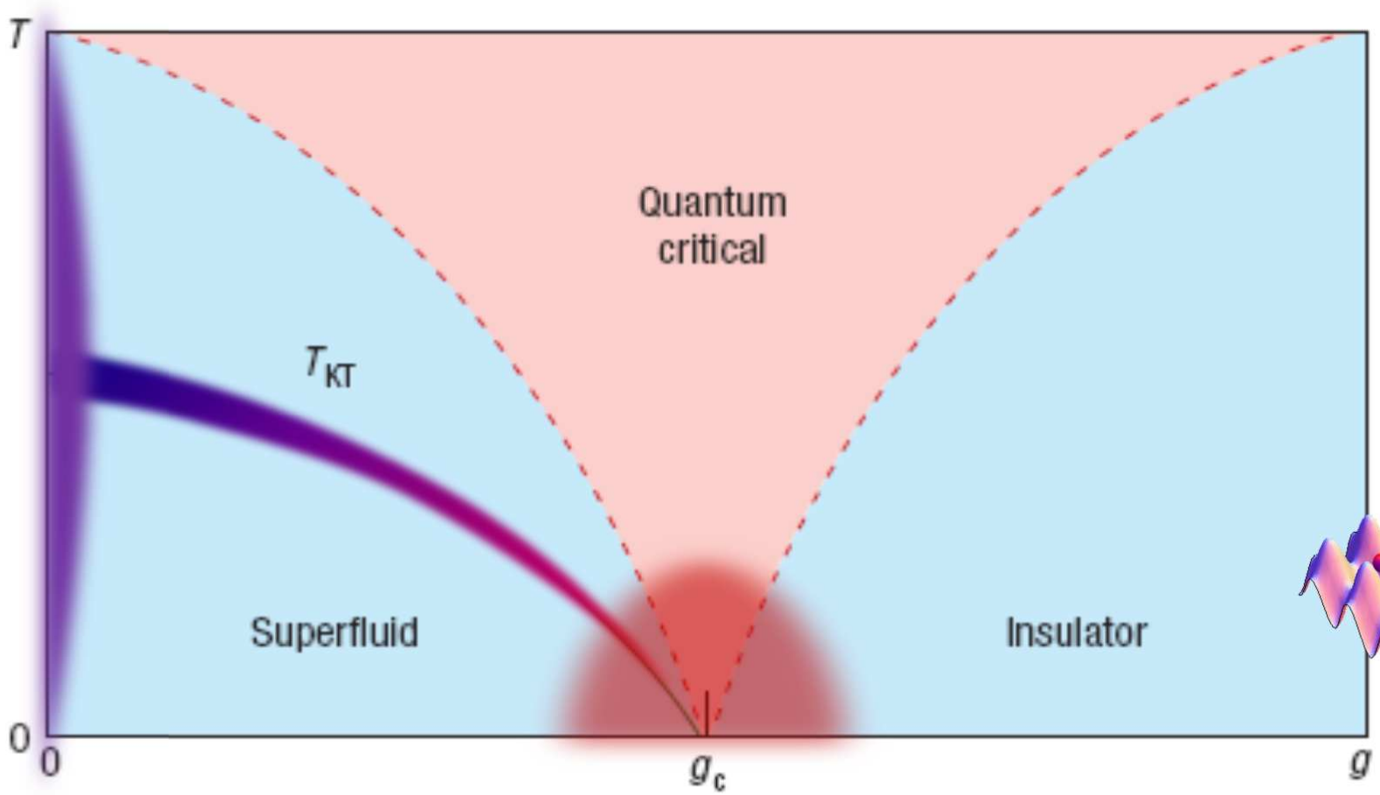
MI plateau appears near <n>=1

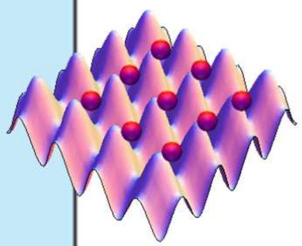


Quantum Monte Carlo calculation
(R. Scalettar, UC Davis)

Universal scaling regimes in 2D optical lattices





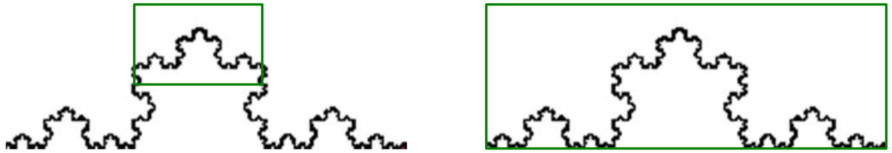


No lattice

(2D gas)

strong lattice

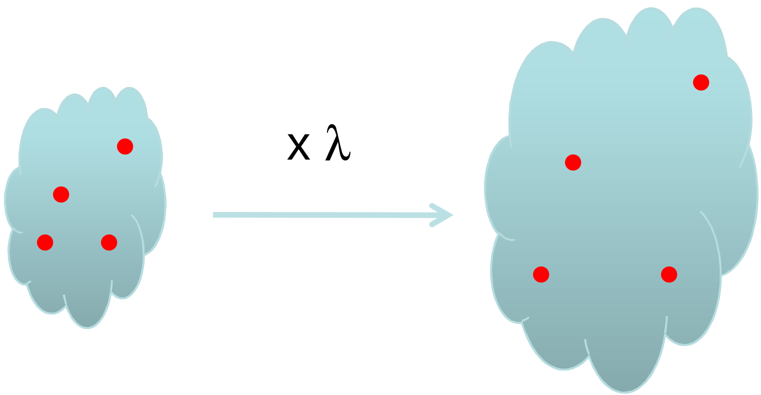
Scaling symmetry



2D gas with <u>constant</u> contact interaction *Pitaevskii and Rosch, PRA (1997)*

$$H=\sum_i \frac{p_i^2}{2m}+\sum_{ij} g\,\delta^2(r_{ij})$$

$$H\psi(\lambda x)=\lambda^{-2}H\psi(\lambda x)$$



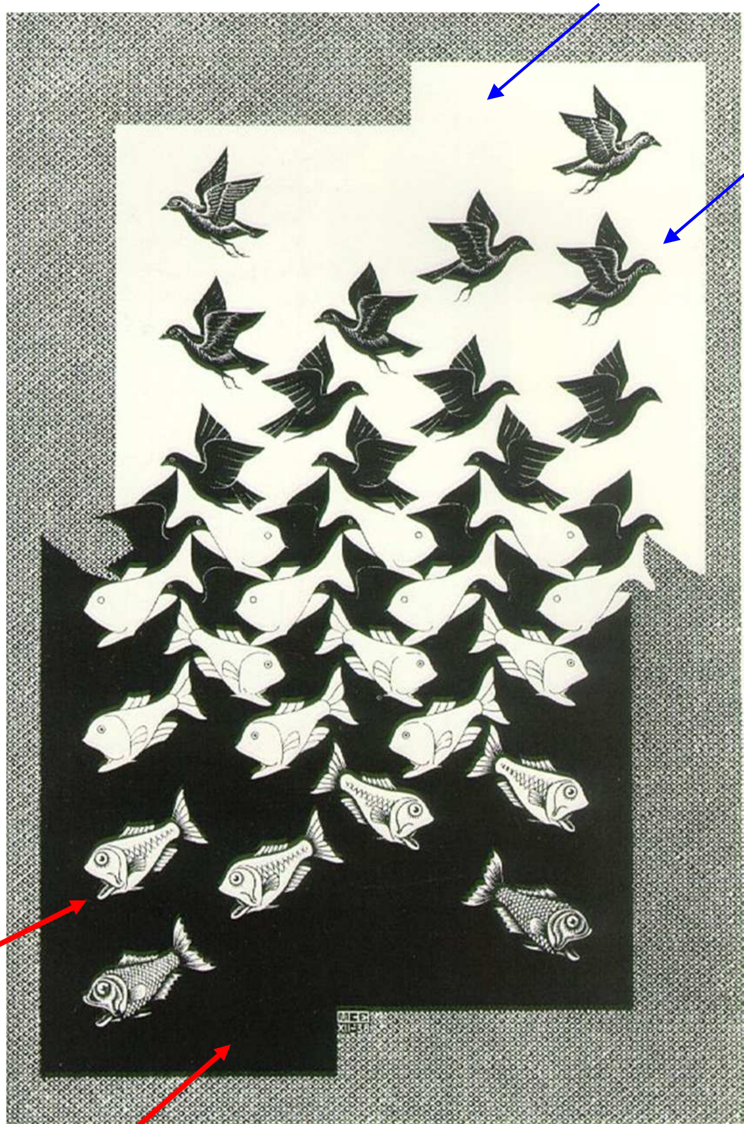
$$E_k \rightarrow \frac{E_k}{\lambda^2} \qquad gn \rightarrow g\,\frac{n}{\lambda^2}$$

Another example: resonant Fermi gas.

