

# Ultracold Atoms

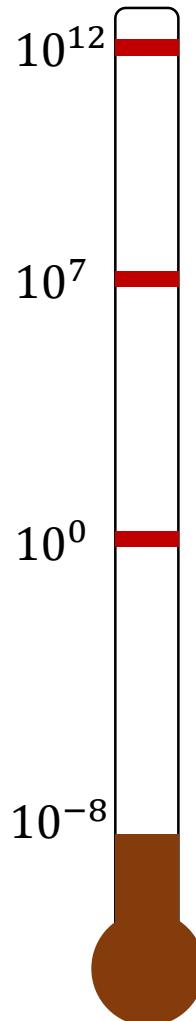
Bing Yang

Heidelberg University

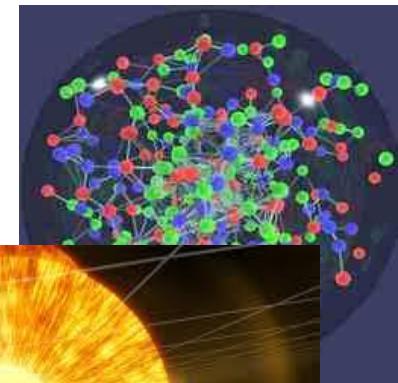
University of Science and Technology of China

# Temperatures of physical systems

$T$  in Kelvin



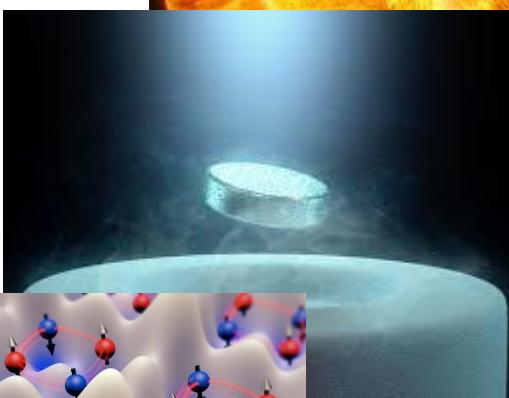
Quark-gluon plasma



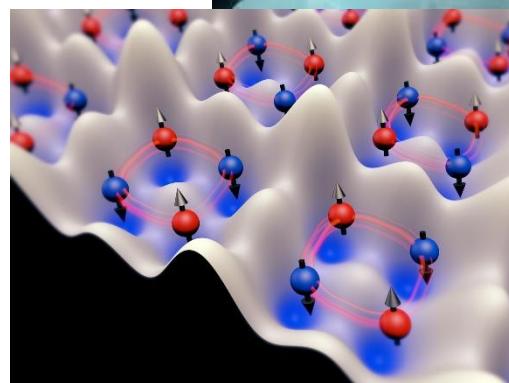
Sun center



Superconductors



Ultracold atoms



# Quantum physics

$$k_B T \quad \longleftrightarrow \quad E_{\text{kin}}/h$$

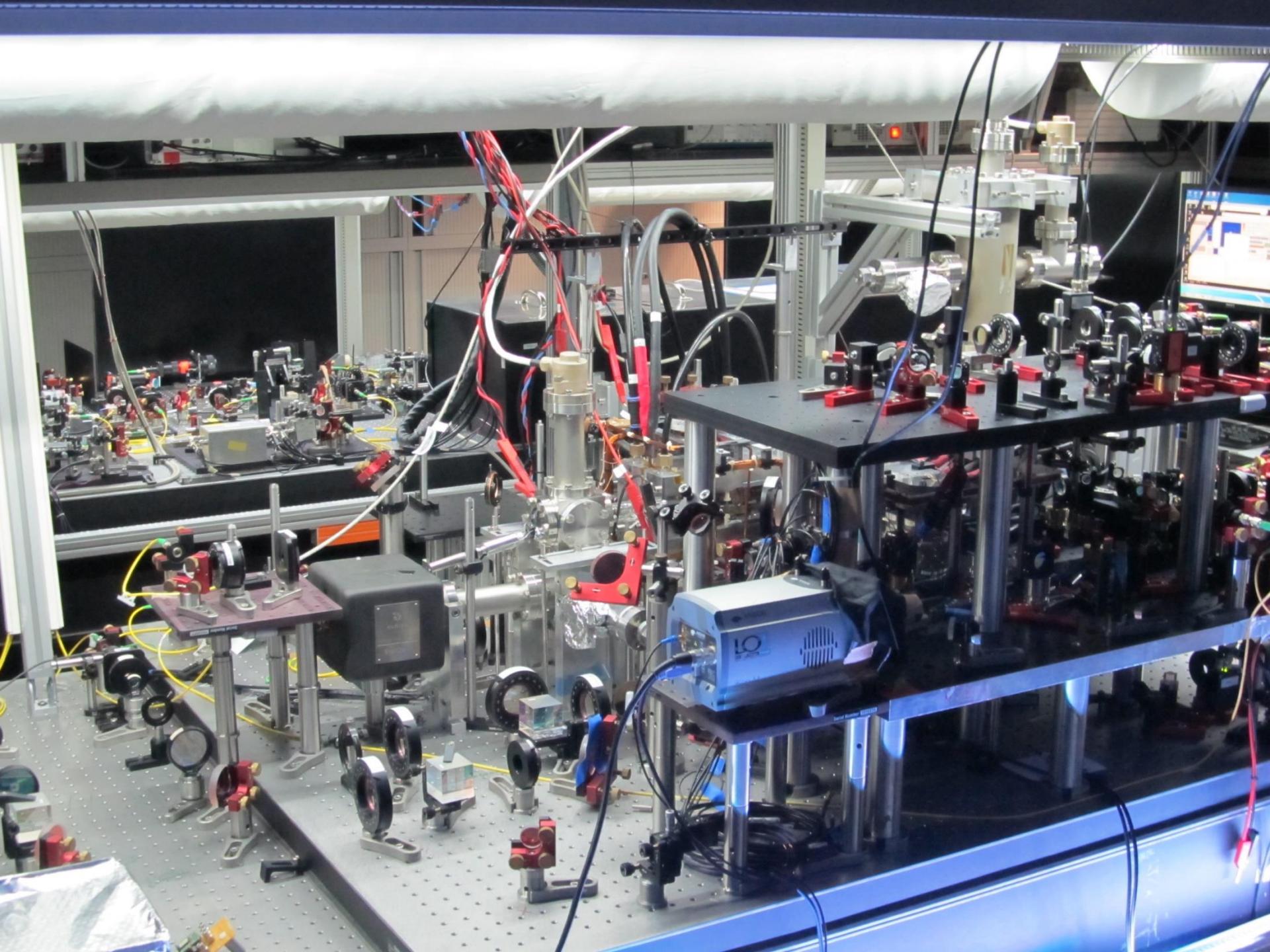
Reveal quantum phenomena

$$\lambda_{deBroglie} \quad \longleftrightarrow \quad a \quad \text{Particle spacing}$$

At  $T = 10^{12}$  K  $\lambda_{deBroglie} \sim 10^{-16}$  m Nuclear physics

$T = 10^0$  K  $\lambda_{deBroglie} \sim 10^{-10}$  m Condense matter

$T = 10^{-8}$  K  $\lambda_{deBroglie} \sim 10^{-6}$  m Ultracold atoms



# Outline

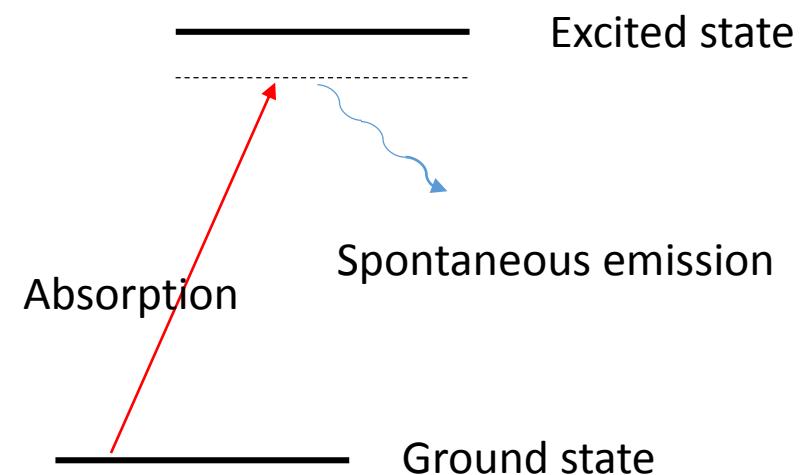
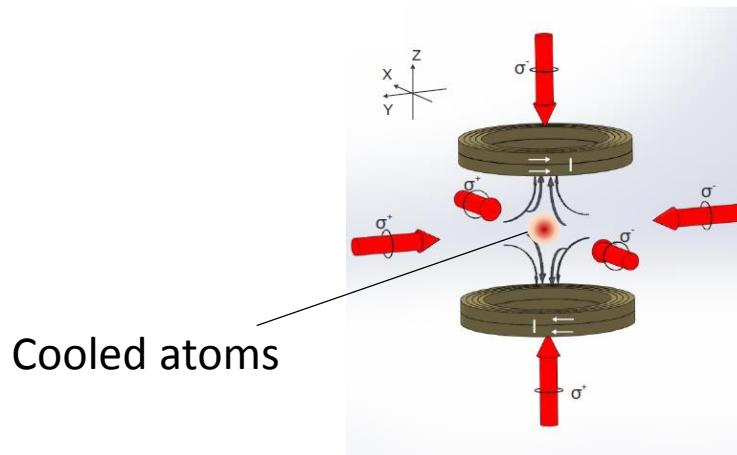
- Creating ultracold gases
- Interactions
- Exotic quantum matters
- Recent experiments: quantum simulations

# Outline

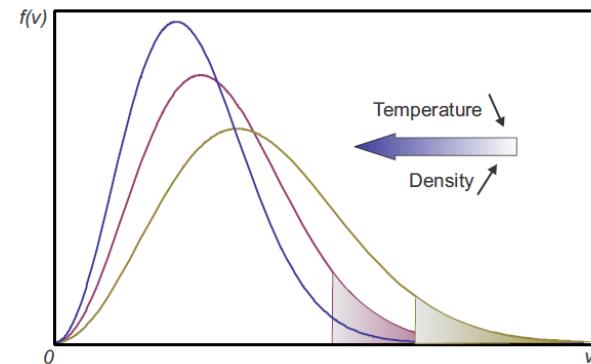
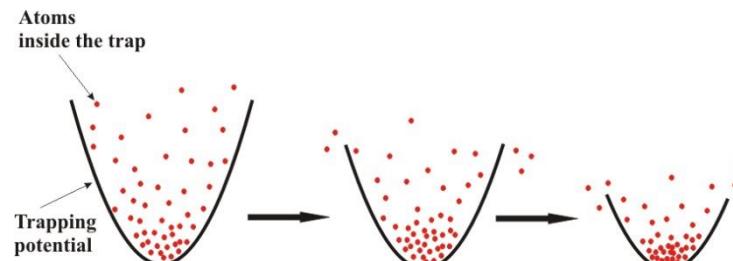
- Creating ultracold gases
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# Cooling neutral atoms