Classical
critical phenomena

Vapor

Droplets in vapor



Bubbles in water

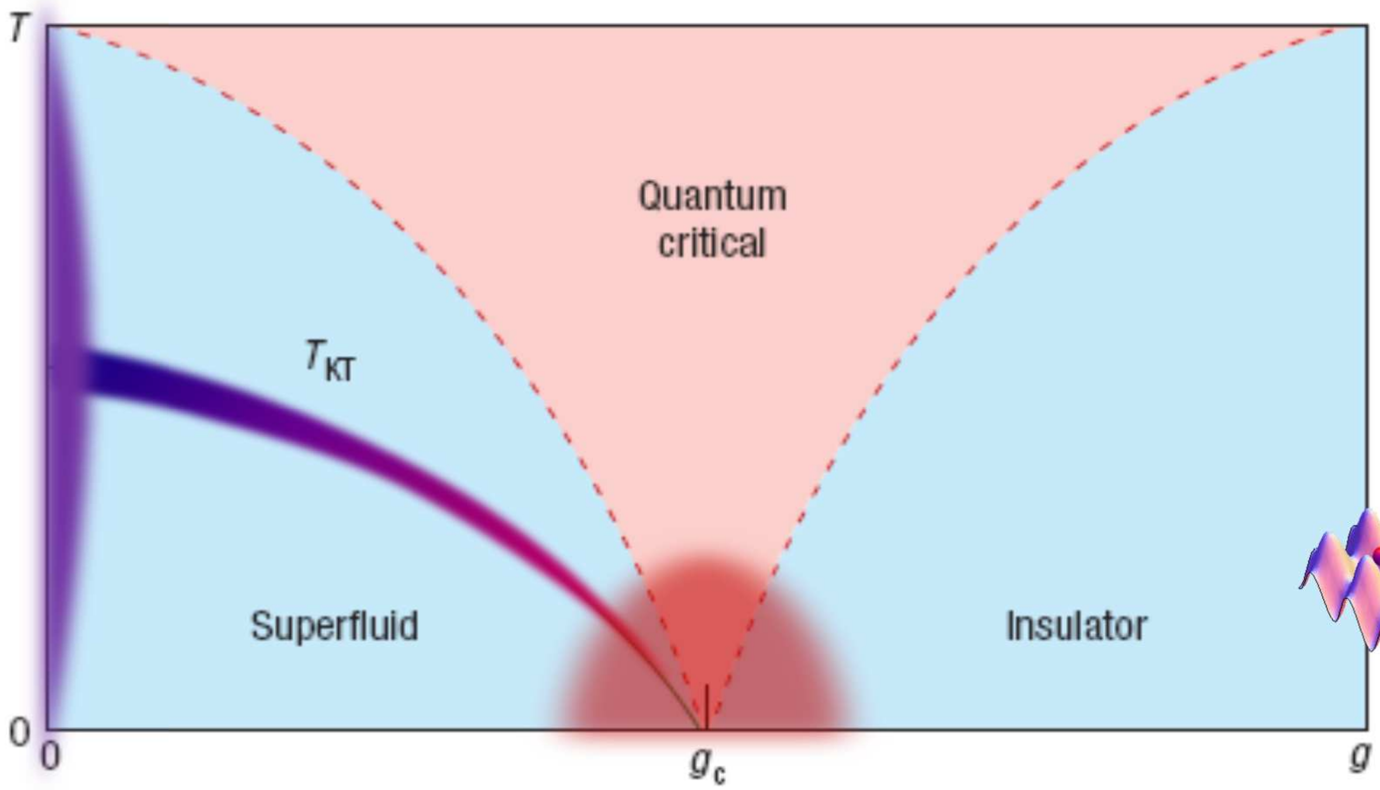
water

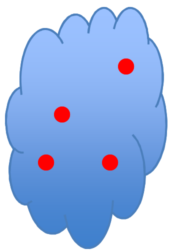
M.C. Escher

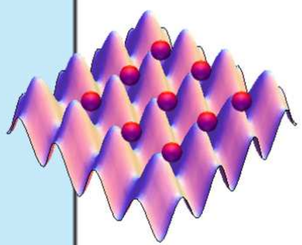
YouTube:
Optical Opalescence

Quantum phase transition in optical lattices

$$H = \sum_i \frac{p_i^2}{2m} + \sum_{ij} g\delta^2(r_{ij}) + V(\sin^2 kx + \sin^2 ky)$$







No lattice

(2D gas)

strong lattice

Only the ratio of the length scale matters $\Psi(x) = \lambda^{\alpha}\Psi(\lambda x)$

Examples:

Equation of state $n(\mu, T) = \lambda_{dB}^{-2} F(\tilde{\mu})$ $\tilde{\mu} = \dfrac{\mu}{kT}$

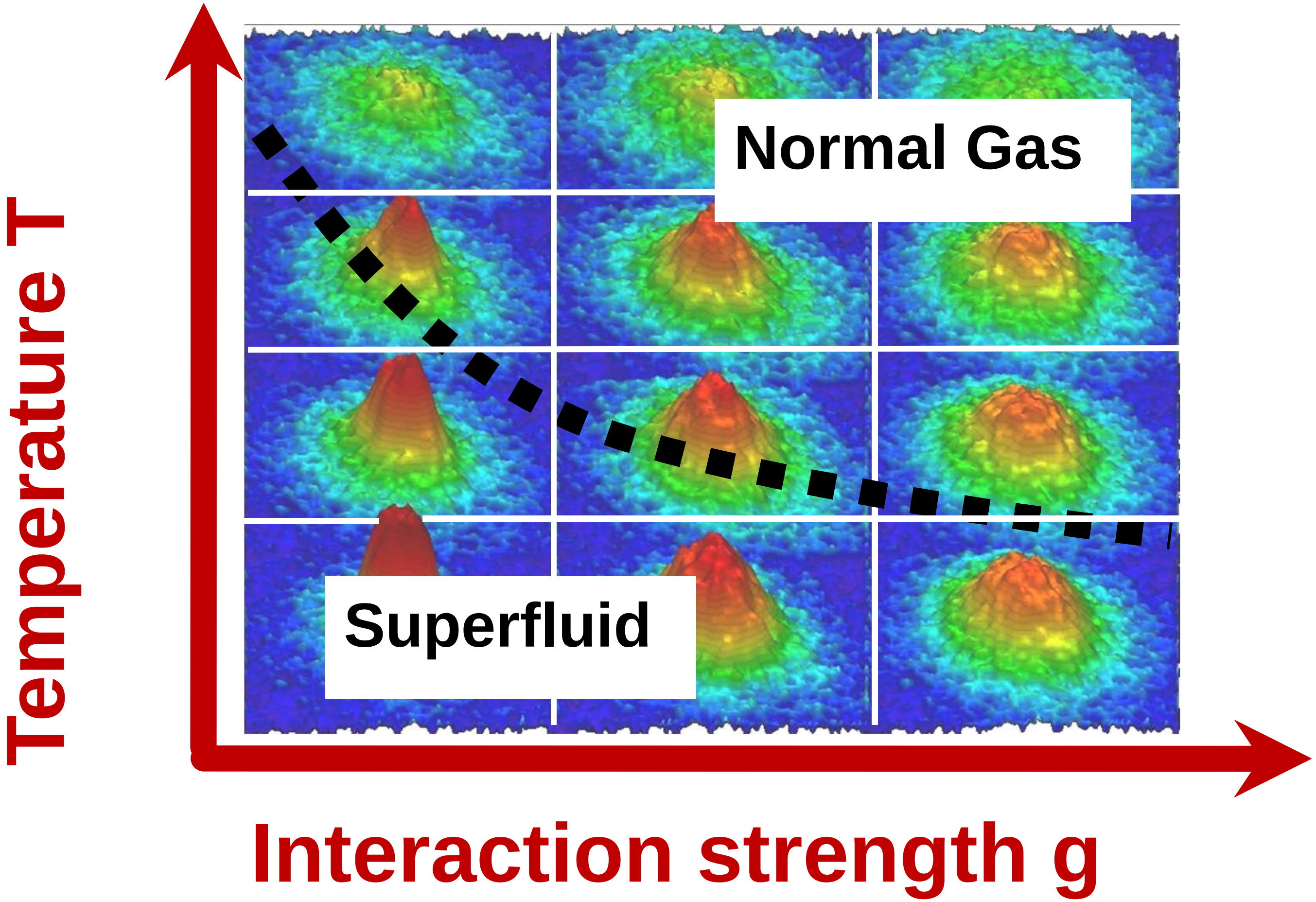
Corollary : Grand potential can be fully determined by EoS.

$$\cancel{d\Omega = -s(\mu, T)dT - n(\mu, T)d\mu}$$

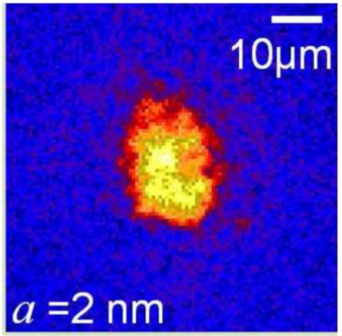
$$d\Omega = [-2\int F(x)dx - F(\tilde{\mu})\,]\,T^2 d\tilde{\mu}$$

$$\tilde{n} = n\lambda_{dB}^{2}$$

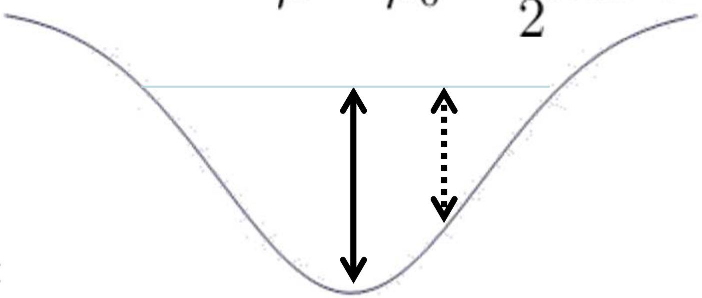
Scale invariance and universality in 2D gases



Temperature T and chemical Potential μ

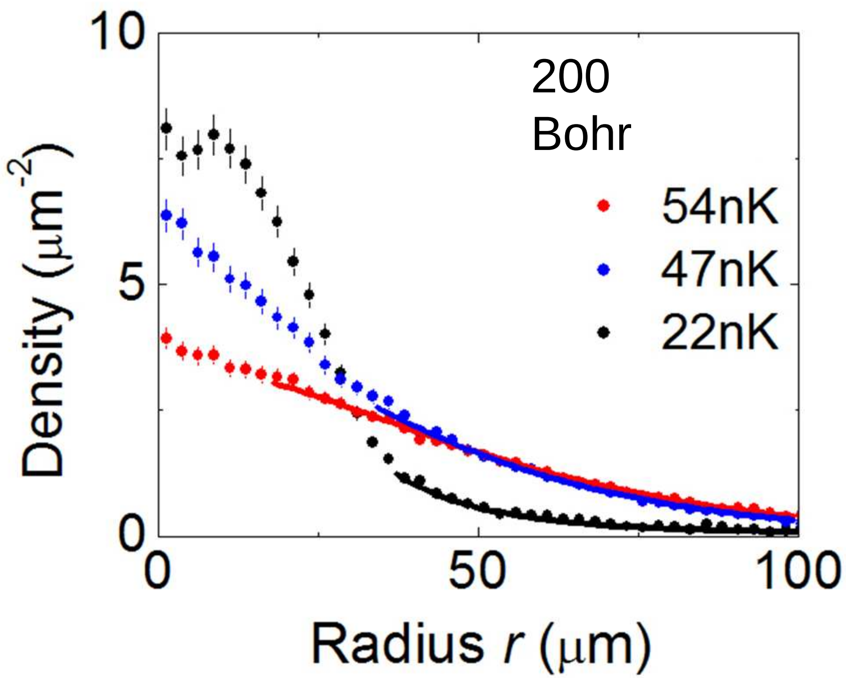


$$\mu = \mu_0 - \frac{1}{2} m\omega^2 r^2$$



LDA:
Local Density
Approximation

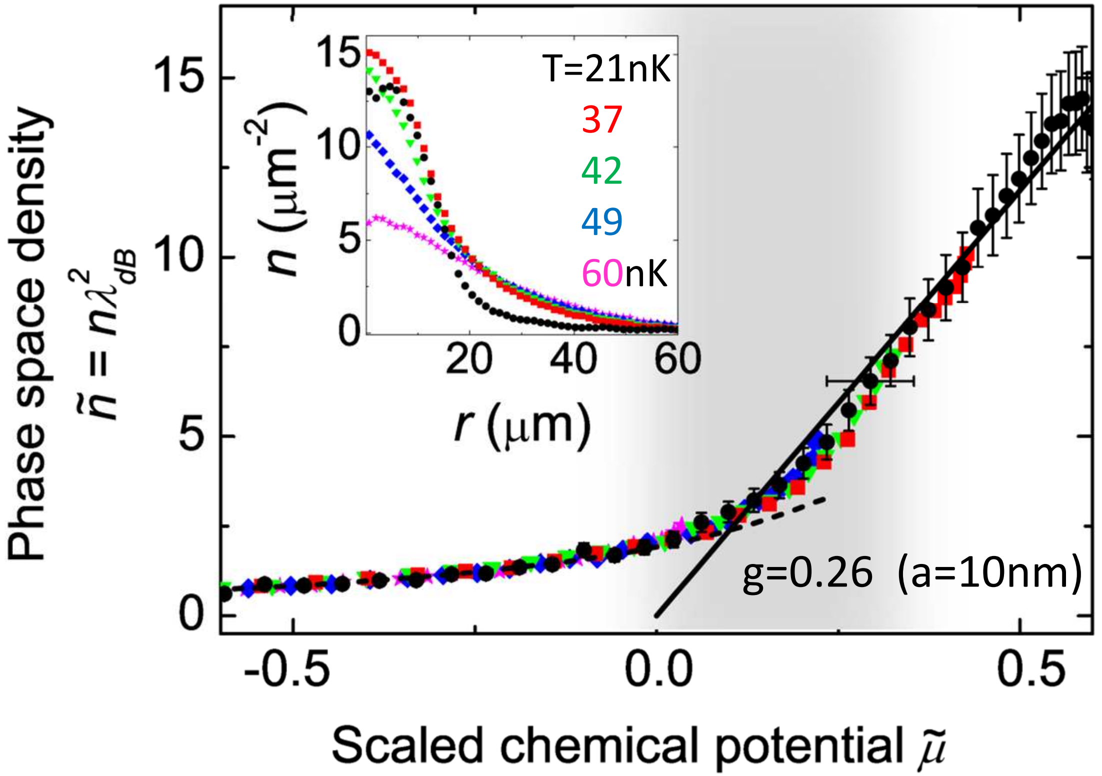
averaged density



$$n(\mu, T) = -\lambda_{dB}^{-2} \ln[1 - \exp(\mu/k_B T - gn\lambda_{dB}^2/\pi)]$$

Rath et. al., PRA 82, 013609 (2010)

Scale Invariance - Density $\tilde{n} = n\lambda_{dB}^2 = F(\frac{\mu}{kT})$



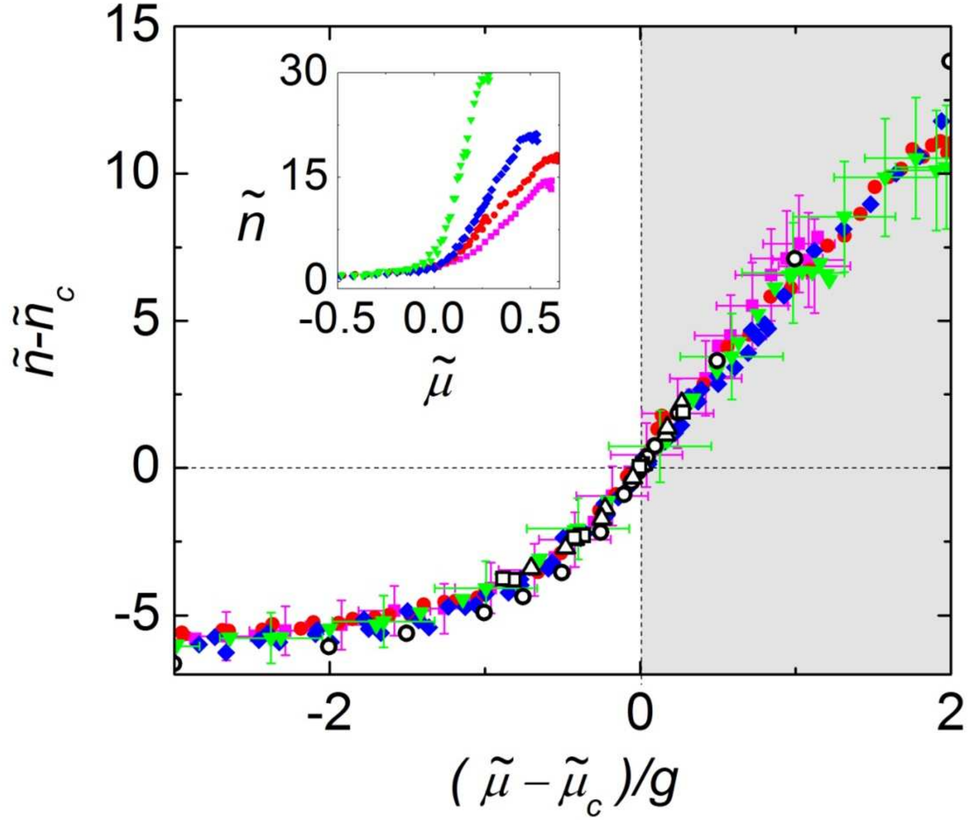
- - - - $n(\mu, T) = -\lambda_{dB}^{-2} \ln[1 - \exp(\mu/k_B T - g n \lambda_{dB}^2/\pi)]$

——— $\tilde{n} = 2\pi\tilde{\mu}/g$ (Thomas Fermi approximation)

Universality – Density

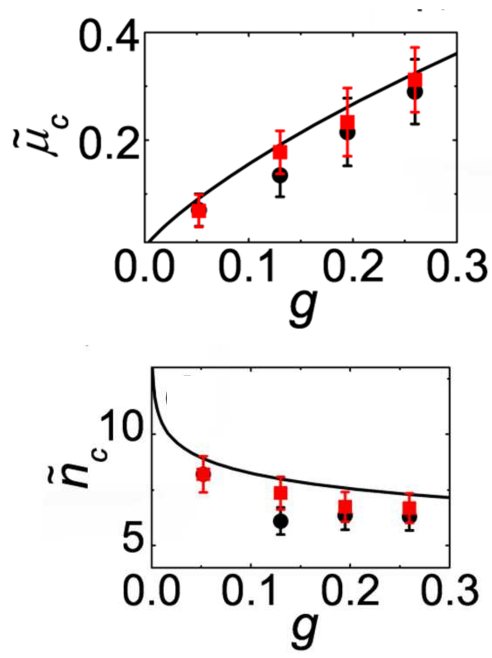
$$\tilde{n} - \tilde{n}_c = H\left(\frac{\mu - \mu_c}{kTg}\right)$$

g=0.26, 0.19, 0.13, 0.05



△ □ Holzmann et. al., PRA 81, 043622 (2010)

○ Prokof'ev et. al., PRA 66, 043608 (2002)