## Laser cooling and trapping



## Evaporative cooling



# Cooling neutral atoms

$$T \approx 10 \text{ } \mu\text{K}$$

$$\nu \sim 10 \text{ cm/s}$$

Laser cooling

$$N \approx 10^9 \text{ atoms}$$

$$n \approx 10^{10} \text{ cm}^{-3}$$

$$a \sim 10 \text{ } \mu\text{m}$$

$$T \approx 100 \text{ } n\text{K}$$

$$\nu \sim 1 \text{ mm/s}$$

Evaporative cooling

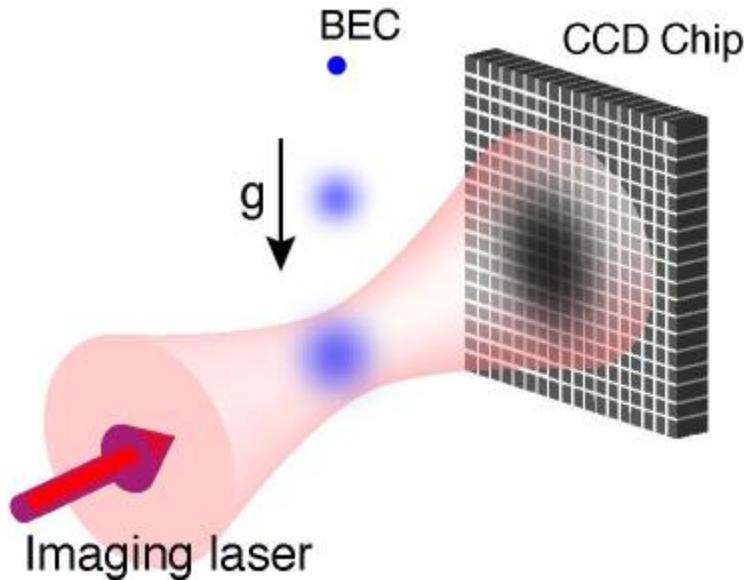
$$N \approx 10^6 \text{ atoms}$$

$$n \approx 10^{13} \text{ cm}^{-3}$$

$$a \sim 1 \text{ } \mu\text{m}$$

# Detection of cold atoms

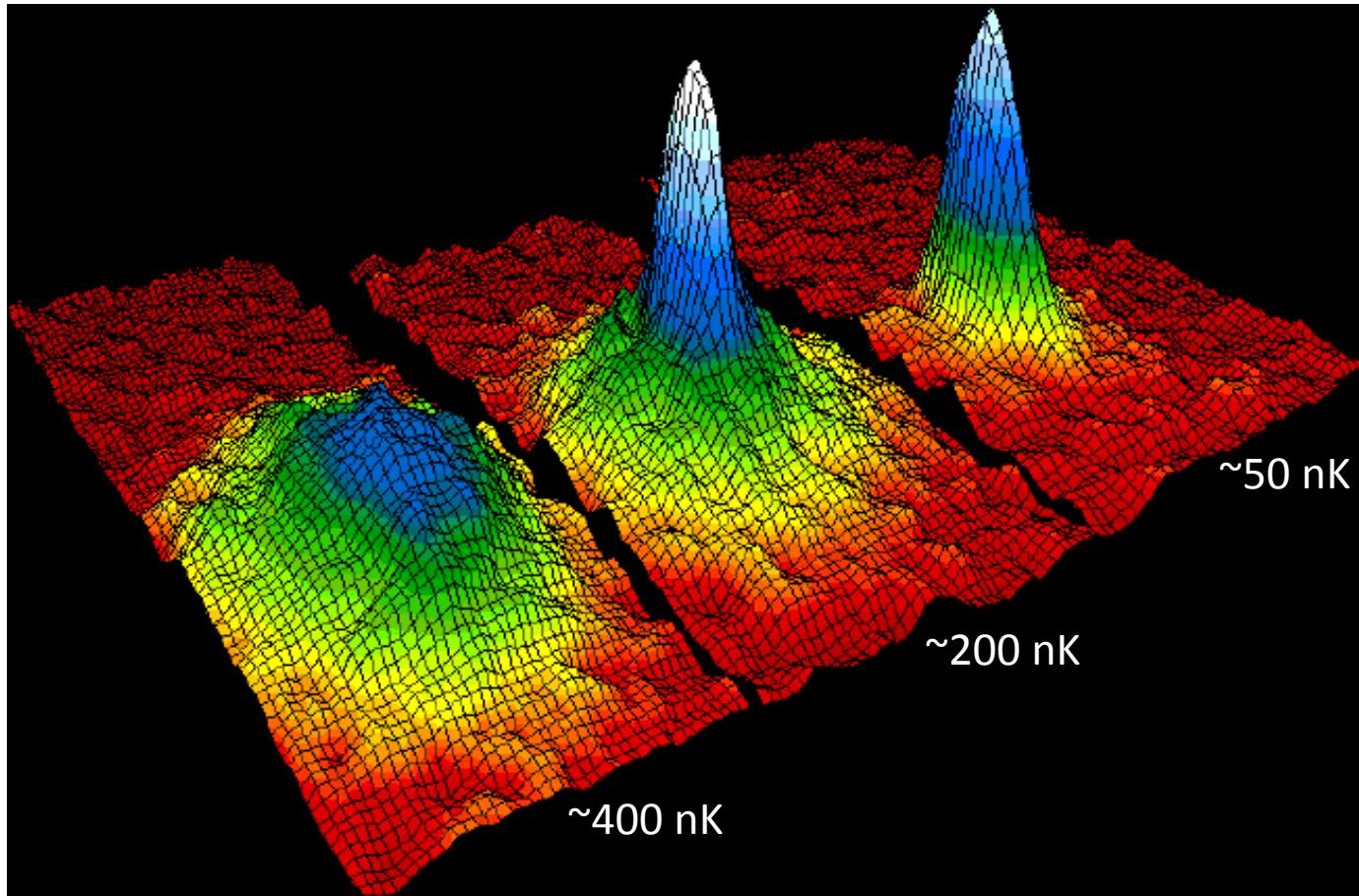
Time of flight → Momentum distribution



Absorption imaging

$$\sigma_0 = \frac{3\lambda^2}{2\pi} \quad \text{Cross section}$$

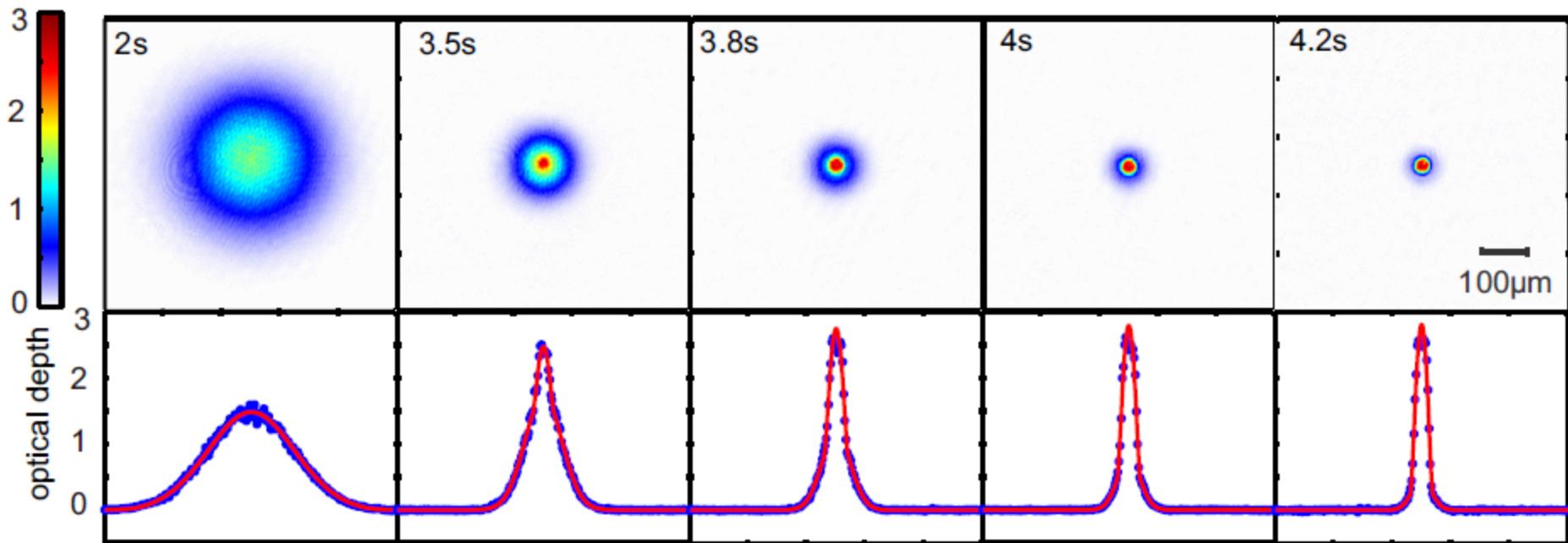
# Bose-Einstein condensate



JILA, 1995

# Bose-Einstein condensate

In our lab, Bose-Einstein condensate of Rubidium 87



# Condensates of elements

hydrogen 1 <b>H</b> 1.0079	boron 4 <b>Be</b> 9.0122	carbon 6 <b>C</b> 12.011	nitrogen 7 <b>N</b> 14.007	oxygen 8 <b>O</b> 15.999	fluorine 9 <b>F</b> 18.998	neon 10 <b>Ne</b> 20.180							
lithium 3 <b>Li</b> 6.941	magnesium 12 <b>Mg</b> 24.305	aluminum 13 <b>Al</b> 26.982	silicon 14 <b>Si</b> 28.086	phosphorus 15 <b>P</b> 30.974	sulfur 16 <b>S</b> 32.065	chlorine 17 <b>Cl</b> 35.453							
sodium 11 <b>Na</b> 22.990	calcium 20 <b>Ca</b> 40.078	gallium 31 <b>Ga</b> 69.723	germanium 32 <b>Ge</b> 72.61	arsenic 33 <b>As</b> 74.922	selenium 34 <b>Se</b> 78.95	krypton 36 <b>Kr</b> 83.80							
potassium 19 <b>K</b> 39.098	scandium 21 <b>Sc</b> 44.956	yttrium 39 <b>Y</b> 88.906	zirconium 40 <b>Zr</b> 91.224	tin 41 <b>Nb</b> 92.906	technetium 42 <b>Mo</b> 95.94	ruthenium 43 <b>Tc</b> [98]							
rubidium 37 <b>Rb</b> 85.468	titanium 22 <b>Ti</b> 47.967	neodymium 44 <b>Ru</b> 101.07	rhodium 45 <b>Rh</b> 102.91	roentgenium 46 <b>Pd</b> 106.42	osmium 47 <b>Ag</b> 107.87	cadmium 48 <b>Cd</b> 112.41							
cesium 55 <b>Cs</b> 132.91	vanadium 23 <b>V</b> 50.942	rhenium 75 <b>Re</b> [98]	iridium 76 <b>Os</b> 190.23	platinum 77 <b>Pt</b> 192.22	platinum 78 <b>Au</b> 196.08	mercury 80 <b>Hg</b> 196.97							
bromine 87 <b>Br</b> [223]	chromium 24 <b>Cr</b> 51.996	lutetium 71 <b>Lu</b> 174.97	tautulium 72 <b>Hf</b> 178.49	thulium 73 <b>Ta</b> 180.95	thulium 74 <b>W</b> 183.84	thulium 75 <b>Re</b> 186.21							
rubidium 87 <b>Ra</b> [223]	actinium 57-70 <b>Ba</b> 137.33	yttrium 76 <b>Os</b> 190.23	thulium 77 <b>Ir</b> 192.22	thulium 78 <b>Pt</b> 196.08	thulium 79 <b>Au</b> 196.97	thulium 80 <b>Hg</b> 200.59							
francium 87 <b>Fr</b> [223]	cerium 58 <b>Ce</b> 140.12	thulium 79 <b>Bh</b> [264]	thulium 100 <b>Hs</b> [265]	thulium 108 <b>Mt</b> [266]	thulium 109 <b>Uun</b> [267]	thulium 110 <b>Uuu</b> [268]							
lanthanum 57 <b>La</b> 138.91	praseodymium 59 <b>Pr</b> 140.91	neodymium 60 <b>Nd</b> 144.24	promethium 61 <b>Pm</b> [145]	samarium 62 <b>Sm</b> 150.36	europeum 63 <b>Eu</b> 151.96	gadolinium 64 <b>Gd</b> 157.25	dysprosium 66 <b>Dy</b> 162.50	holmium 67 <b>Ho</b> 164.93	erbium 68 <b>Er</b> 167.26	thulium 69 <b>Tm</b> 169.93	yterbium 70 <b>Yb</b> 173.04		
actinium 89 <b>Ac</b> [227]	cerium 90 <b>Th</b> 232.04	thorium 91 <b>Pa</b> 231.04	protactinium 92 <b>U</b> 238.03	neptunium 93 <b>Np</b> [237]	plutonium 94 <b>Pu</b> [244]	americium 95 <b>Am</b> [243]	curium 96 <b>Cm</b> [247]	berkelium 97 <b>Bk</b> [247]	californium 98 <b>Cf</b> [251]	eserrium 99 <b>Es</b> [252]	fermium 100 <b>Fm</b> [257]	mendelevium 101 <b>Md</b> [259]	nobelium 102 <b>No</b> [259]

\* Lanthanide series

lanthanum 57 <b>La</b> 138.91	cerium 58 <b>Ce</b> 140.12	praseodymium 59 <b>Pr</b> 140.91	neodymium 60 <b>Nd</b> 144.24	promethium 61 <b>Pm</b> [145]	samarium 62 <b>Sm</b> 150.36	europeum 63 <b>Eu</b> 151.96	gadolinium 64 <b>Gd</b> 157.25	terbium 65 <b>Tb</b> 158.93	dysprosium 66 <b>Dy</b> 162.50	holmium 67 <b>Ho</b> 164.93	erbium 68 <b>Er</b> 167.26	thulium 69 <b>Tm</b> 169.93	yterbium 70 <b>Yb</b> 173.04
actinium 89 <b>Ac</b> [227]	cerium 90 <b>Th</b> 232.04	thorium 91 <b>Pa</b> 231.04	protactinium 92 <b>U</b> 238.03	neptunium 93 <b>Np</b> [237]	plutonium 94 <b>Pu</b> [244]	americium 95 <b>Am</b> [243]	curium 96 <b>Cm</b> [247]	berkelium 97 <b>Bk</b> [247]	californium 98 <b>Cf</b> [251]	eserrium 99 <b>Es</b> [252]	fermium 100 <b>Fm</b> [257]	mendelevium 101 <b>Md</b> [259]	nobelium 102 <b>No</b> [259]

\*\* Actinide series

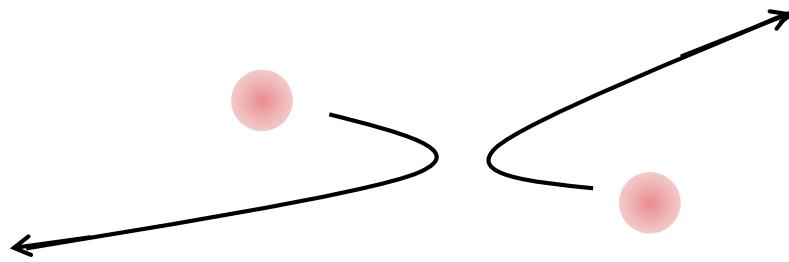
# Outline

- Creating ultracold gases
- Interactions
- Exotic quantum matters
- Recent experiments: quantum simulations

# Interactions

## ■ Short-range interaction

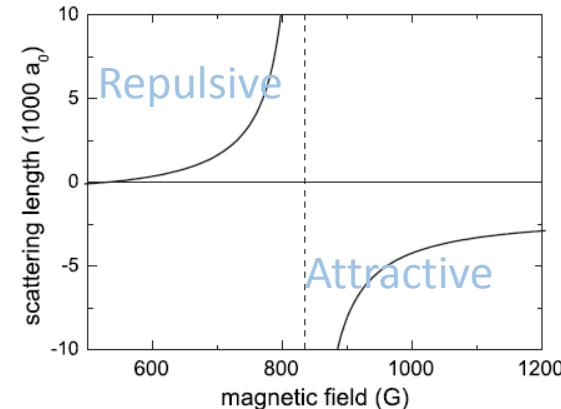
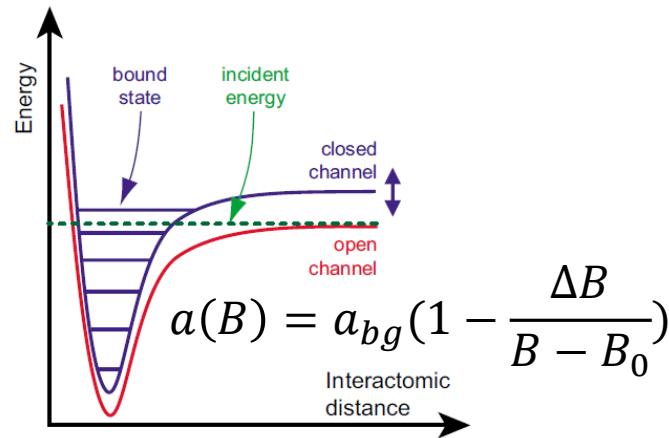
Atoms interact by colliding with each other.



s-wave collisions dominate in ultracold gases

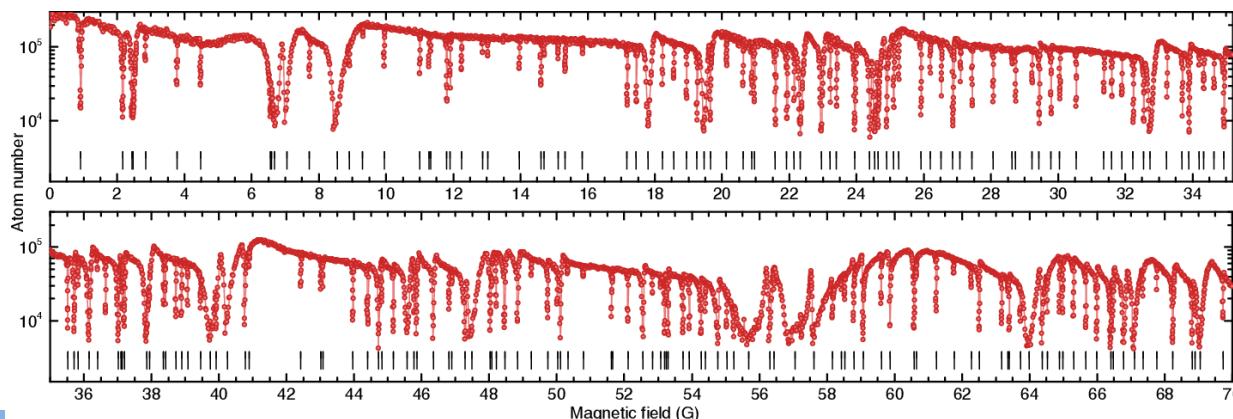
# Short-range Interactions

We can tune this interaction via Feshbach resonance



Chaotic Feshbach resonance of Erbium

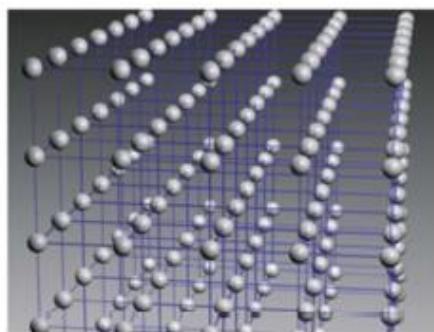
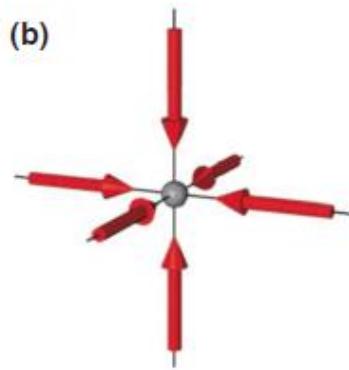
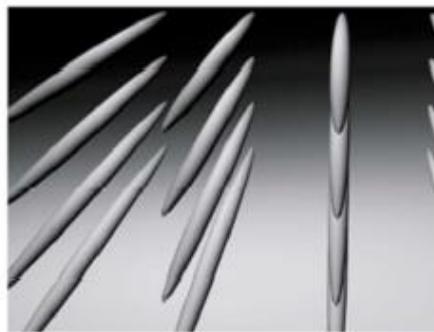
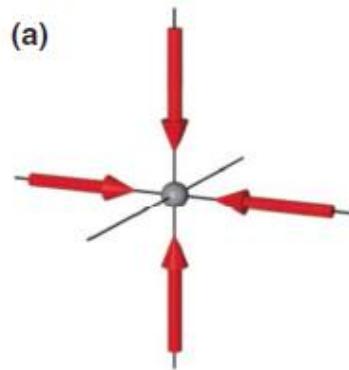
I. Bloch, Rev. Mod. Phys. **80**, 885 (2008).