$\tilde{n}_c = \ln(\xi/g) \qquad \xi = 380$

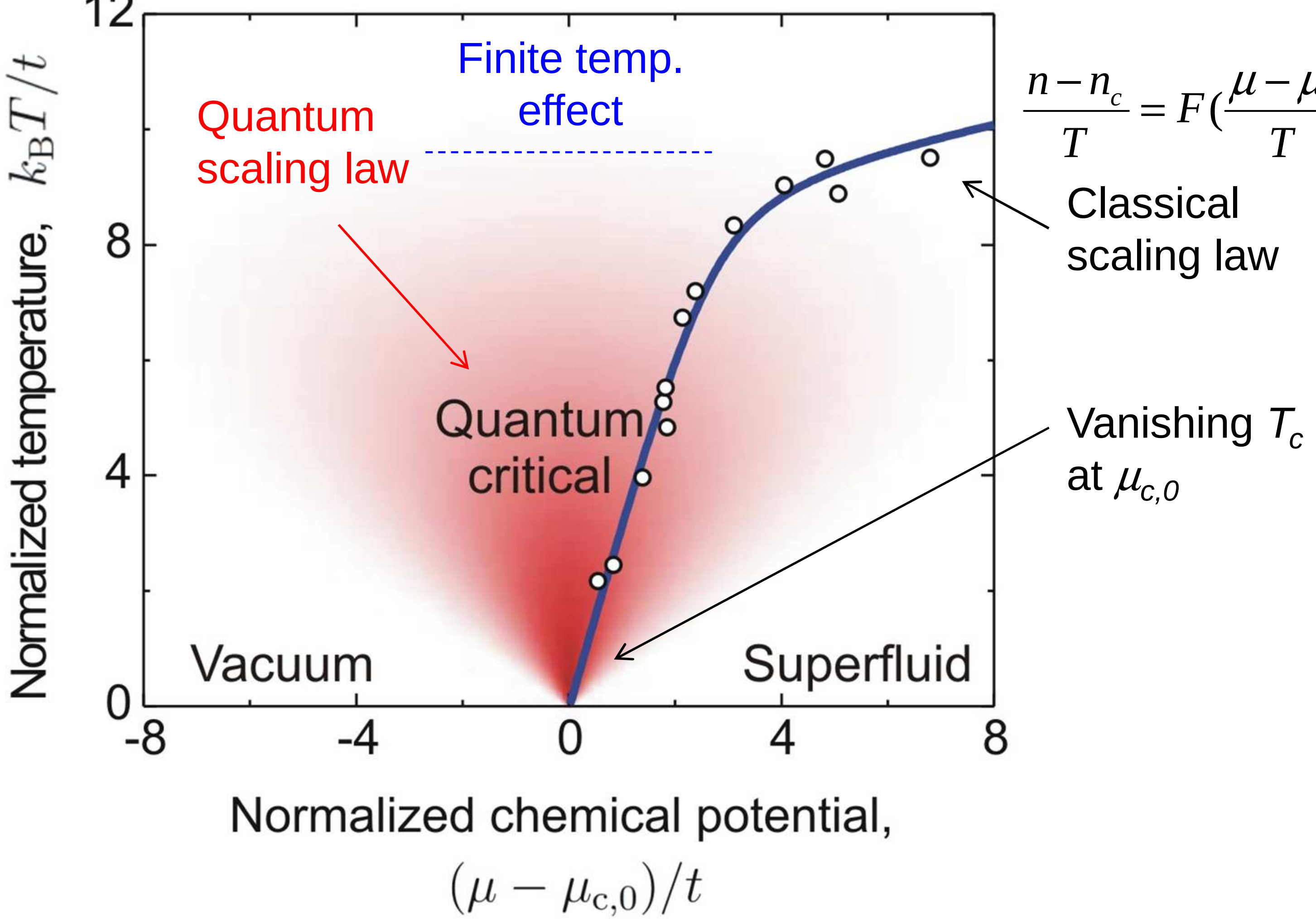
$\tilde{\mu}_c = (g/\pi)\ln(\xi_\mu/g) \qquad \xi_\mu = 13.2$

Prokof'ev et. al., PRL 87, 270402 (2001)

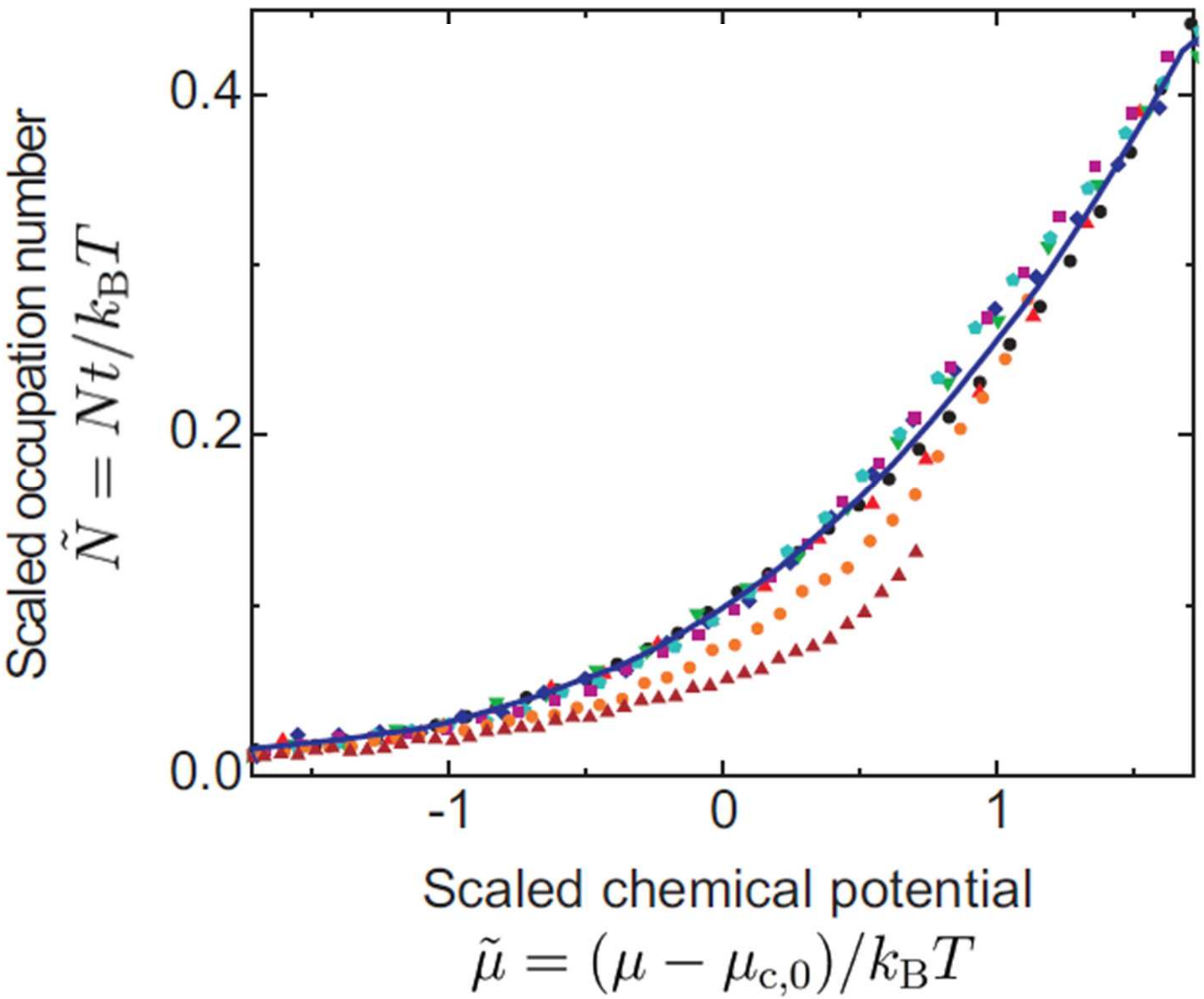
Quantum phase transition in 2D lattice at V=7 E_R

$$\frac{n}{T^{d/z+1-1/\nu z}} = G\left(\frac{\mu-\mu_{c,0}}{T^{1/\nu z}}\right)$$

$$\frac{n-n_c}{T} = F\left(\frac{\mu-\mu_c}{T}\right)$$



1. Universal scaling.



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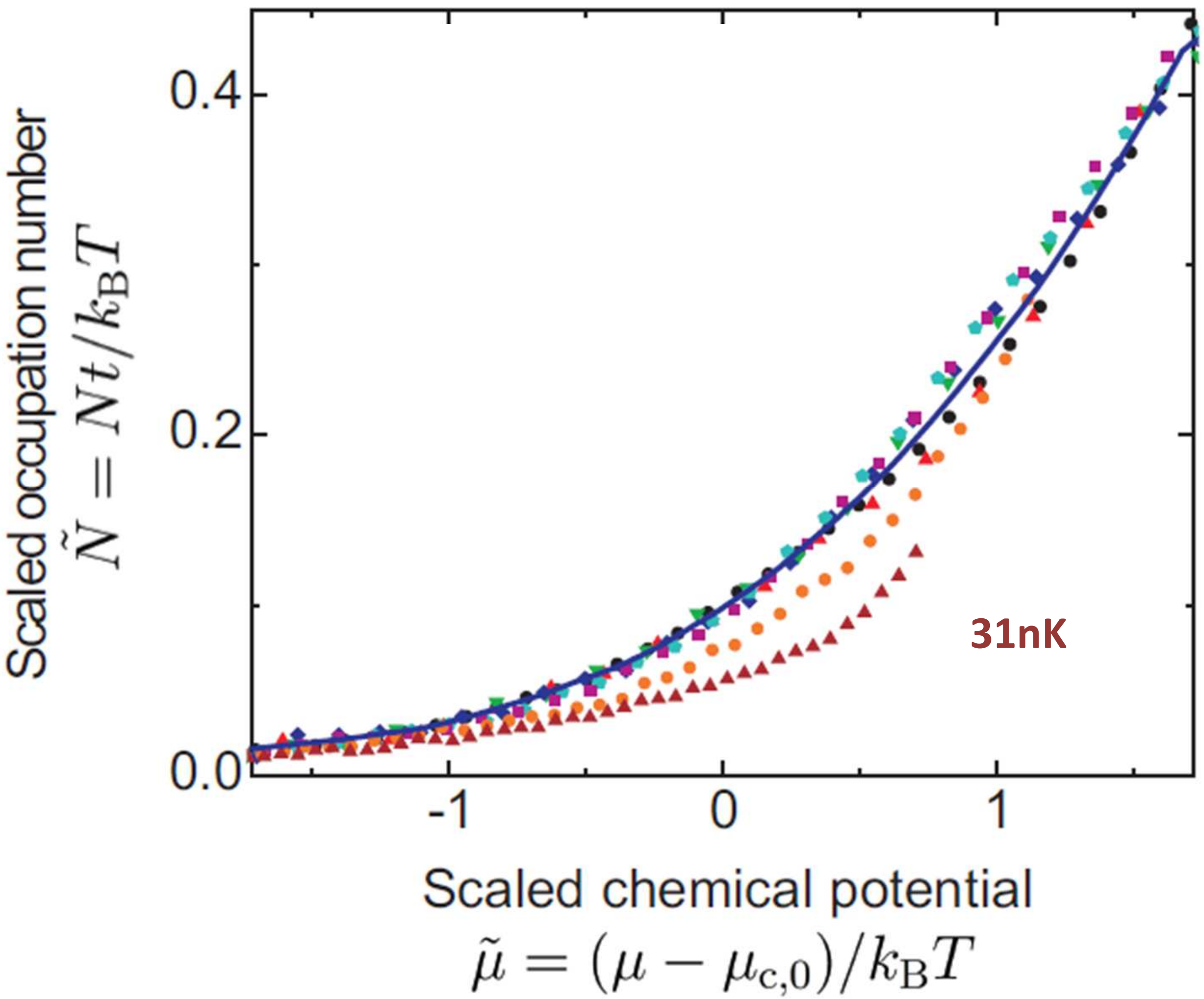

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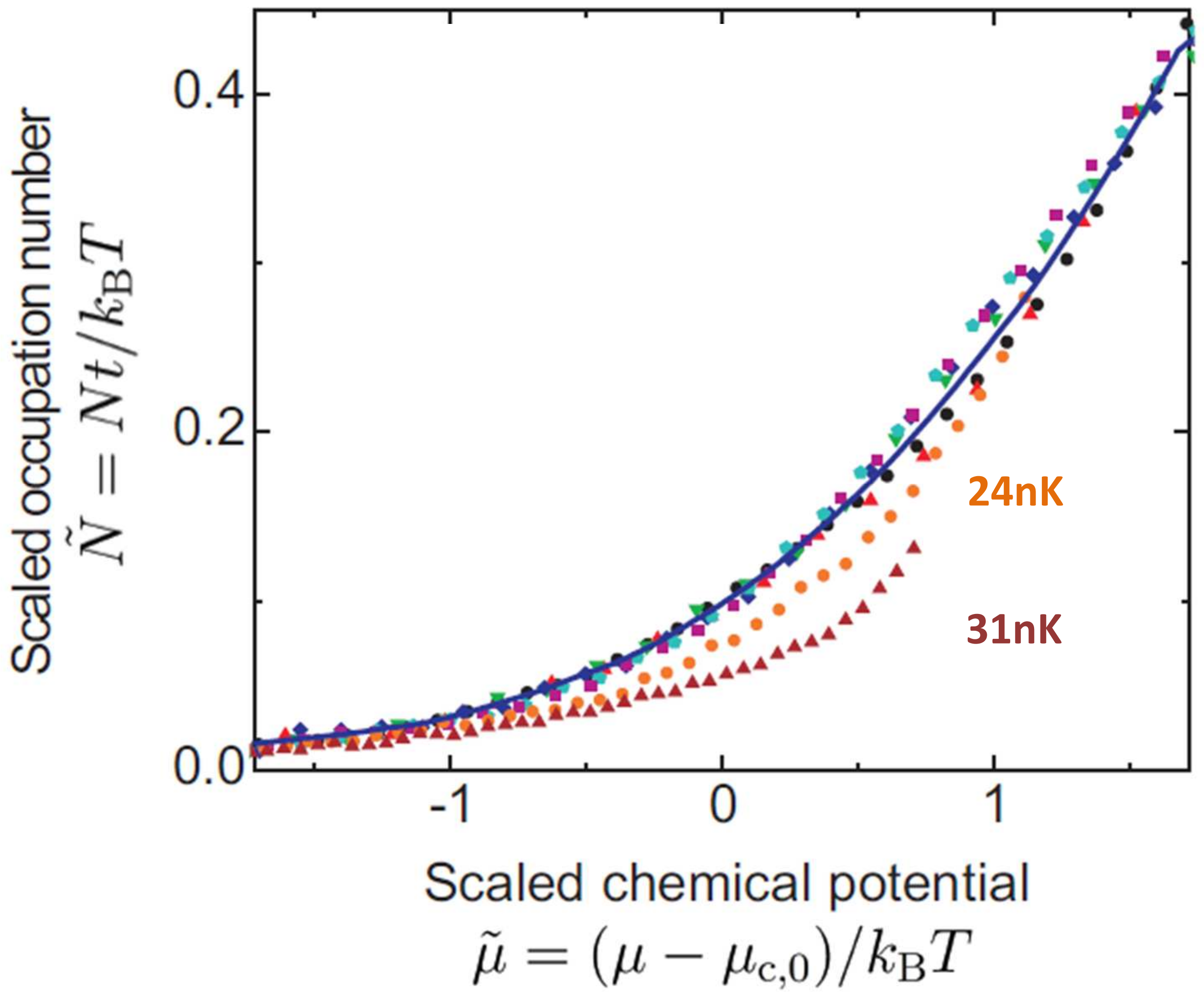

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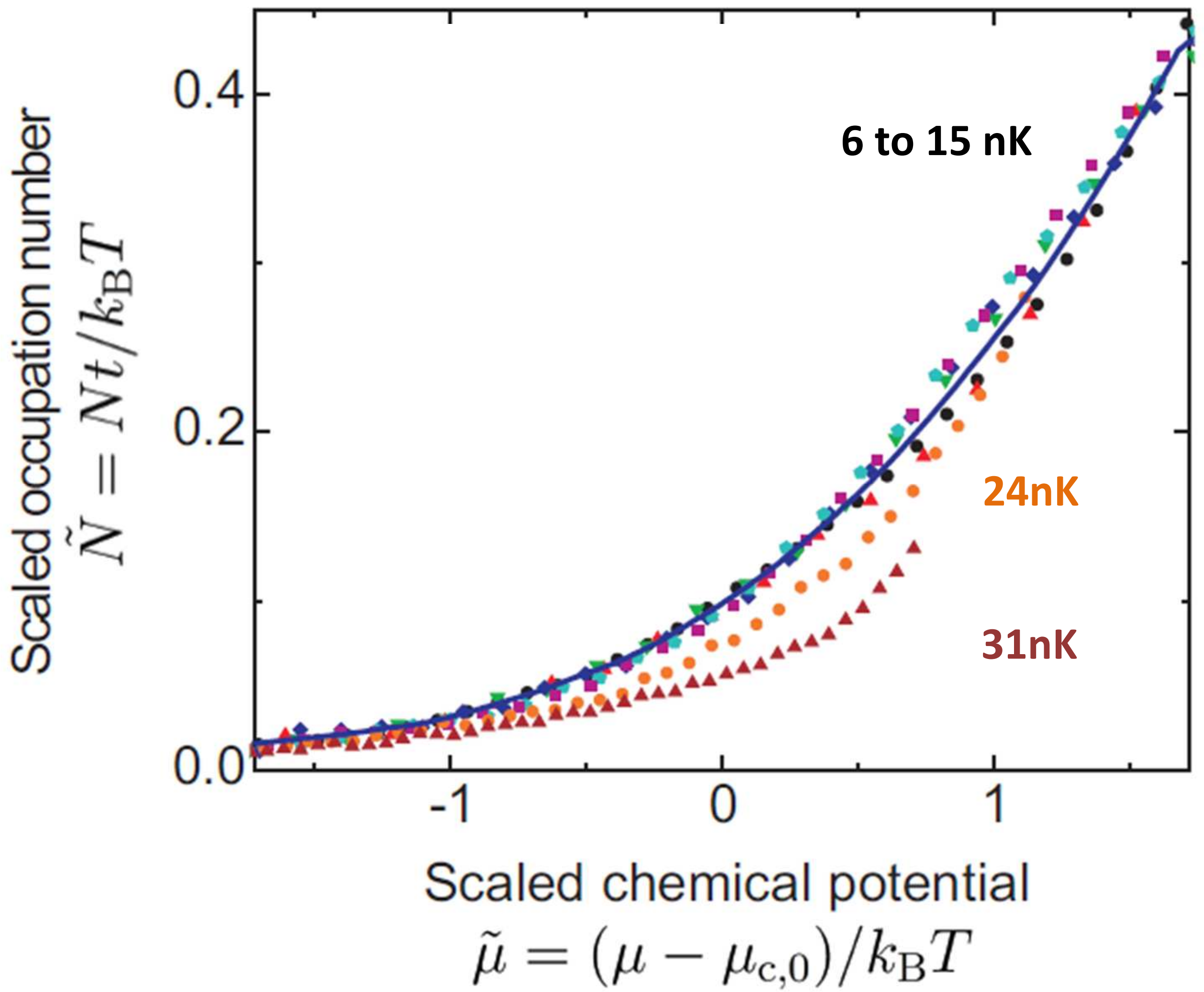
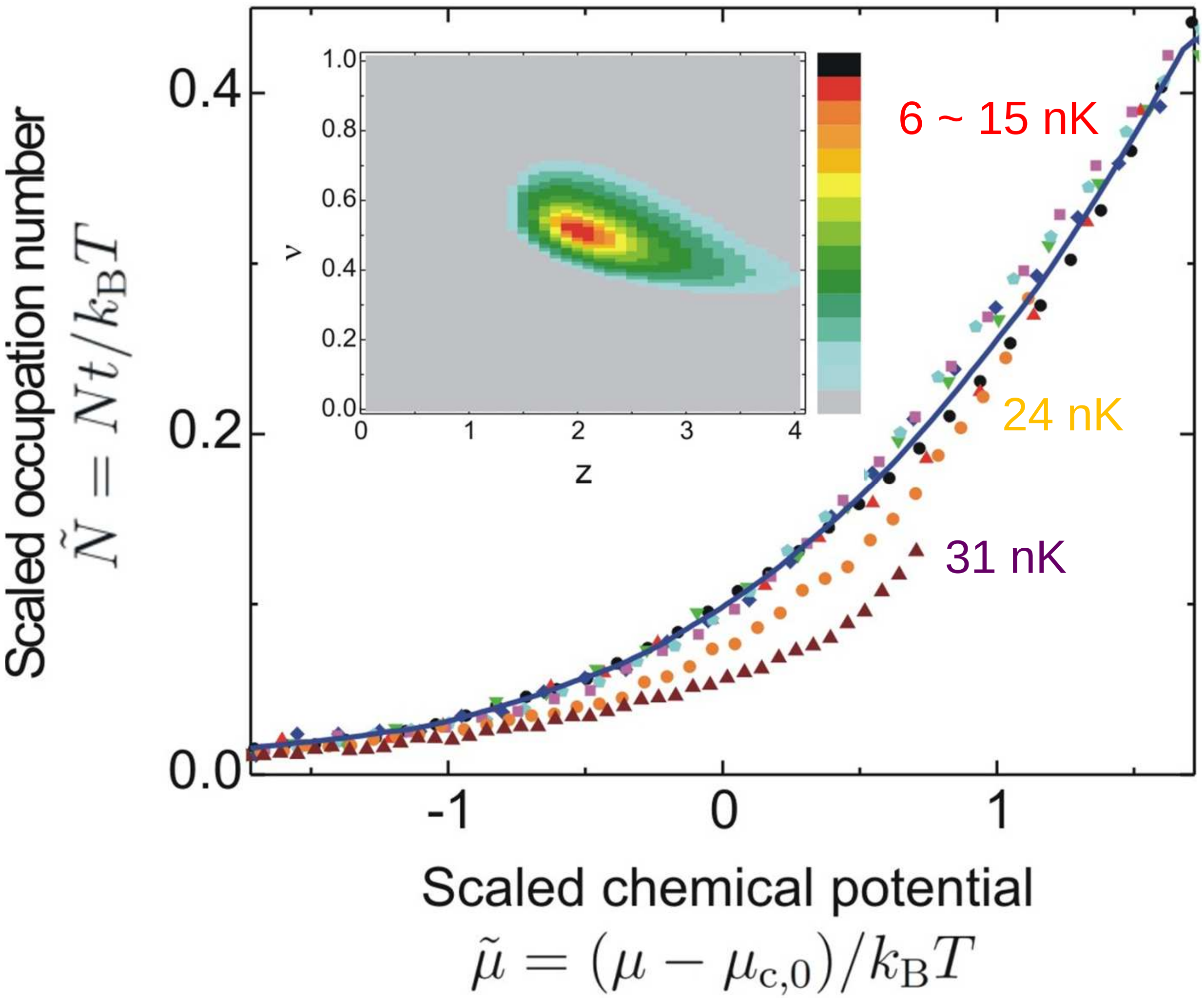