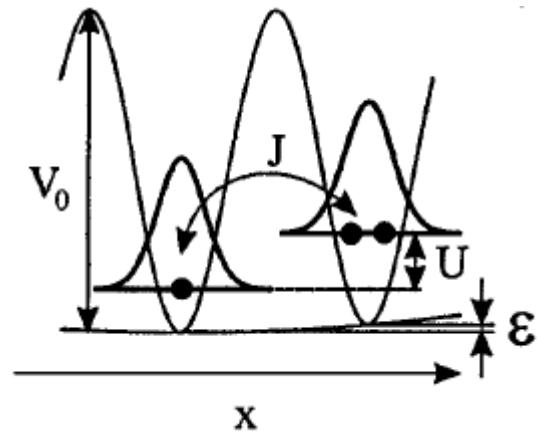
A. Frisch, Nature **507**, 475 (2014).

# Ultracold atoms in optical lattice

Enhance interactions by engineering trap potentials.



Strongly-correlated particles.

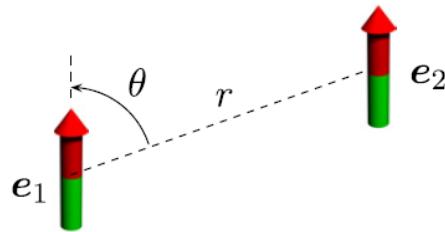


Bose-Hubbard model

$$H = -J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

# Long-range interaction

## Dipole-dipole interaction



$$U_{dd}(\mathbf{r}) = \frac{C_{dd}}{4\pi} \frac{1 - 3 \cos^2 \theta}{r^3},$$

- Atoms with large magnetic dipoles, e.g. Cr, Er, Dy.
- Dipolar molecules, e.g. KRb, NaK.
- Rydberg atoms, excite atom to  $n \sim 100$  orbit.

# Ingredients

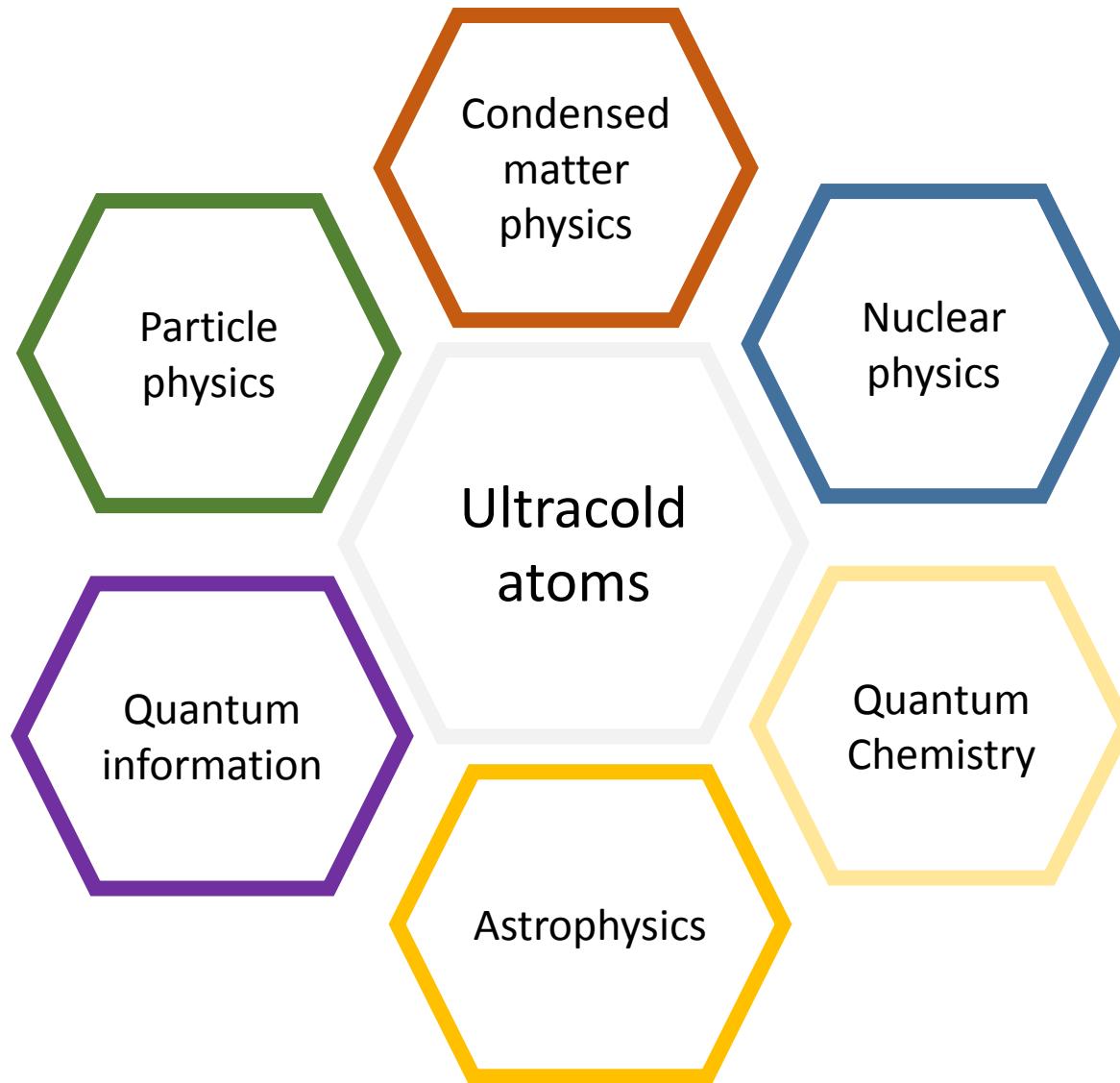
## Tunable parameters

- Temperature
- Interactions
- Elements
- Atomic density
- Spatial structure of atoms.



Great platform for studying many-body physics

# Many body physics

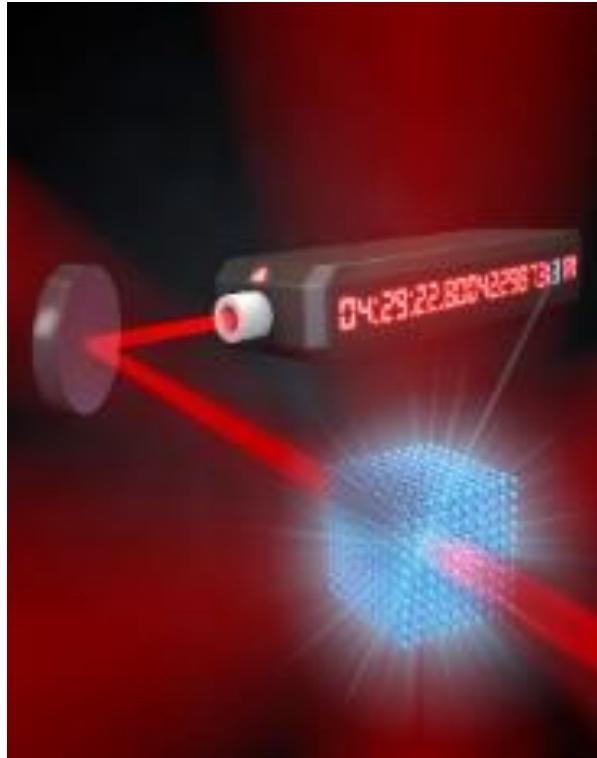


# Outline

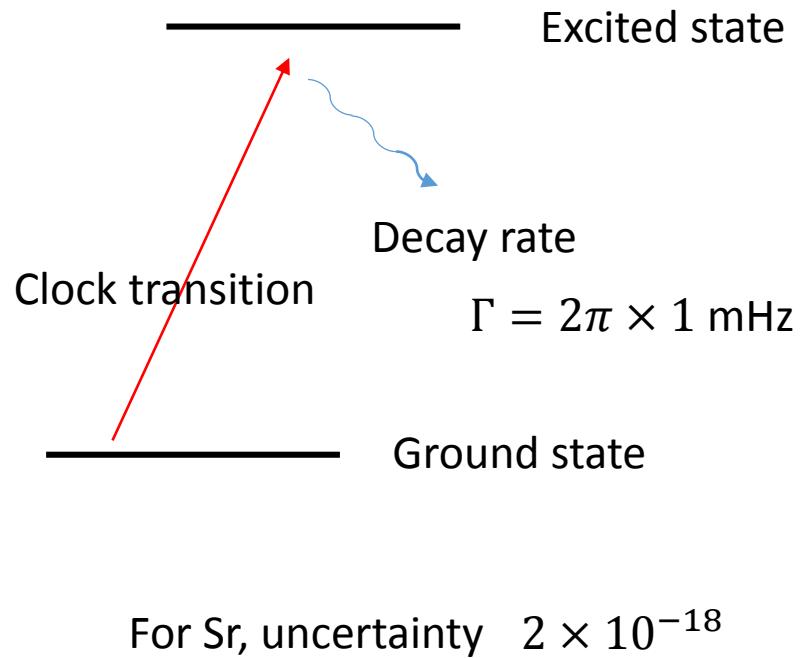
- Creating ultracold gases
- Interactions
- **Exotic quantum matters**
- Recent experiments: quantum simulations

# Precision measurements

One of the most precise frequency standards

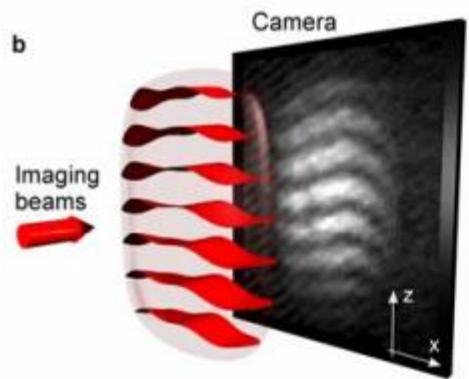
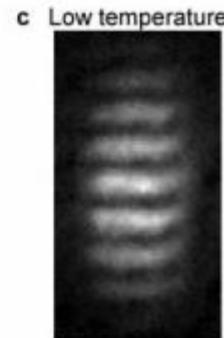
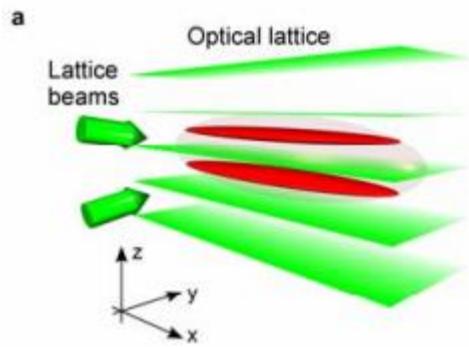


Optical lattice clock



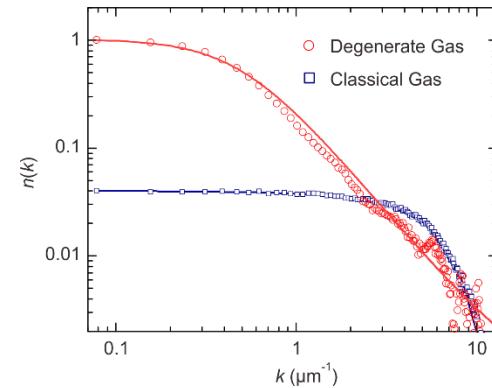
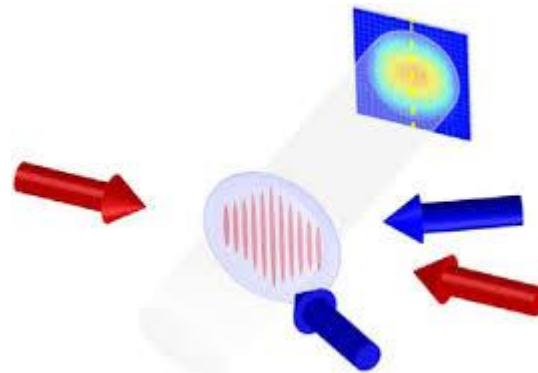
# Low-dimension quantum matter

## Two-dimensional



Berezinski-Kosterlitz-Thouless transition

## One-dimensional



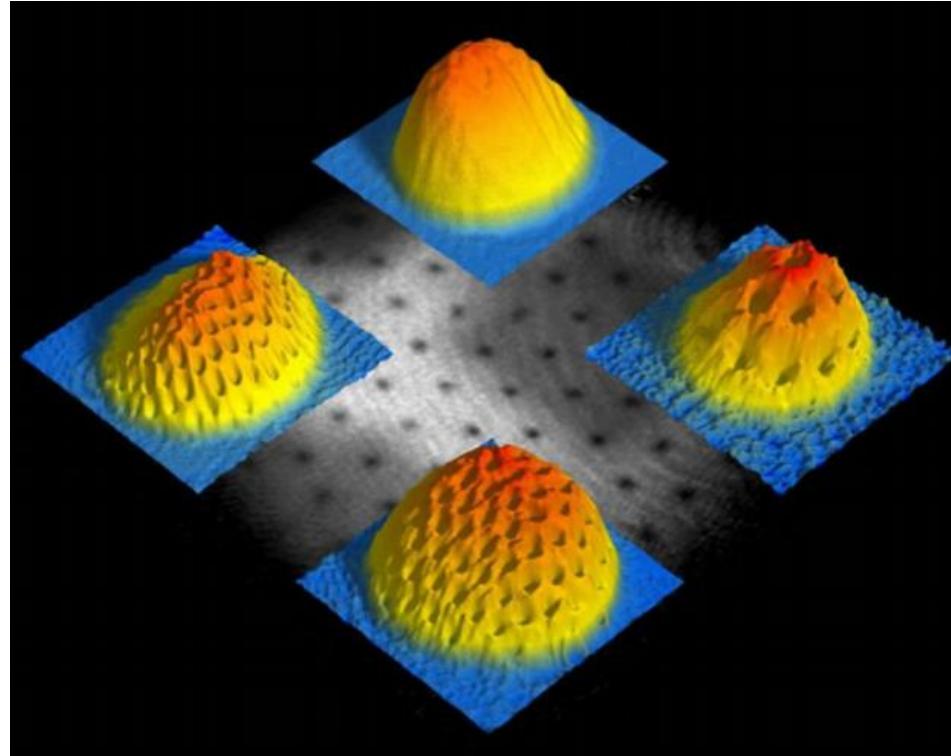
Tomonaga-Luttinger liquid

Z. Hadzibabic, et al. *Nature*, **41** 1118 (2006).

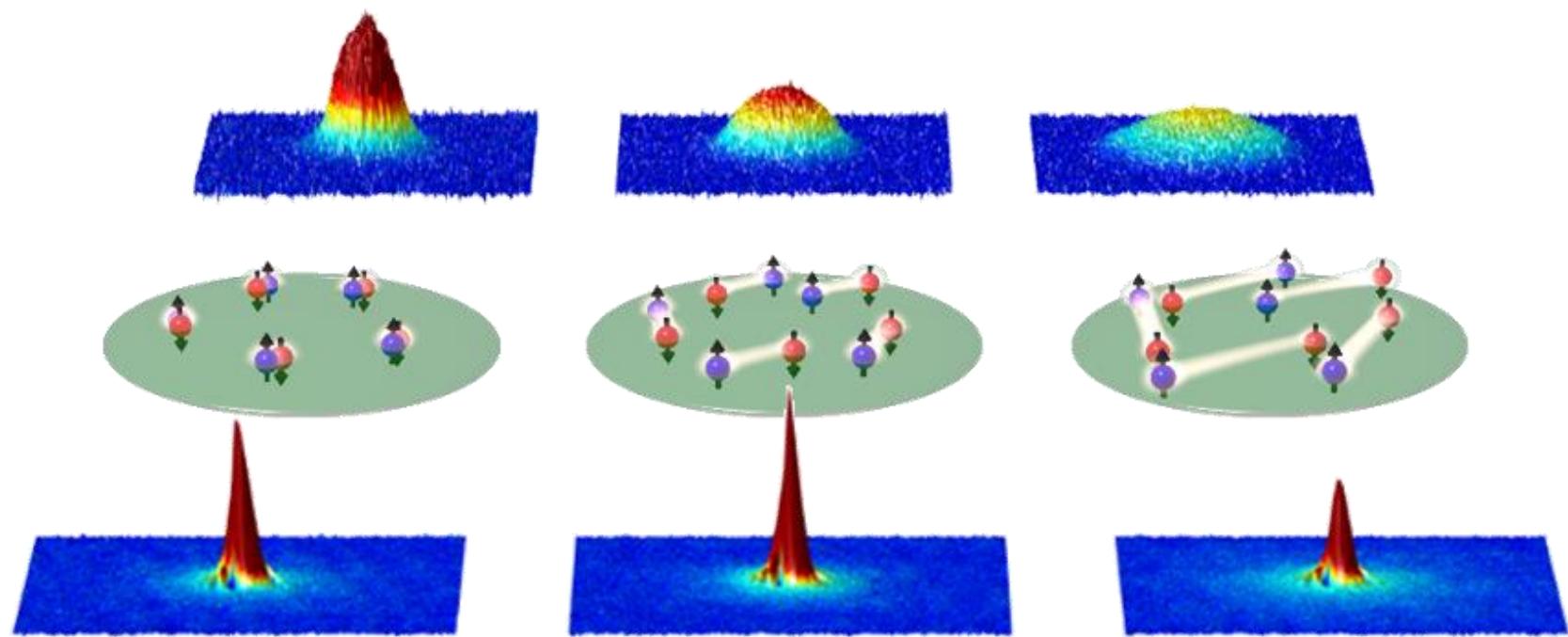
B. Yang, et al. *PRL*, **119** 165701 (2017).

# Superfluidity

Vortex Lattices in Bose-Einstein Condensates

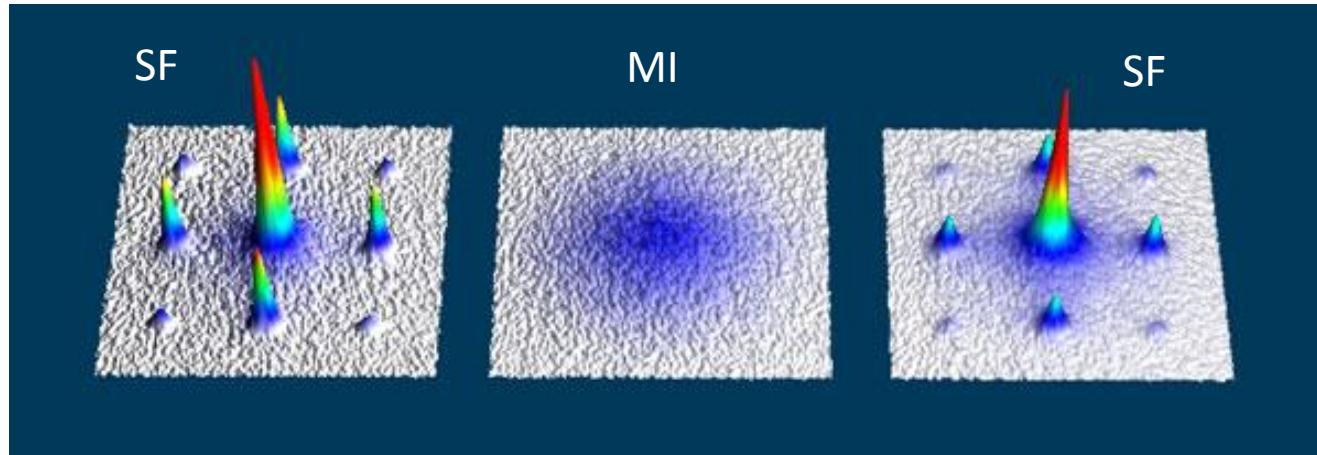


# BCS-BEC crossover



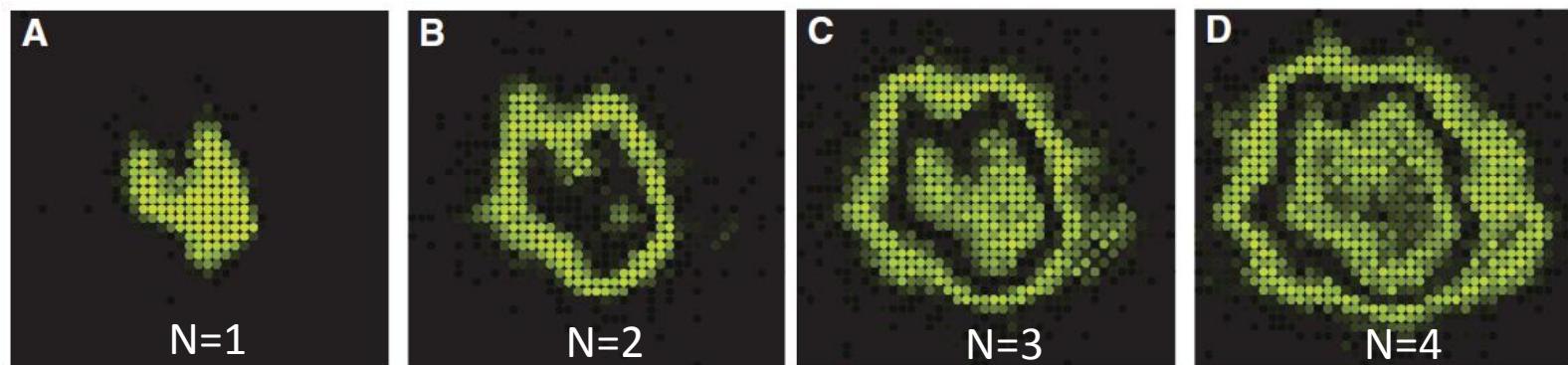
# Superfluid-Mott insulator

## Matter wave interference



## Quantum gas microscopy

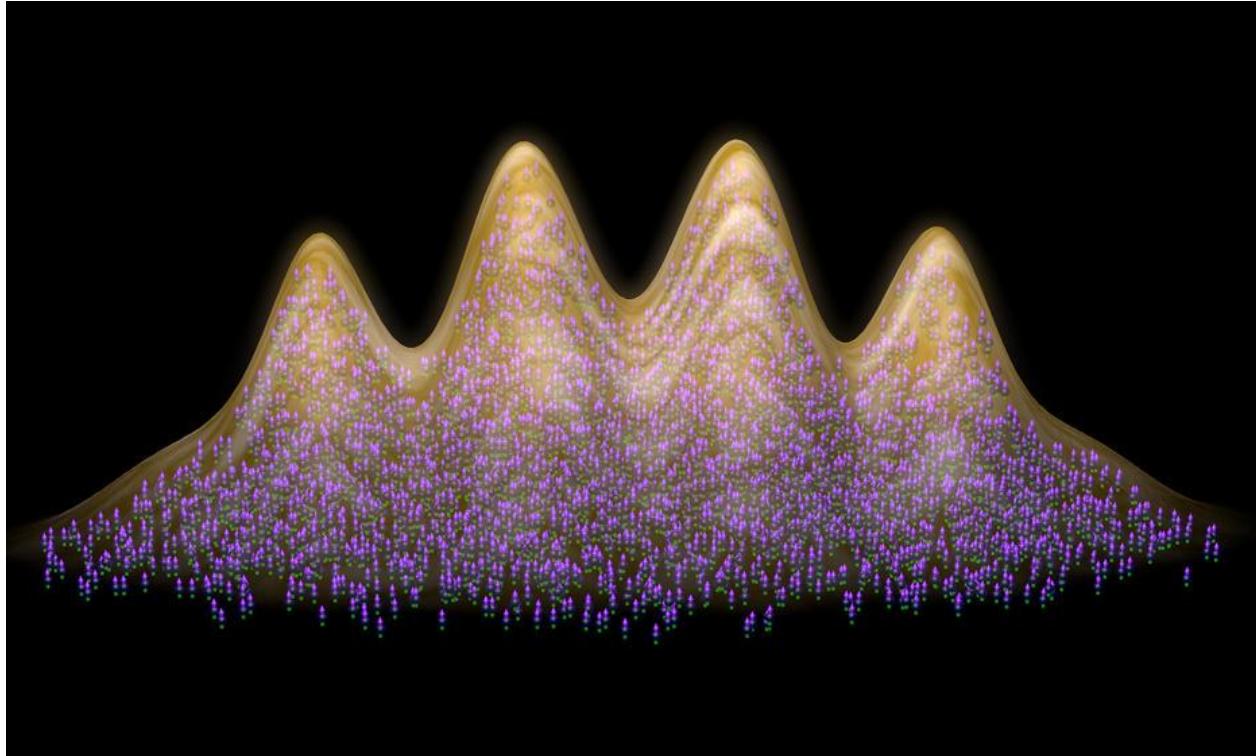
M. Greiner, et al. Nature, 415 39 (2002).



W. S. Bakr, et al. Science, 329 547 (2010).

# Supersolid

Supersolid phase in dipolar Bose-Einstein condensates



L. Chomaz et al., Phys. Rev. X **9**, 021012 (2019).

L. Tanzi, et al., Nature. **574**, 382 (2019).

M. Guo et al., Nature. **574**, 386 (2019).

# Outline

- Creating ultracold gases
- Interactions
- Exotic quantum matters
- Recent experiments: quantum simulations

# Recent experiments

- Cooling a quantum gas in optical lattices.
- High-fidelity Bell states.
- Quantum simulations of lattice gauge theory.

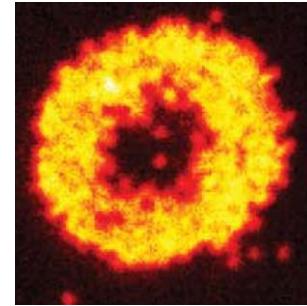
# A quantum simulator

Degenerated quantum gas

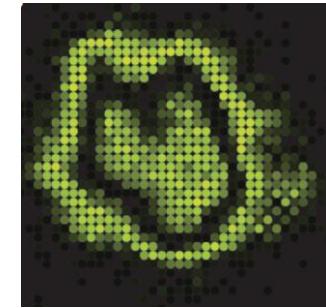
Strongly interacting

Hubbard Model

$$\hat{H} = -J \sum_{\langle i,j \rangle} a_i^\dagger a_j + \frac{U}{2} \sum_i n_i(n_i - 1) + \sum_i \mu_i n_i$$



Mott insulator



Bloch, 2010

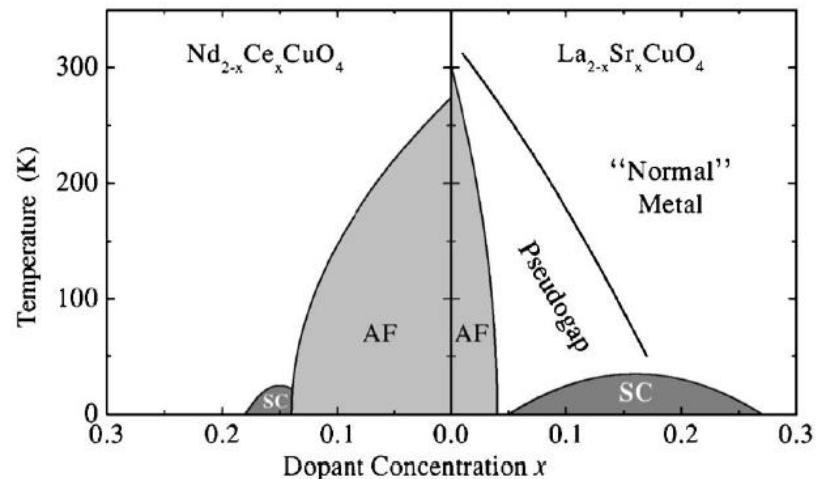
Greiner, 2010

Lower temperature

Spin Models

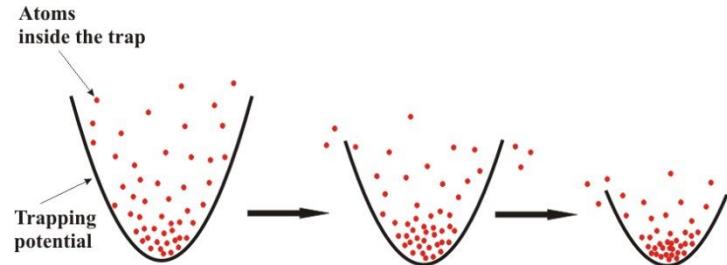
$$\hat{H} = -J_{\text{ex}} \hat{S}_i \hat{S}_j$$

Simulate high-T<sub>c</sub> superconductivity



# Conventional cooling method

## ➤ Evaporative cooling

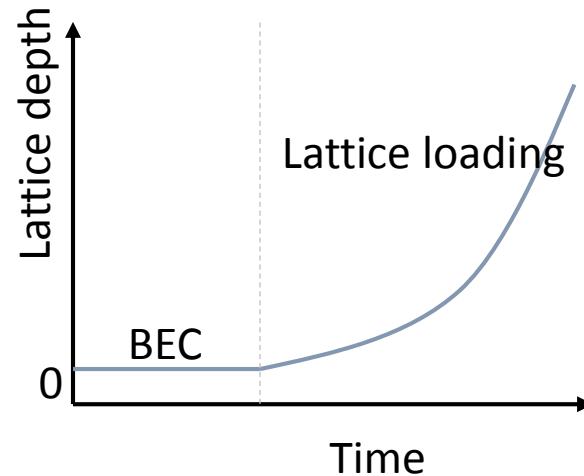


Lower T  $\iff$  Slower thermalization

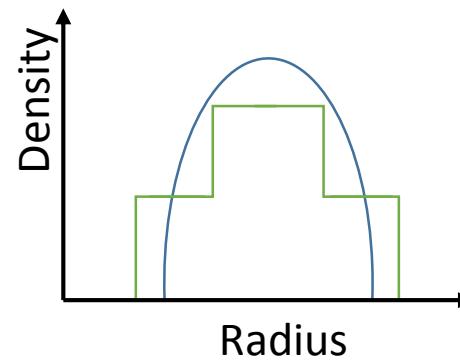
## ➤ Select low entropy regime

$$S/N \propto T/\mu$$

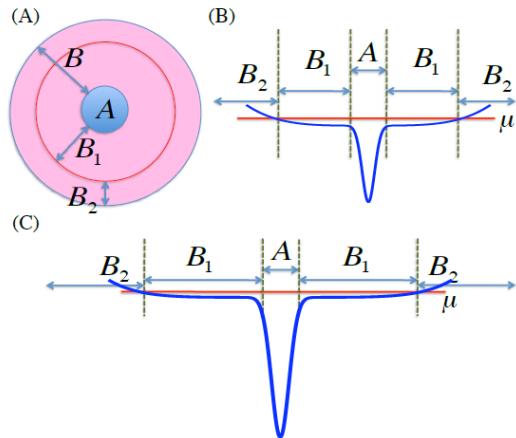
Intrinsic heating  $\sim$  Superexchange energy