Tunneling=3nk

2. Critical exponents *z* and *v*: $\frac{n - n_c}{T^{d/z+1-1/\nu z}} = h(\frac{\mu - \mu_c}{T^{1/\nu z}})$

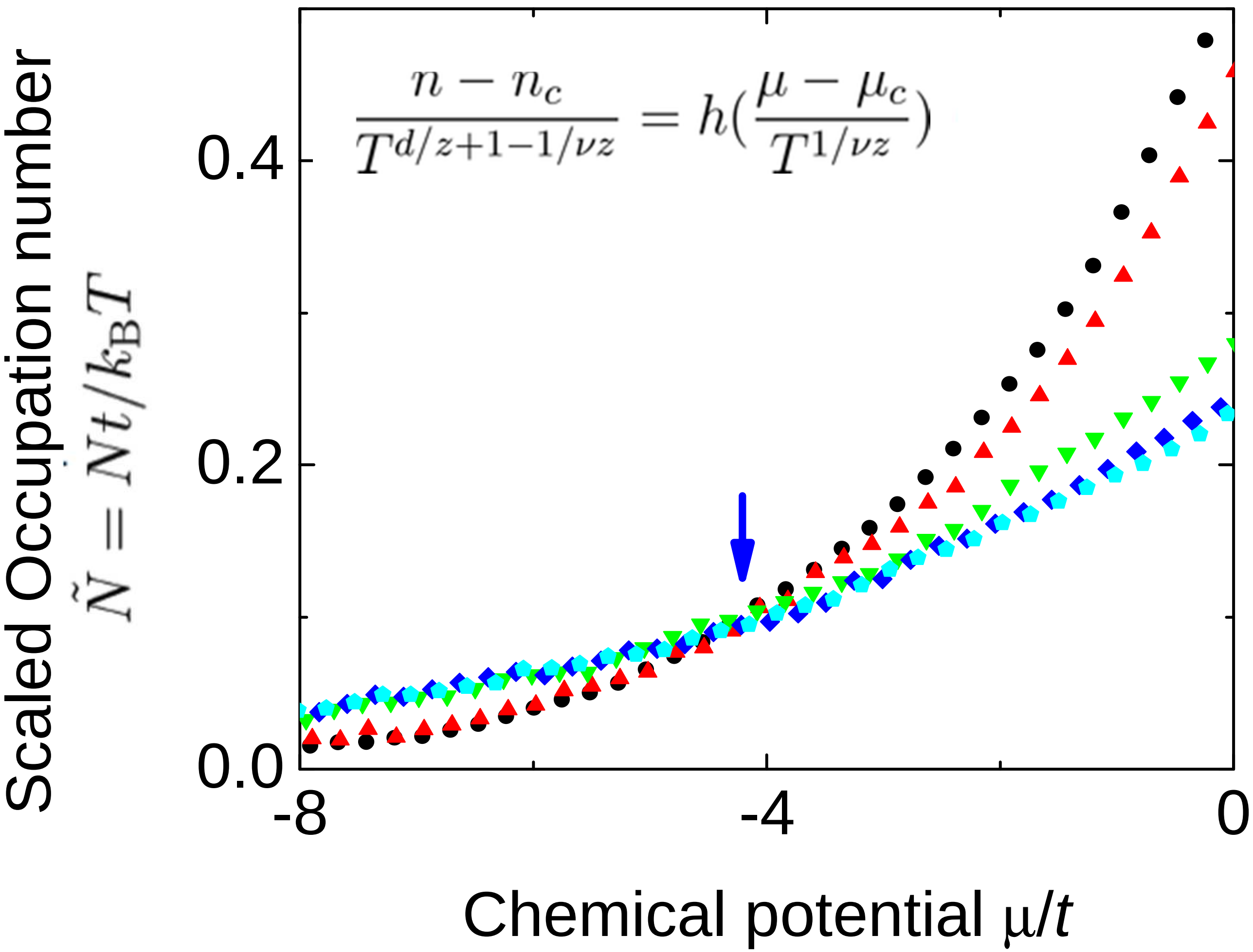


Theory:
z=2
v=1/2

Experiment:
z=2.0 (3)
v=0.53 (5)

3. Quantum Critical Point

$\mu_{c,0} = -4.2(6)t$ (theory: -4t)



Conclusion

Scale invariance and universality in 2D

In situ imaging: Cake structure *Nature (2008)*
Scale invariance and universality *Nature (2010)*
Quantum criticality: QPT in optical lattices …

New experiments:

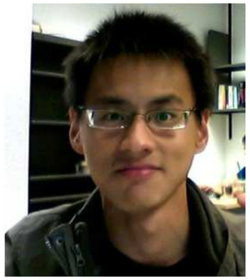
Quantum fluctuations and correlations *NJP (2011)*
Quantum critical transport *PRL (2010), NJP (2011)*

Cold atom experiments at Univ. of Chicago

Group members

Graduate
Chen-Lung Hung

Graduate
Xibo Zhang



New Student
Harry Ha

Postdocs

Dr. Shih-Kuang Tung

Dr. Colin Parker

Theory Collaborators

2D gas:
N. Prokofev, B. Svistunov

Criticality:
Q. Zhou, D.W. Wang, T.-L. Ho,
K. Hazzard, N. Trevidi

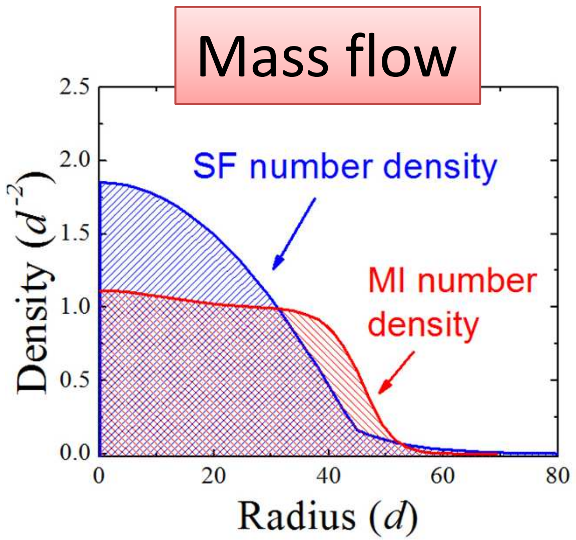
Cold molecules:
P. Julienne, E. Tiesinga

Former group members

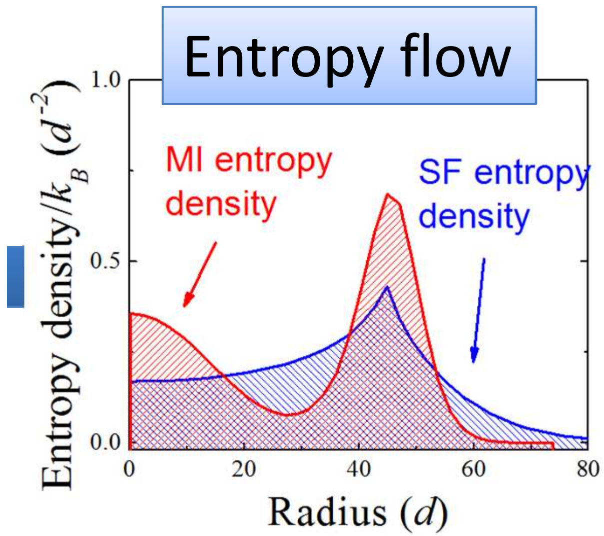
Prof. Nathan Gemelke
(Penn State Univ.)