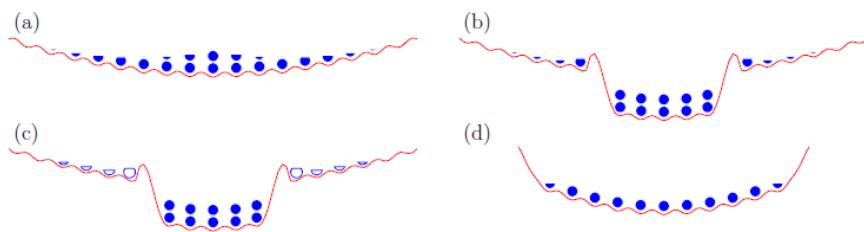
## ➤ Reduce non-adiabaticity



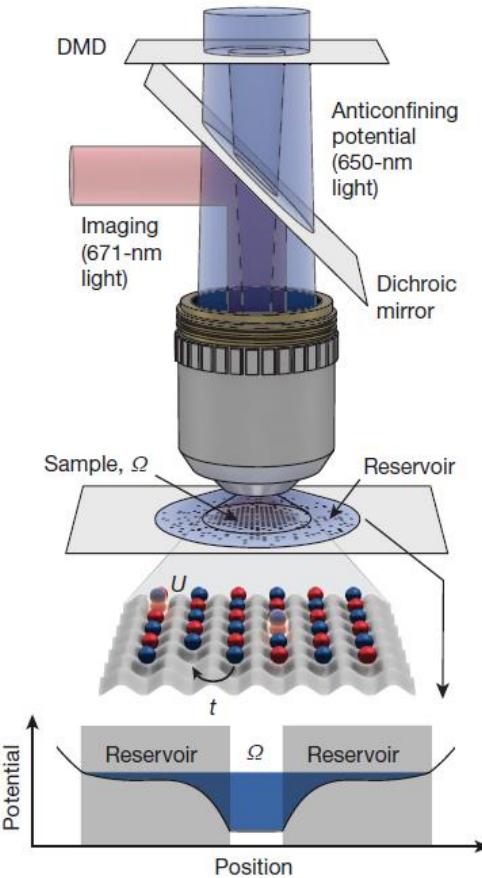
# Move entropy to a surrounding reservoir



T.-L. Ho & Q. Zhou, arXiv:0911.5506v1

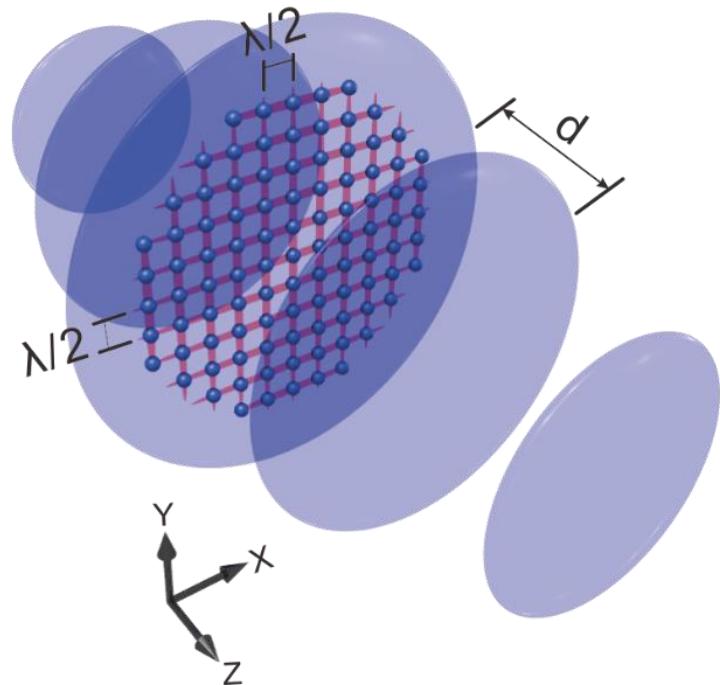


J. Bernier, et al. PRA **79**, 061601R (2009)



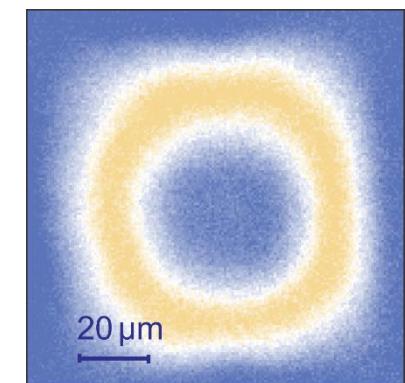
A. Mazurenko, et al. Nature **545**, 462 (2017)

# Experimental system

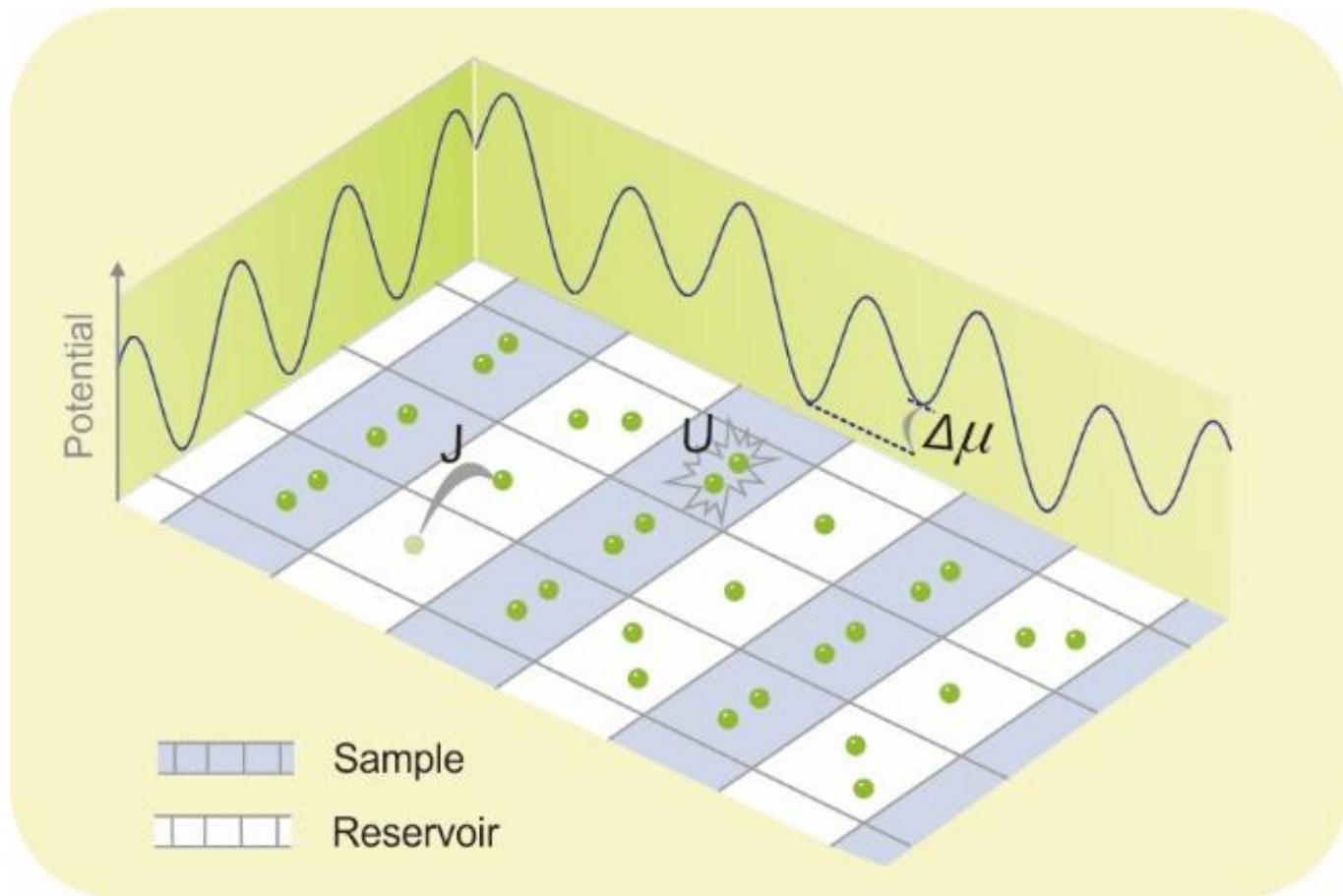


- Single layer of atoms
- 2D superlattices
- in-situ imaging (N.A.=0.48)

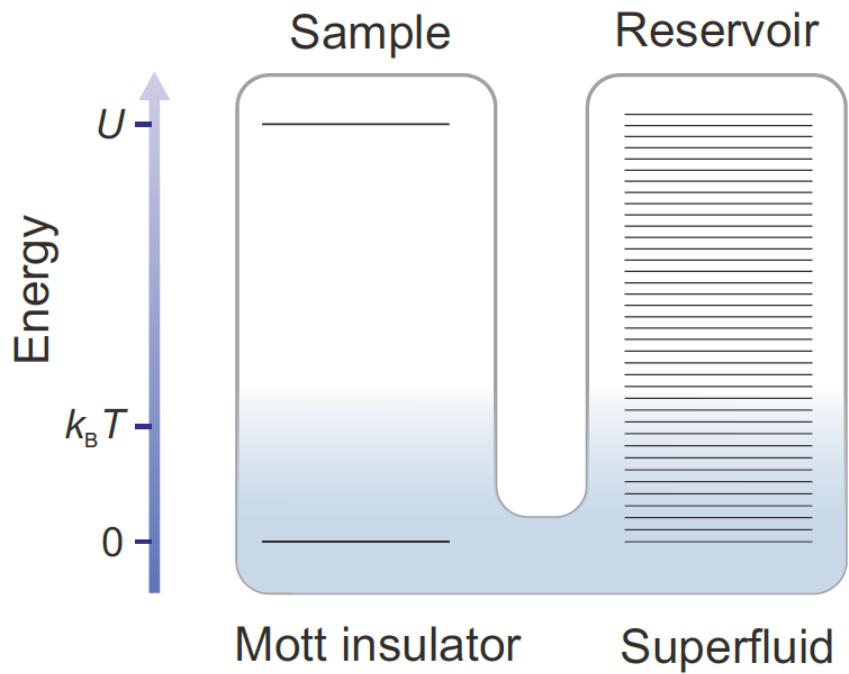
Mott insulator



# Staggered-immersion cooling



# Basic principle of the scheme



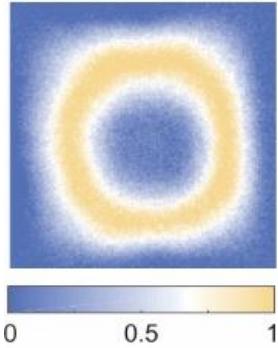
Density of states

$$g(E) = \frac{\partial \rho}{\partial E}$$

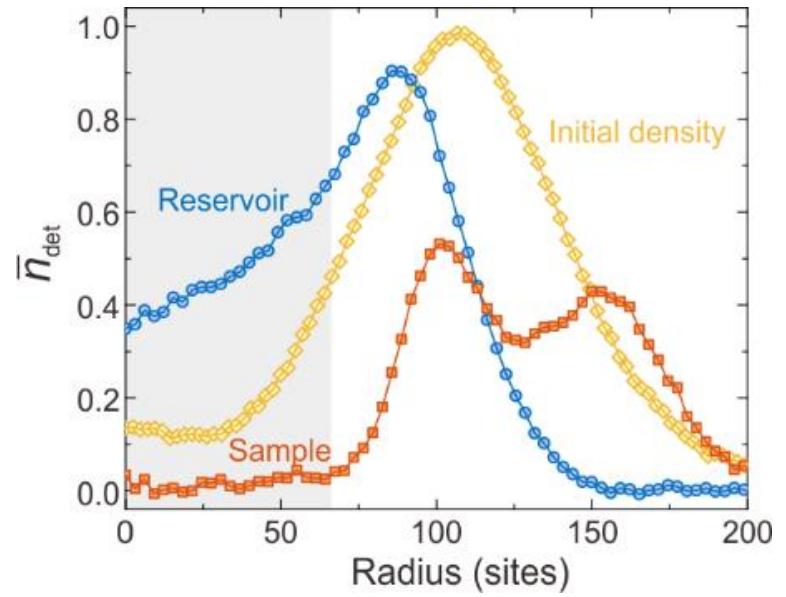
Entropy

$$S = -\text{Tr}\{\rho \log \rho\}$$

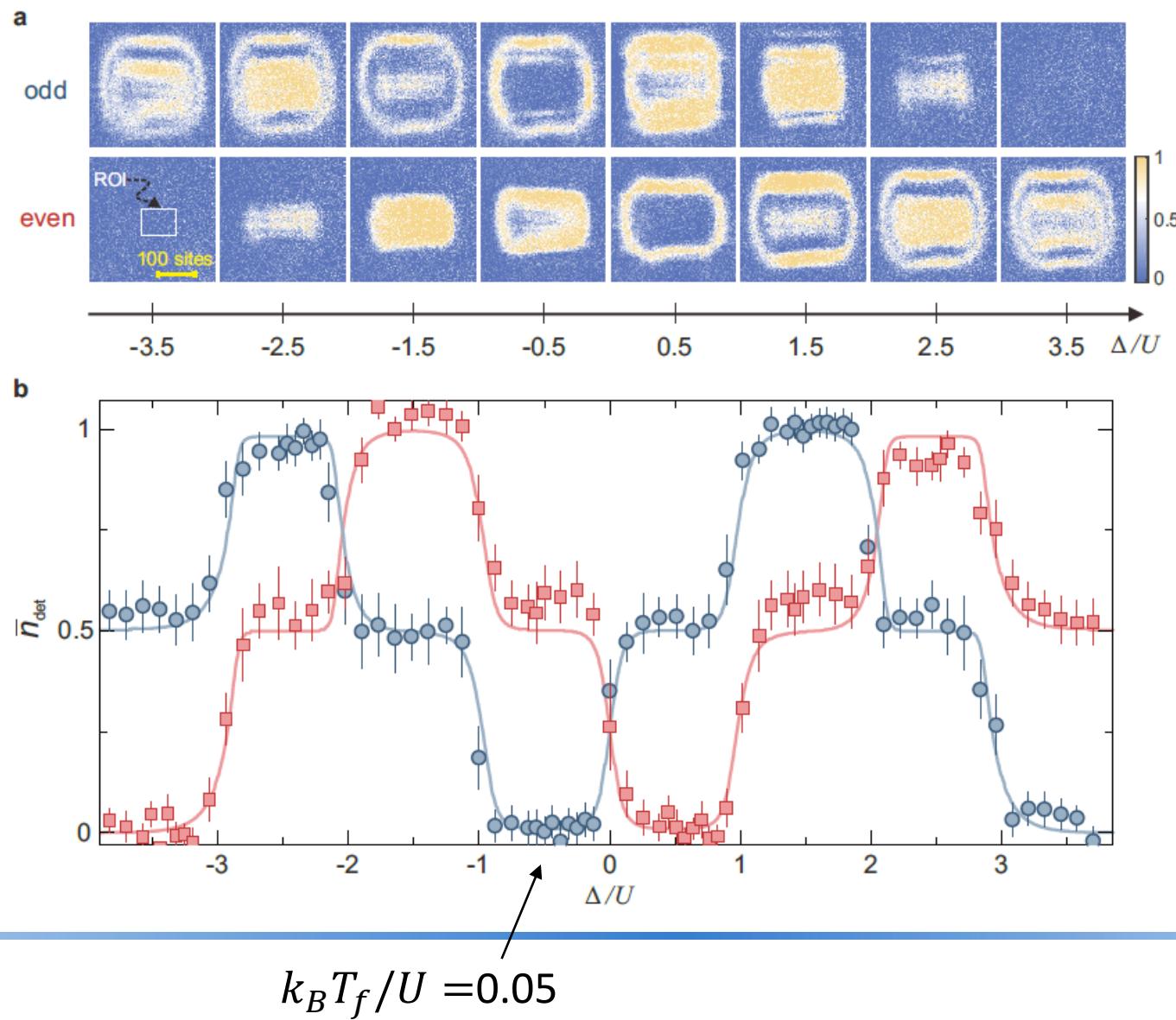
# Cooling effect



Initial Cloud

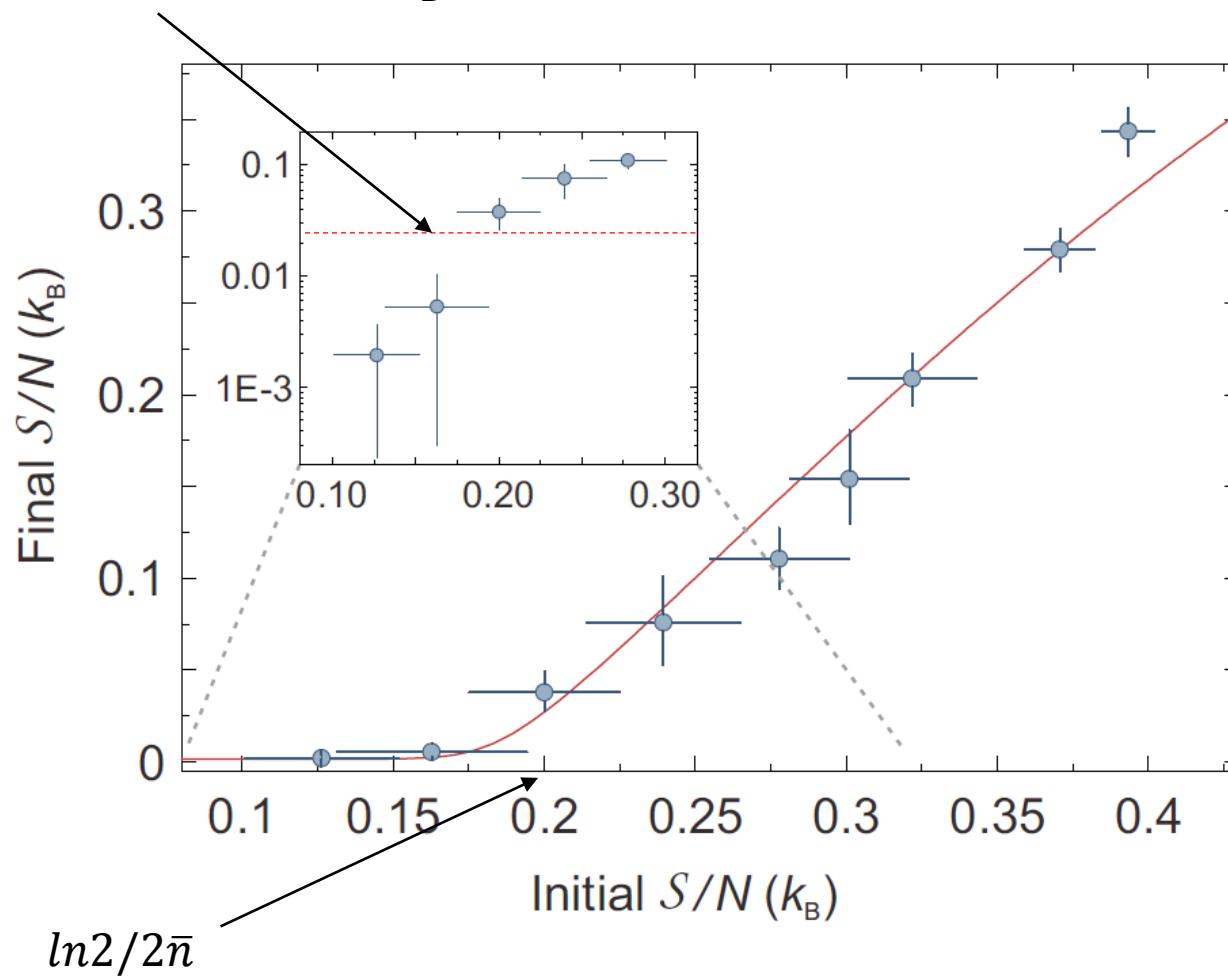


# Mass transport and entropy redistribution

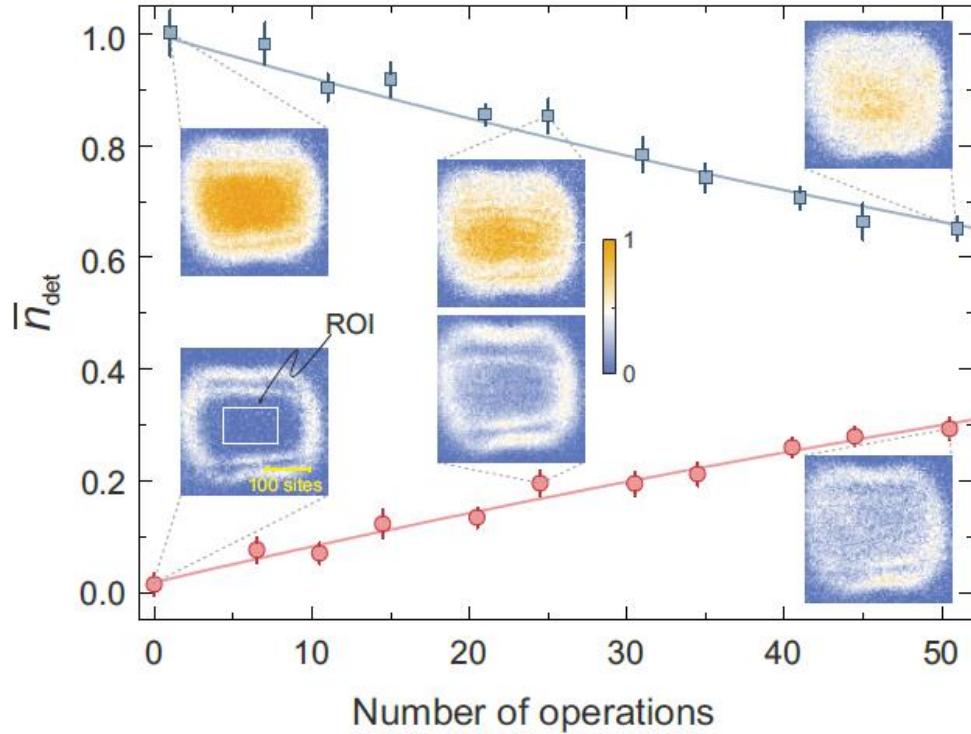


# Performance of the cooling

Intrinsic heating = 0.025(2)  $k_B$



# A defect-free Mott insulator



Lattice sites in ROI

$$N = 10^4$$

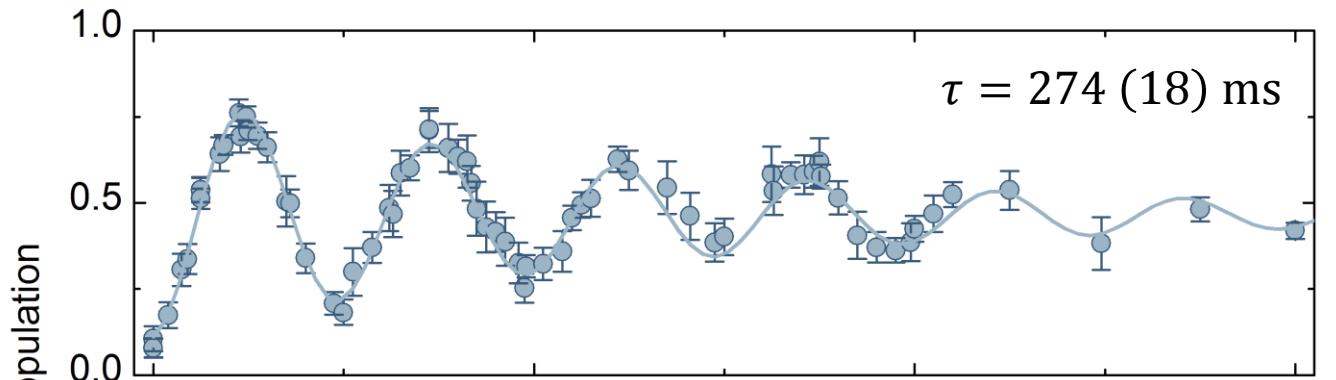
Probability of unity filling

$$P = 0.992(1)$$

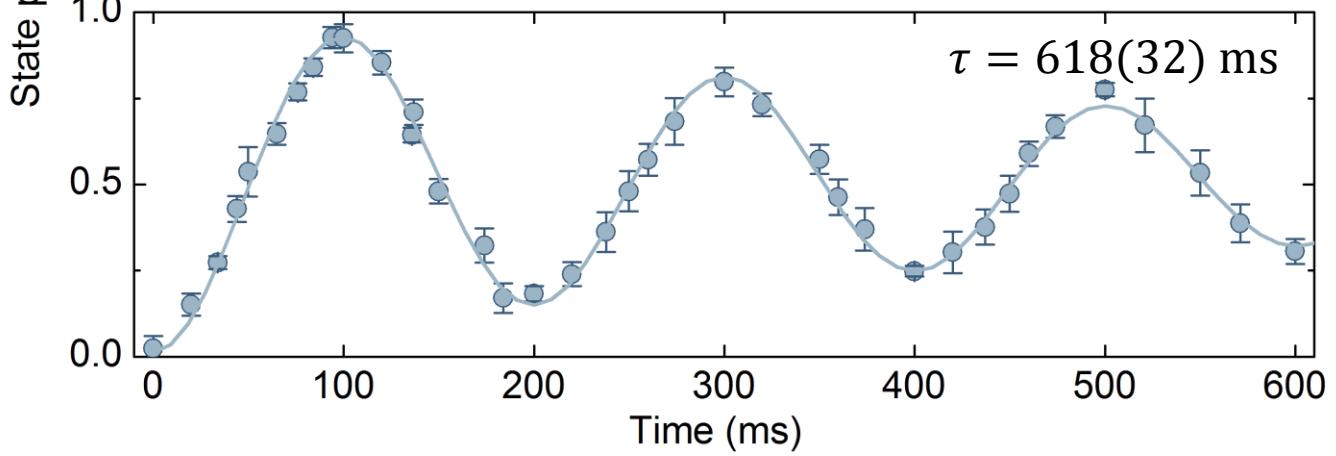
# Entanglement and decoherence

Dai *et al.*, Nature Physics 12, 783 (2016)