Dr. Kathy-Anne Soderberg
(Booz allen Hamilton)

Dynamics across the SF-MI transition



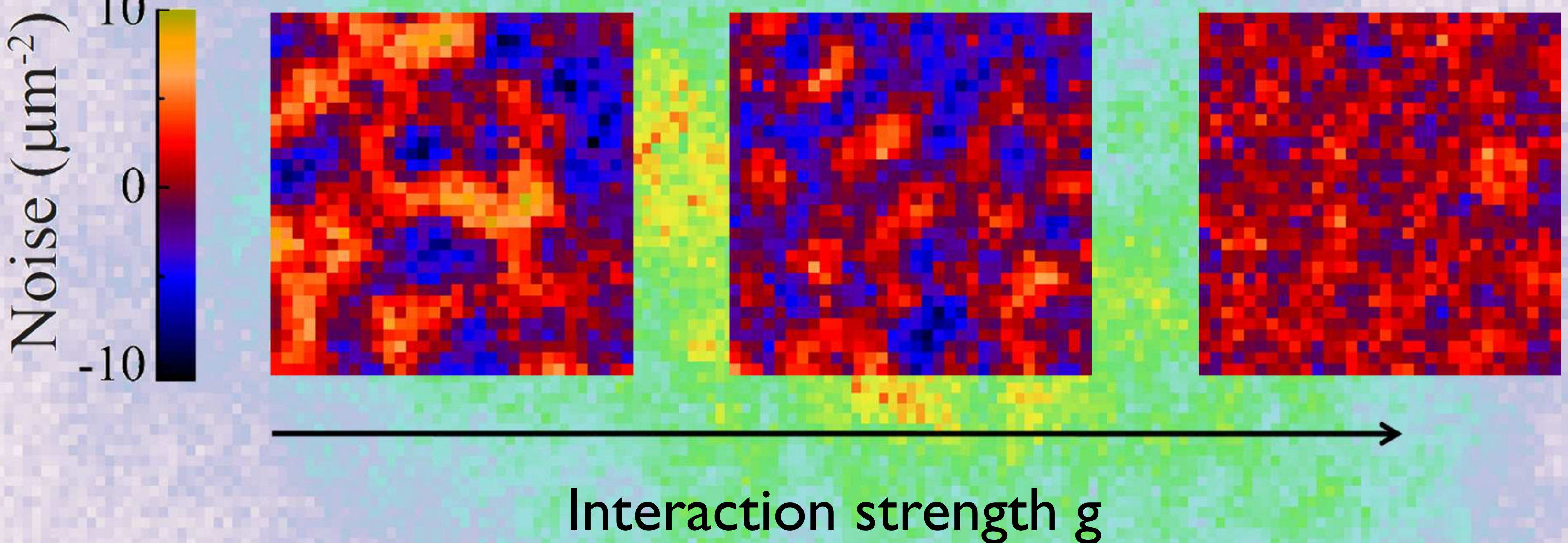
d:lattice constant



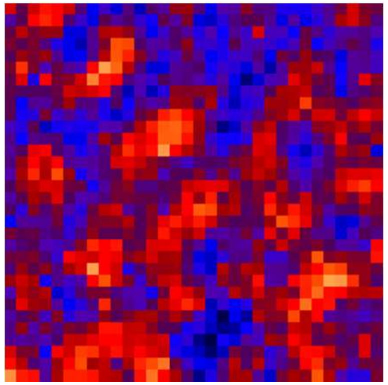
Near-equilibrium dynamics

$$\begin{pmatrix} J_m \\ J_s \end{pmatrix} = -\begin{bmatrix} A_{00} & A_{01} \\ A_{10} & A_{11} \end{bmatrix} \begin{pmatrix} \nabla \mu \\ \nabla T \end{pmatrix}$$

Extracting density-density correlations from in situ images of 2D quantum gases



Discrete Fourier Transform (FFT)
→ Density noise power spectrum

|FFT( **)|**^{2}

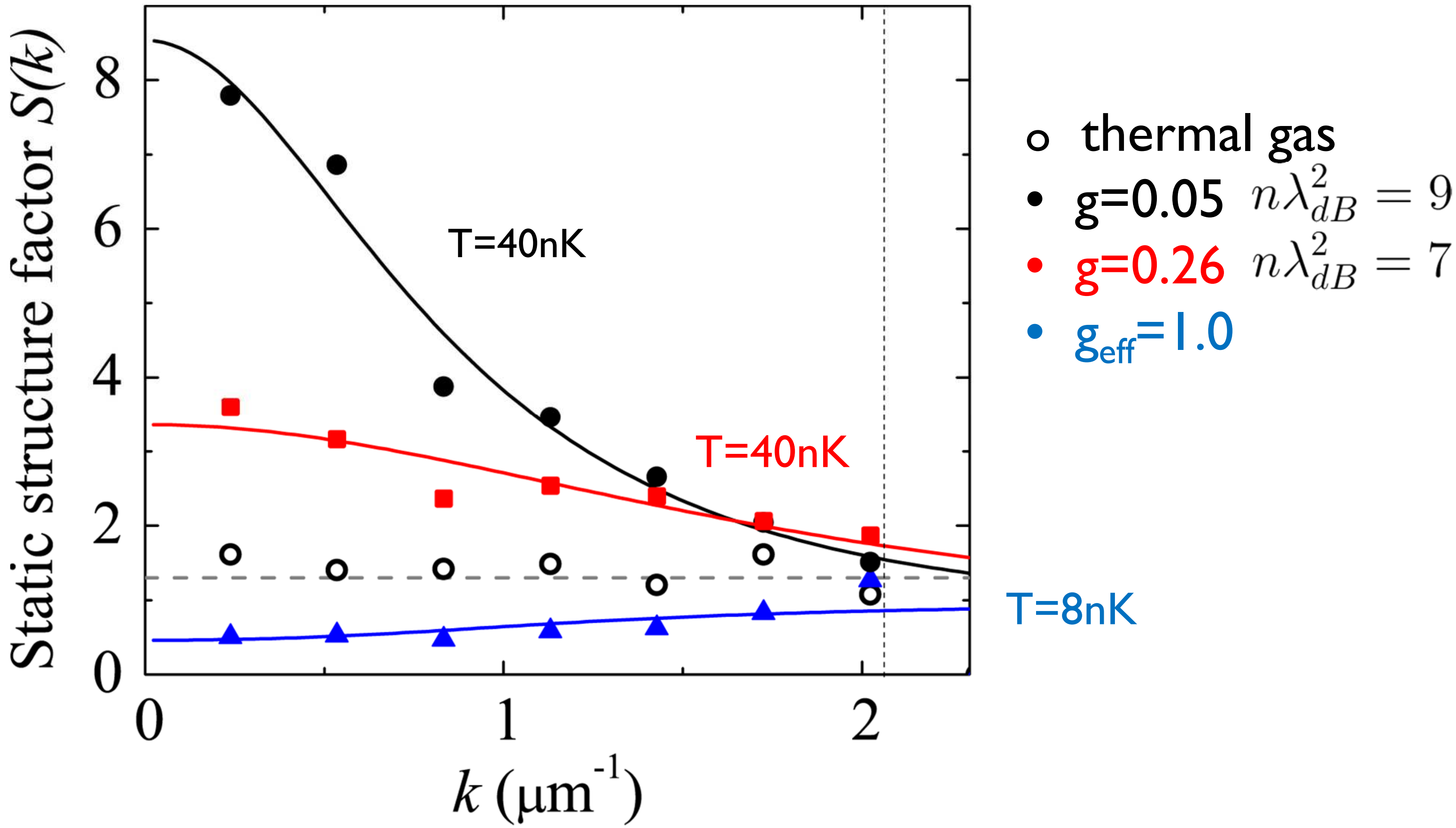
⟶ **Static structure factor $S(k)$**

after removing imaging systematics

$$S(k) = \frac{1}{n}\int \langle \delta n(0)\delta n(r)\rangle e^{-i\mathbf{k}\cdot\mathbf{r}} d^2 r = \frac{\langle |\delta n(k)|^2\rangle}{N}$$

k: spatial frequency

Static structure factor



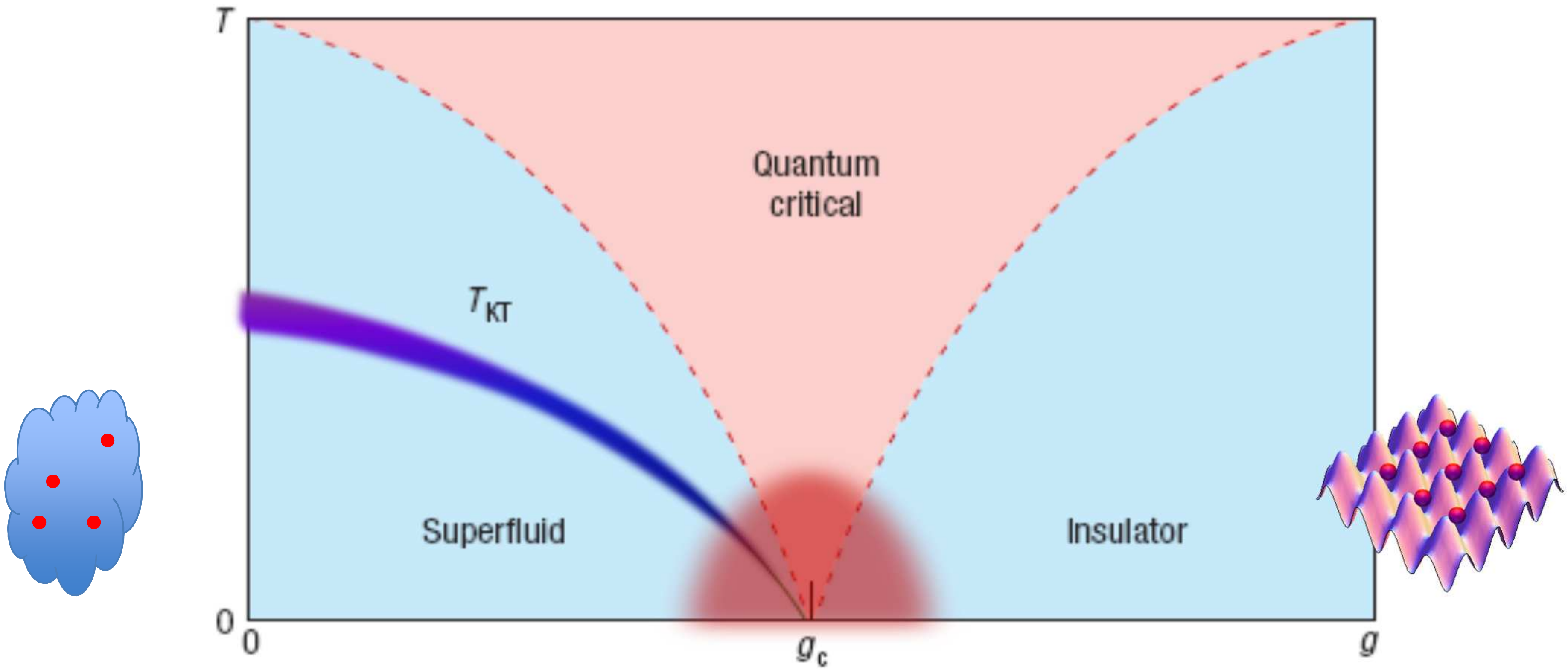
- C.-L. Hung et al. arXiv: 1105.0030 (2011)