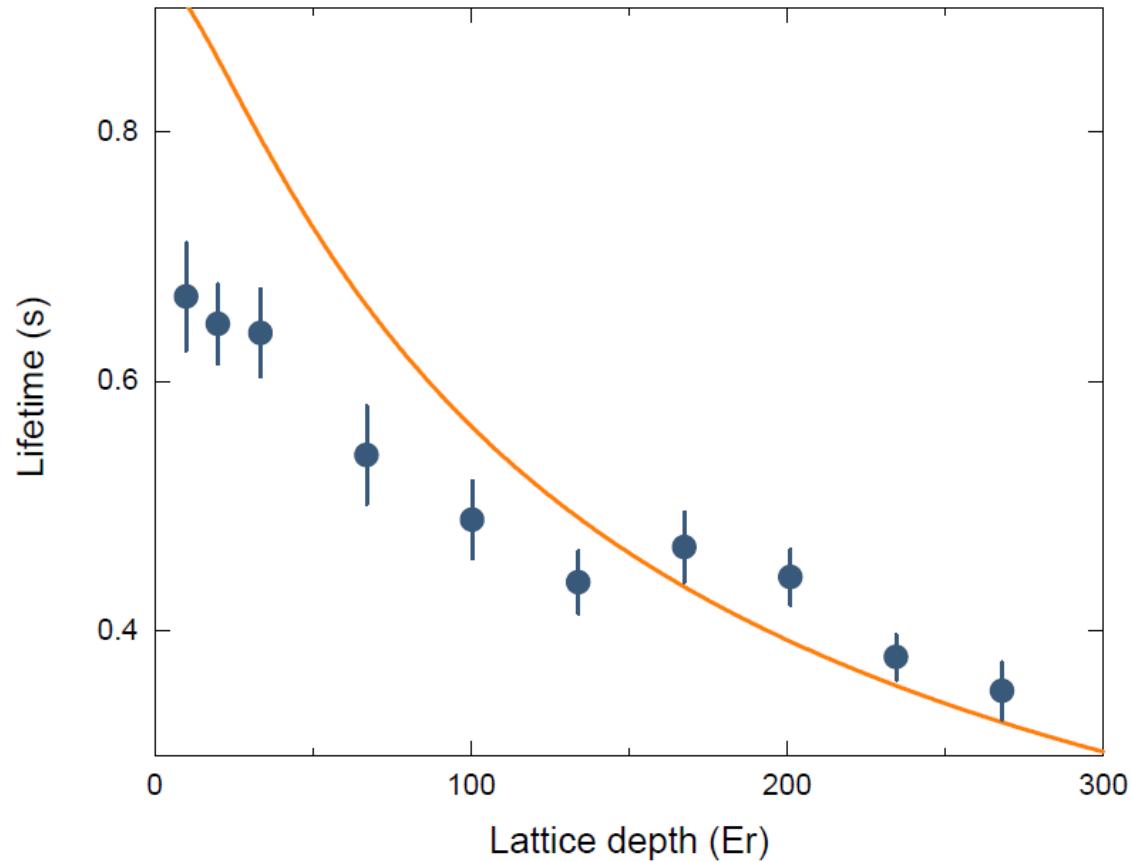
Previous results



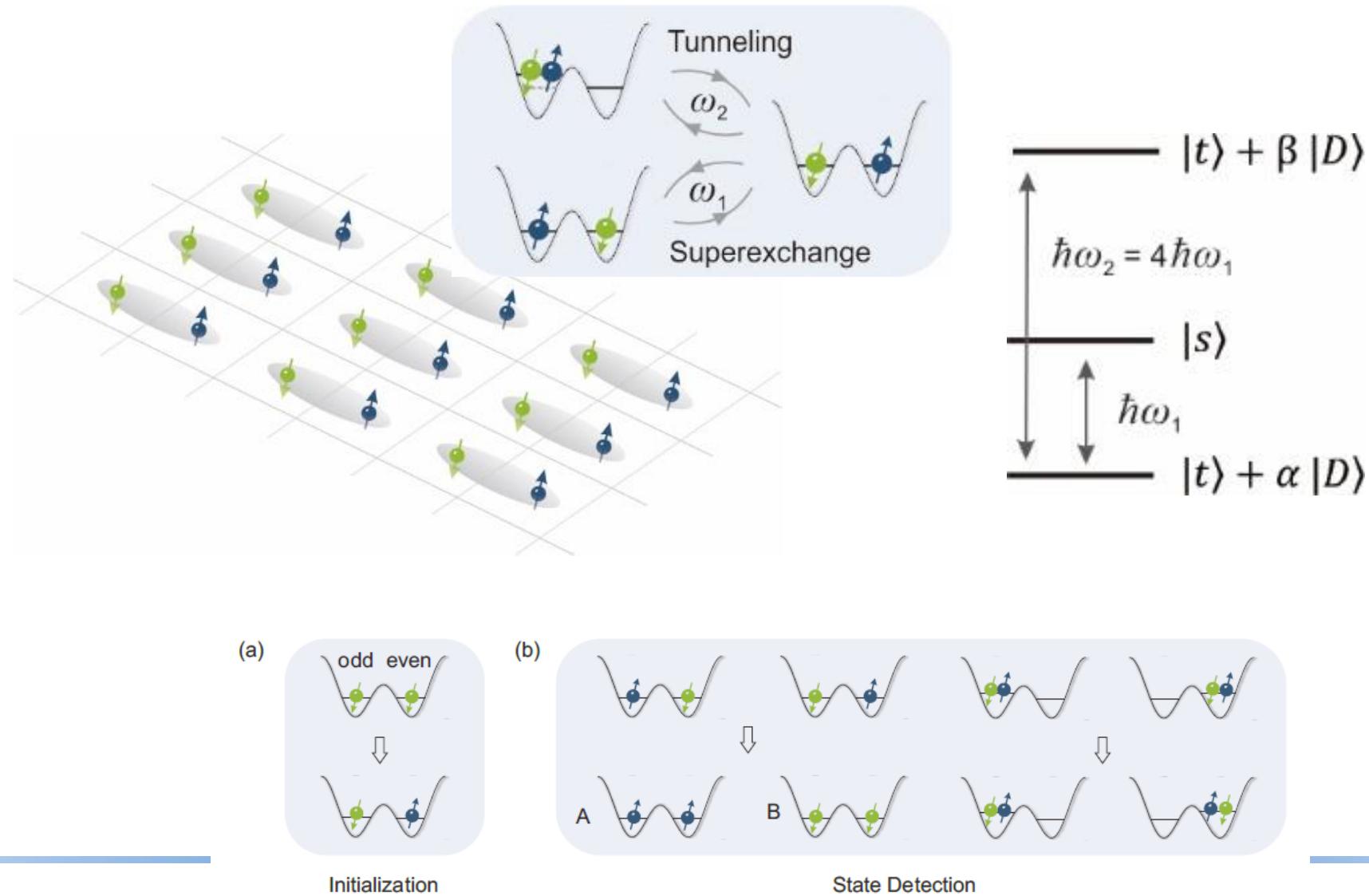
Recent results



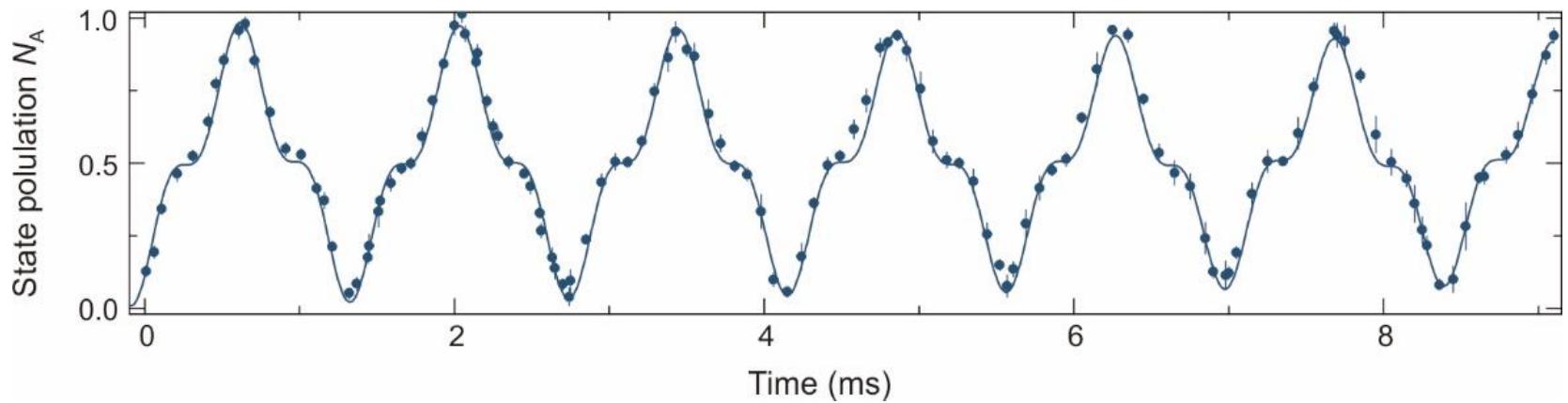
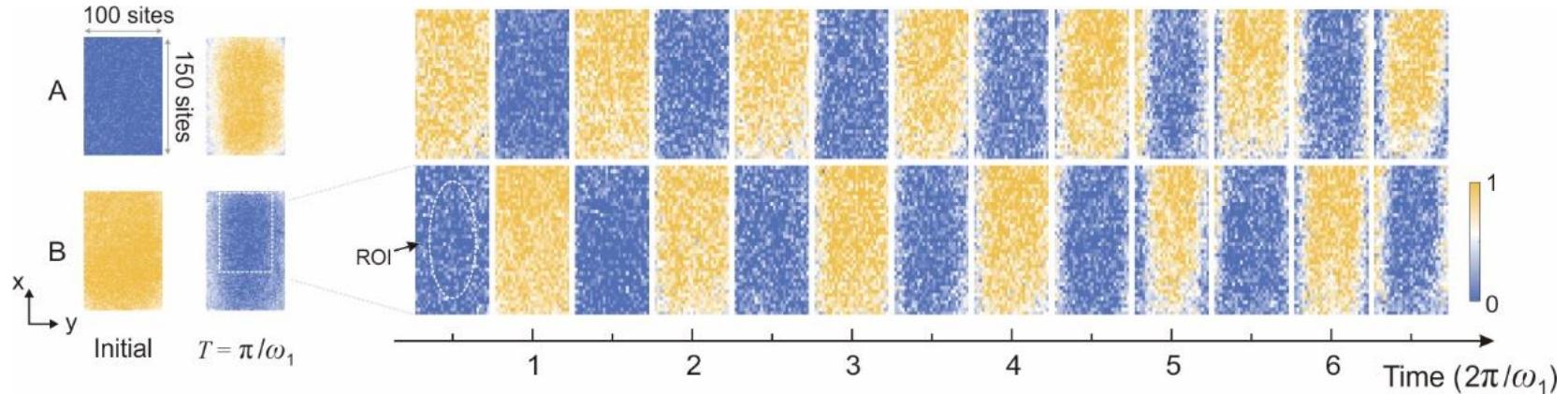
# Mechanism of Decoherence



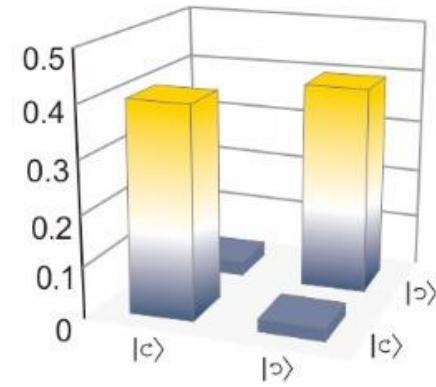
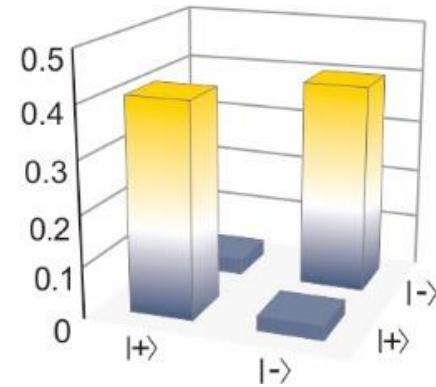
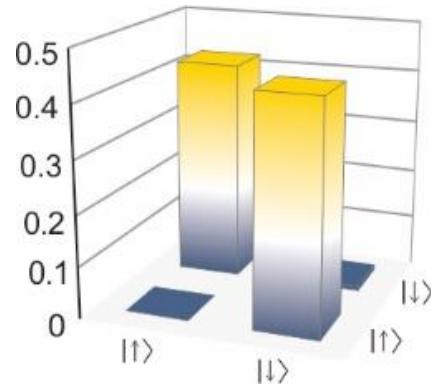
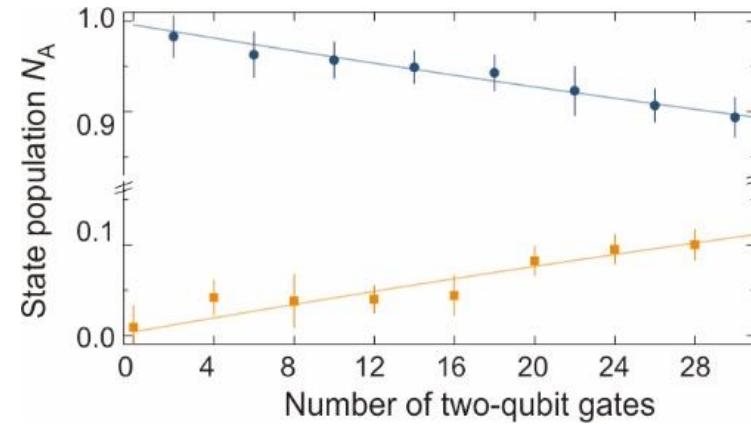
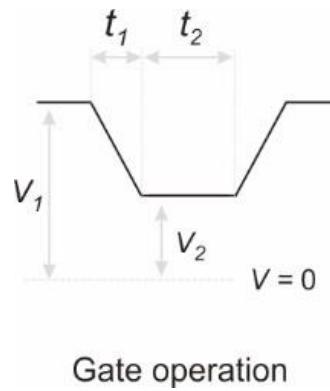
# A high-fidelity entangling gate



# A high-fidelity entangling gate



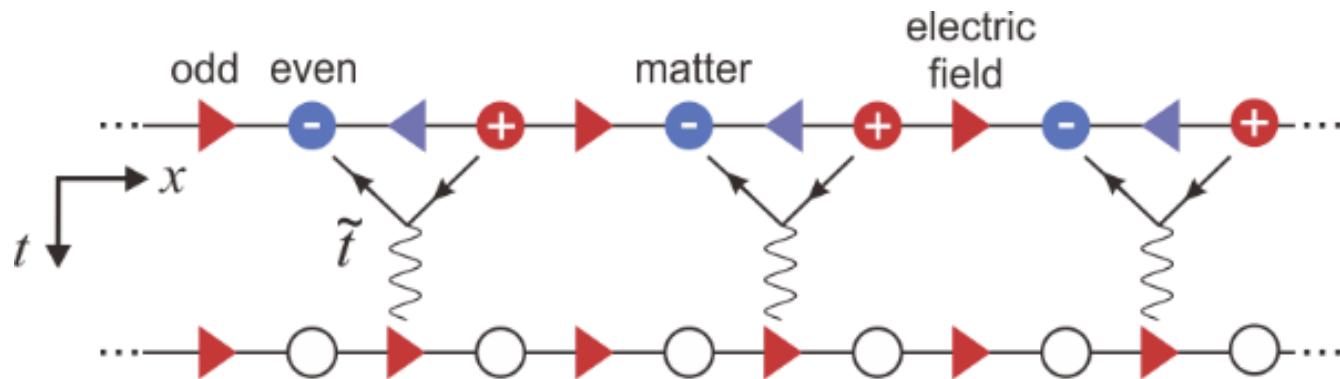
# Thousands Bell pairs



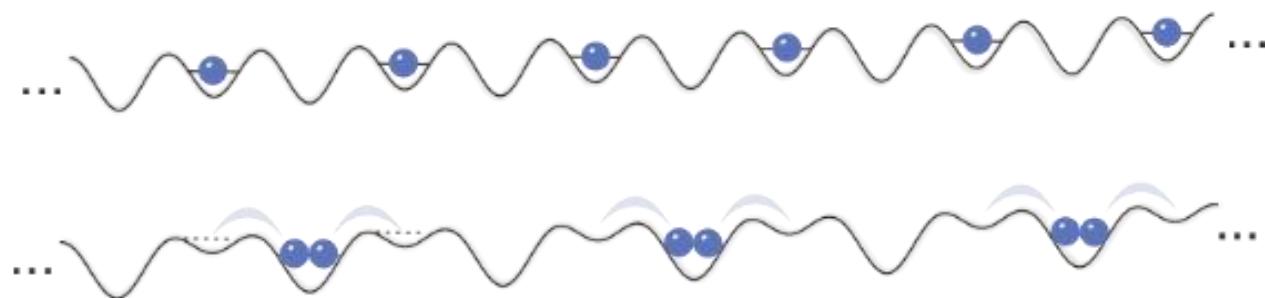
Gate fidelity  $F = 0.993(1)$

# Simulate a Lattice-gauge theory model

Quantum Link model  $\hat{H}_{\text{QLM}} = \sum_{\ell} \left[ -\frac{i\tilde{t}}{2} \left( \hat{\psi}_{\ell} \hat{S}_{\ell, \ell+1}^+ \hat{\psi}_{\ell+1} - \text{H.c.} \right) + m \hat{\psi}_{\ell}^\dagger \hat{\psi}_{\ell} \right]$

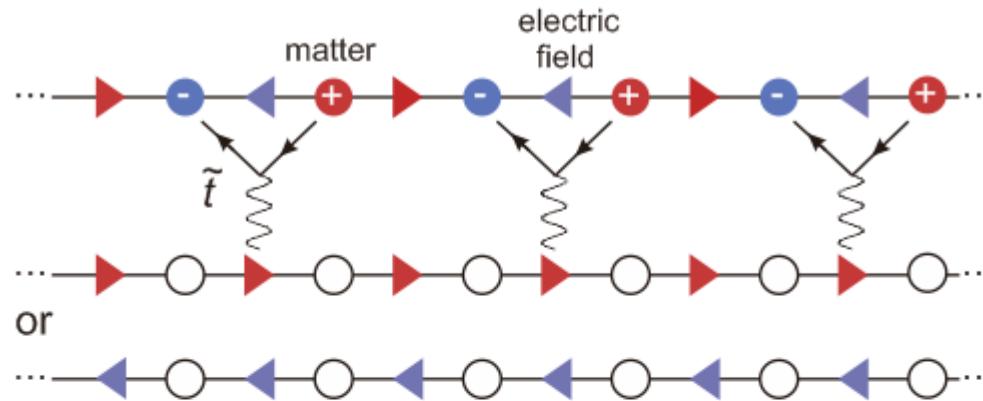


Bose-Hubbard model  $\hat{H}_{\text{BHM}} = \sum_j \left[ -J(\hat{b}_j^\dagger \hat{b}_{j+1} + \text{H.c.}) + \frac{U}{2} \hat{n}_j (\hat{n}_j - 1) + \varepsilon_j \hat{n}_j \right]$