Universal scale behaviors regarding scale invariance and dilute Bose gas universality in 2D
Critical fluctuations and correlations

Classical superfluid phase transition at finite temperatures

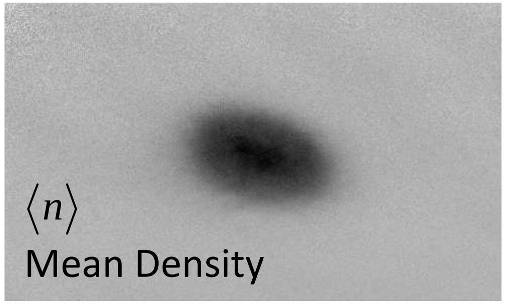
Quantum phase transitions near absolution zero temperature

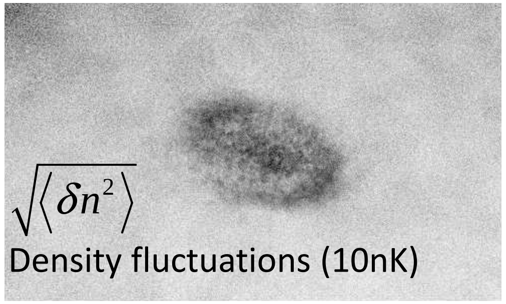
Phase transition and quantum phase transition

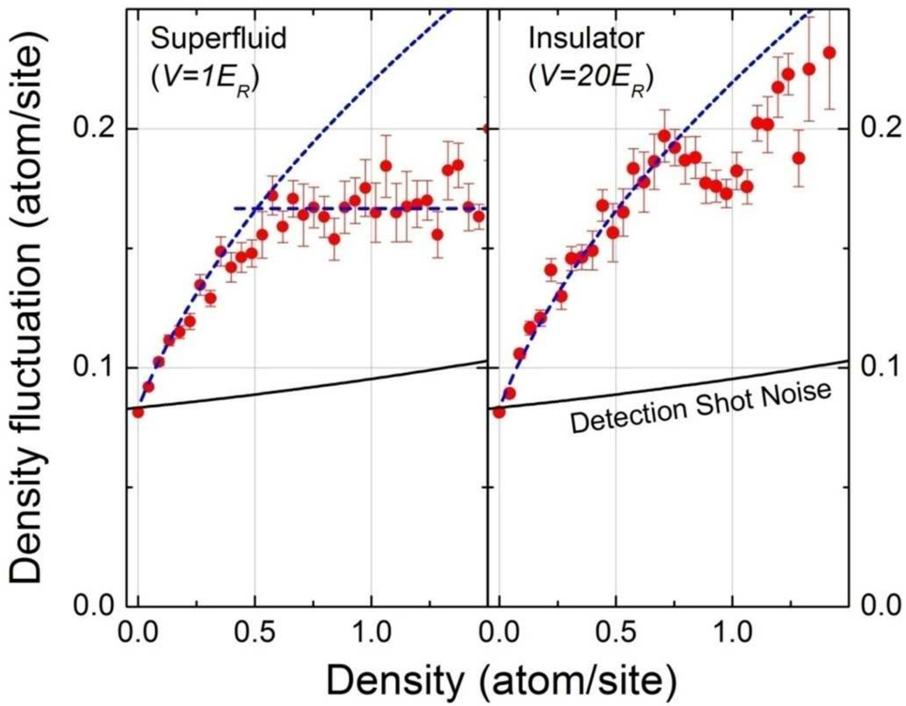


Phase diagram and AdS4-CFT3 duality: Sachdev, Nature physics (2007)

Reduced density fluctuations in a Mott Insulator



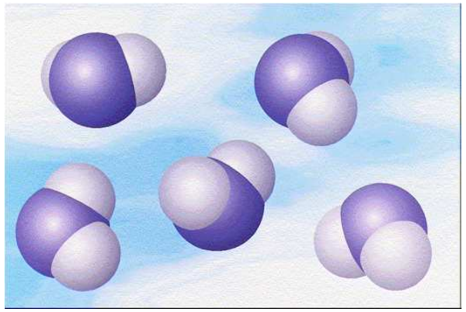




Fluctuation-dissipation theorem

fluctuation $\sum_j < \Delta n_i \, \Delta n_j >= k_B T \kappa_i$ compressibility

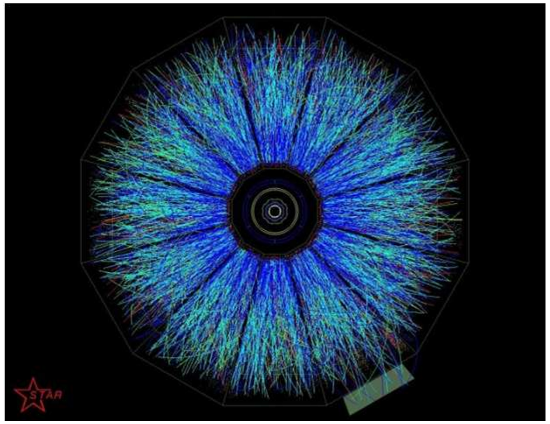
Quantum Simulation



Atoms and molecules

Other applications:
quantum chemistry,
quantum information,
precision metrology

Nuclear physics

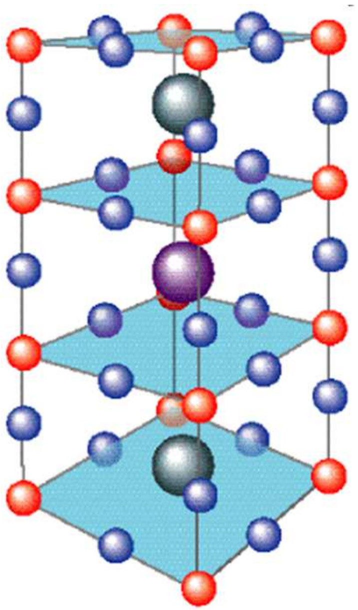


Efimov physics

Quark-gluon plasma

…

Condensed matter physics



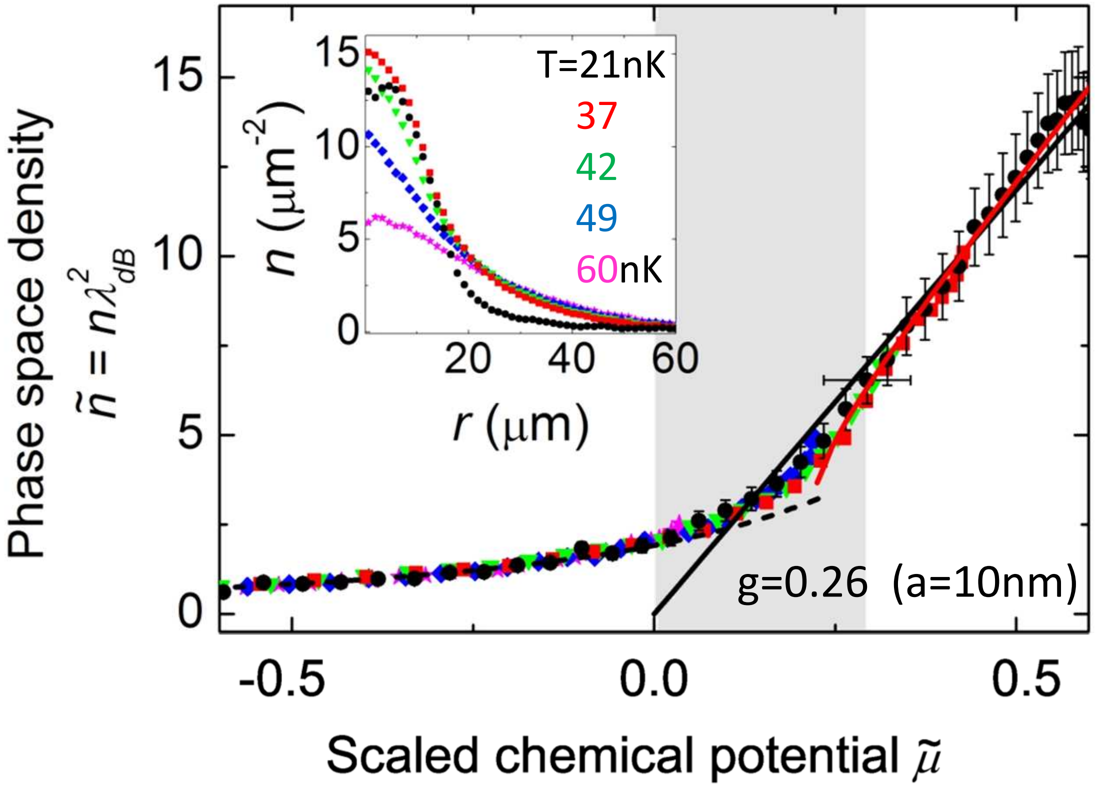
BEC-BCS crossover

Quantum magnetism

…

Illustration of scaling symmetry

Scale Invariance - Density $\tilde{n} = n\lambda_{dB}^2 = F(\frac{\mu}{kT})$



$$n(\mu, T) = -\lambda_{dB}^{-2} \ln[1 - \exp(\mu/k_B T - gn\lambda_{dB}^2/\pi)]$$

$$\tilde{n} = 2\pi\tilde{\mu}/g + \ln(\frac{2\tilde{n}g}{\pi} - 2\tilde{\mu})$$

Prokof'ev and Svistunov, PRA 66, 043608 (2002)