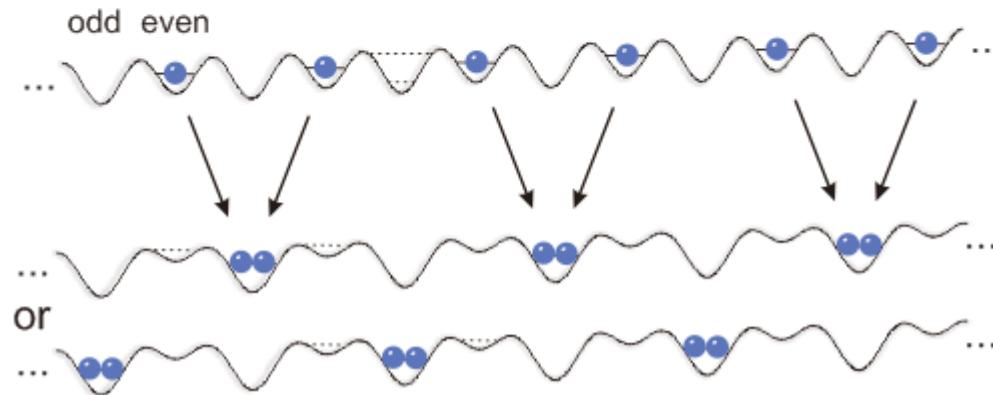


# Spontaneous symmetry breaking

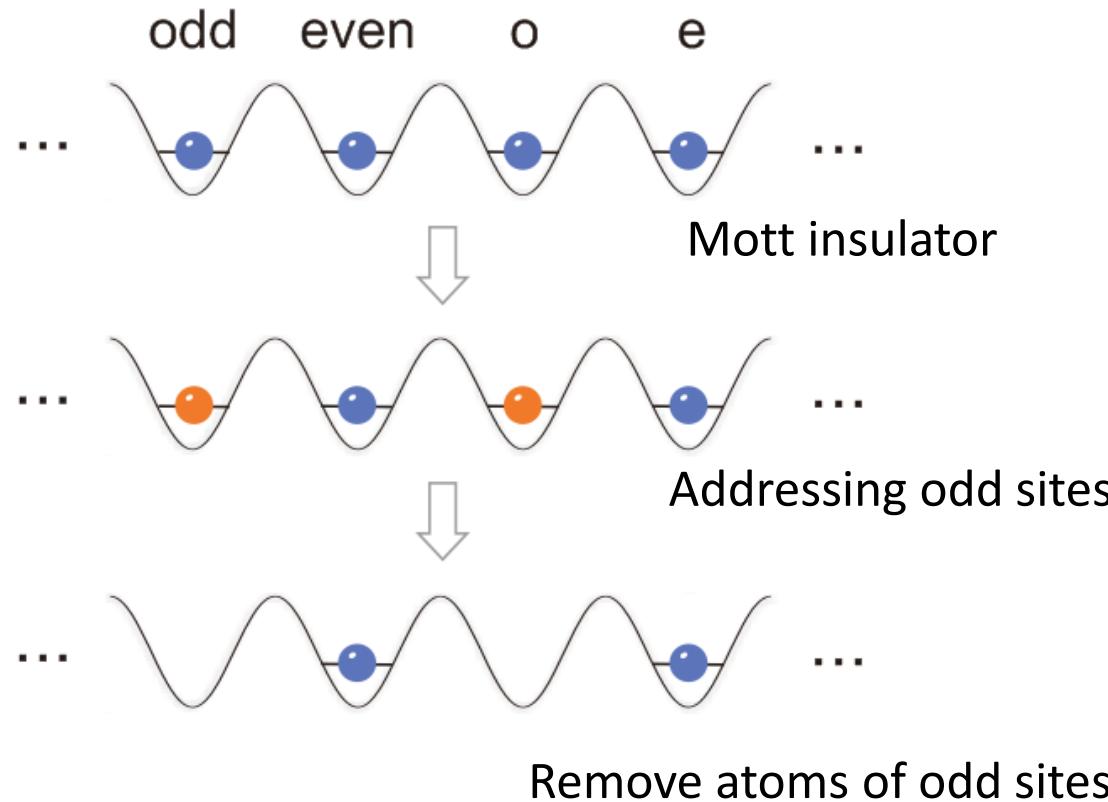
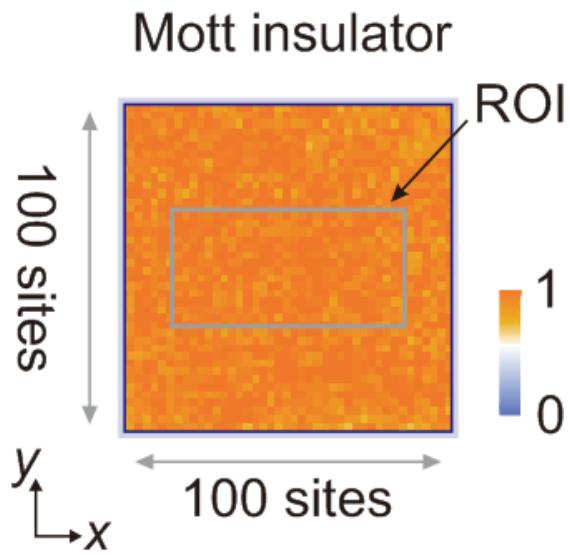
Quantum link model



Bose-Hubbard model

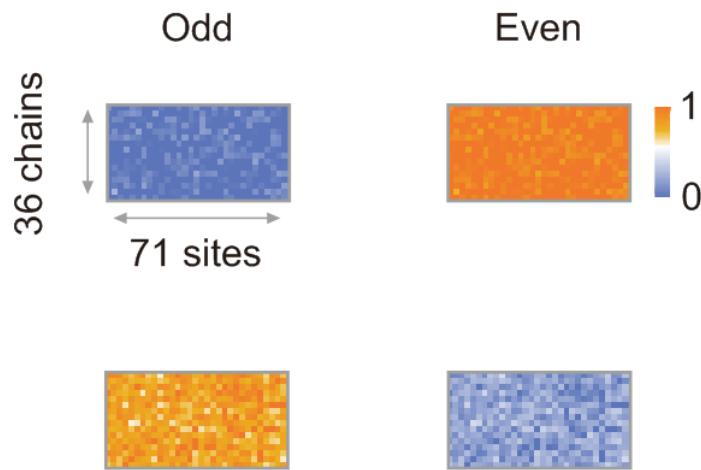
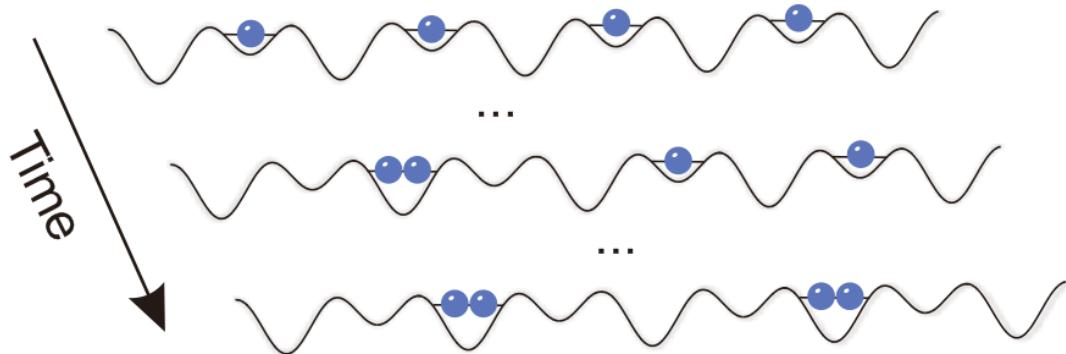
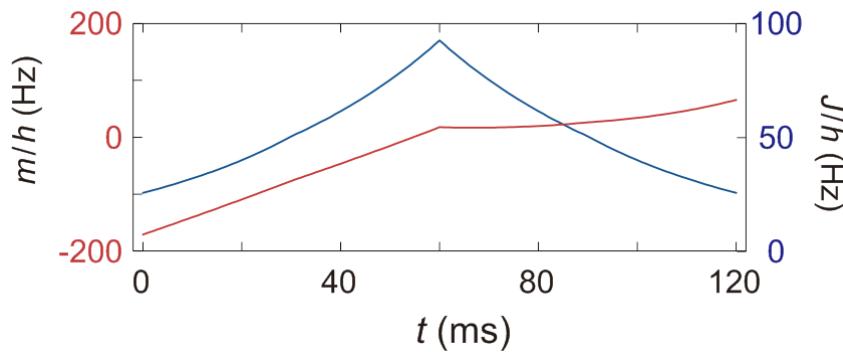


# Realization of a quantum phase transition

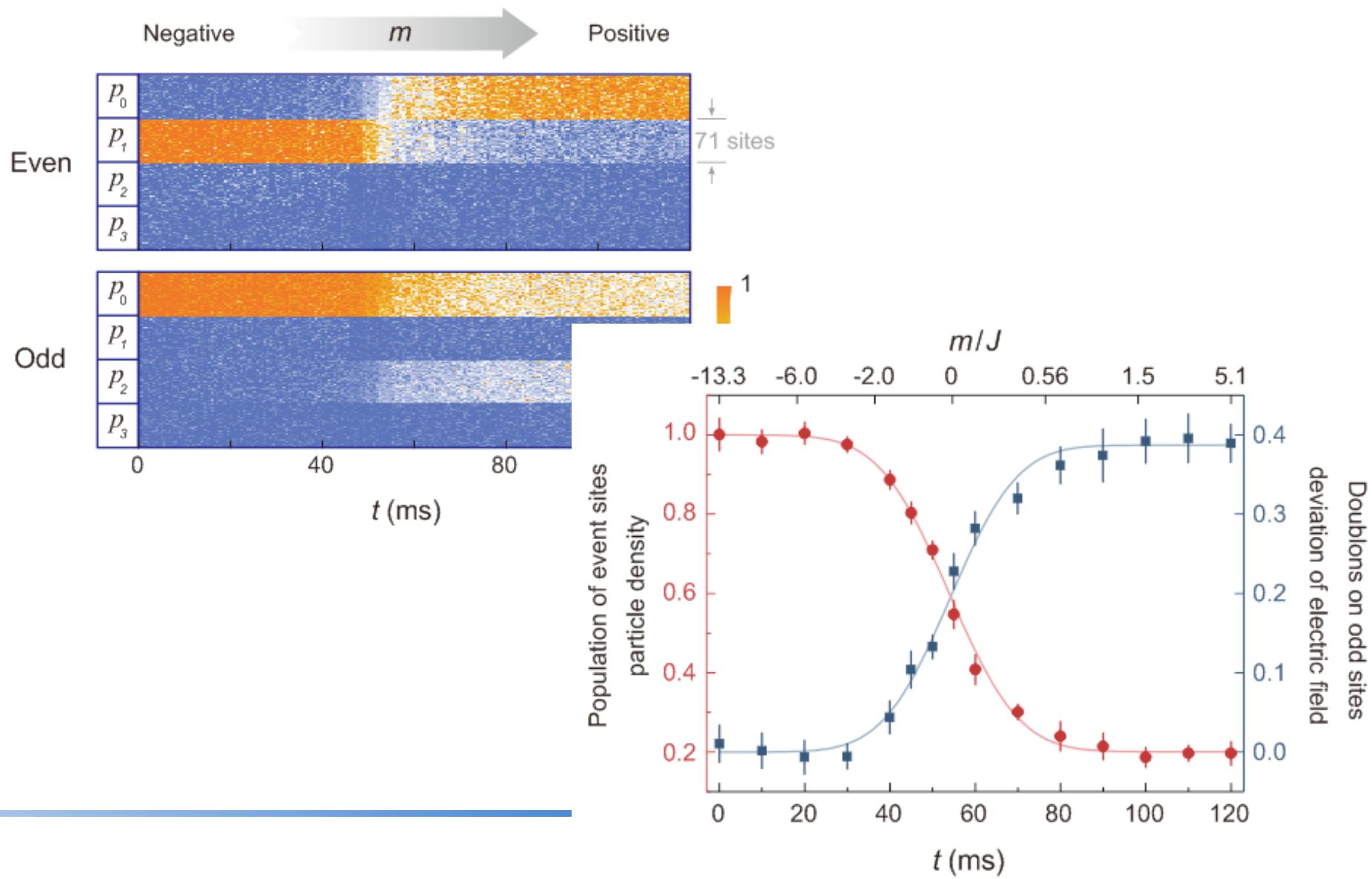


# Realization of a quantum phase transition

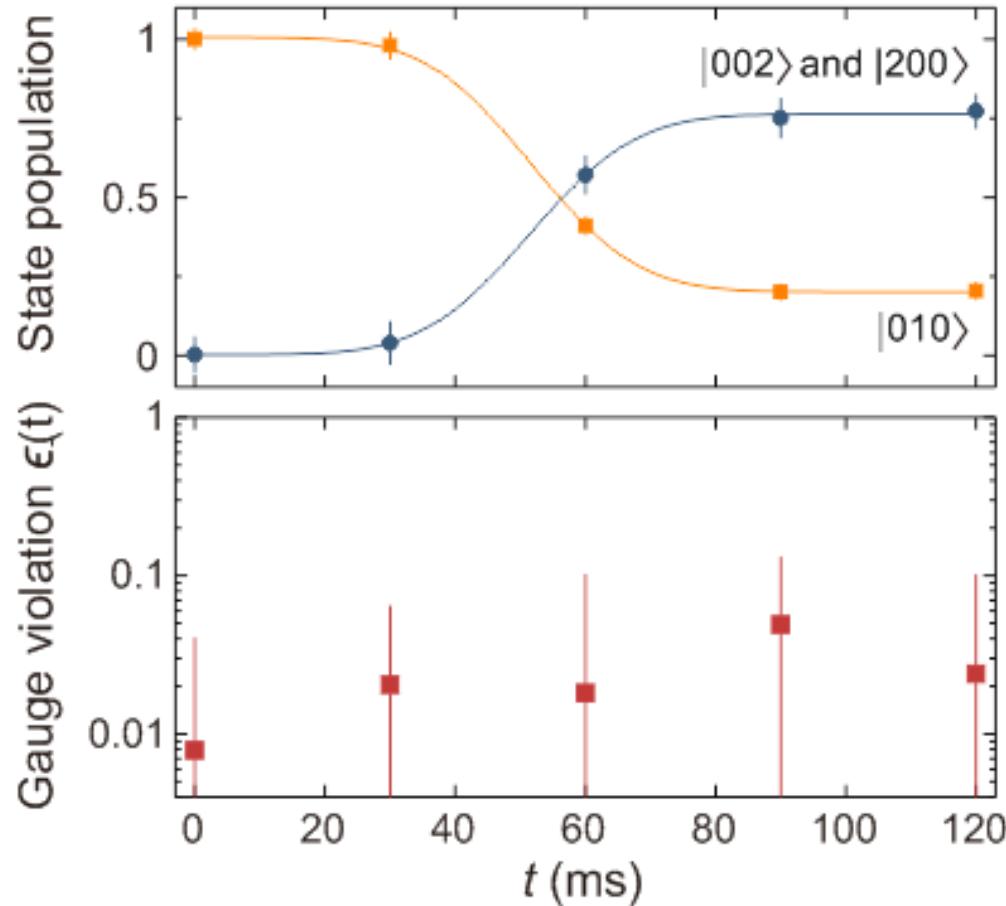
$$m = \delta - U/2$$



# A Quantum phase transition



# Gauge invariance



# Summary

- Creating ultracold gases
- Interactions
- Exotic quantum matters
- Recent experiments: quantum simulations
  - Cooling a quantum gas
  - Creation of Bell pairs
  - Simulation of Quantum link model