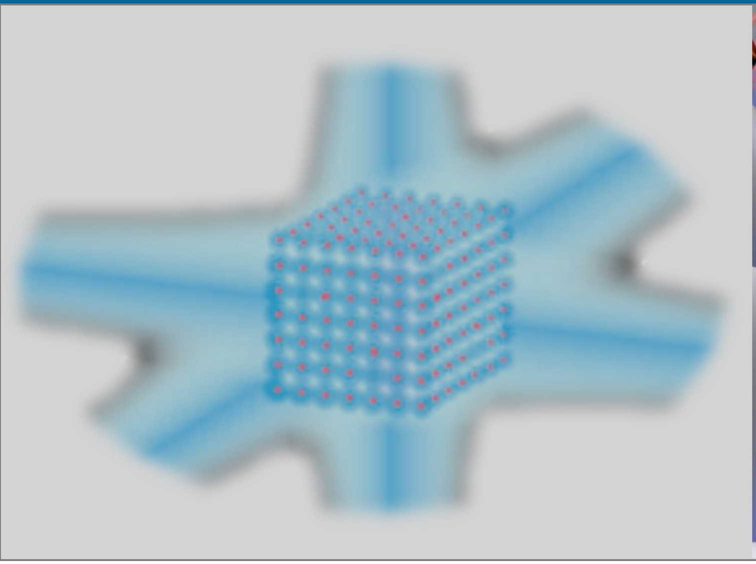

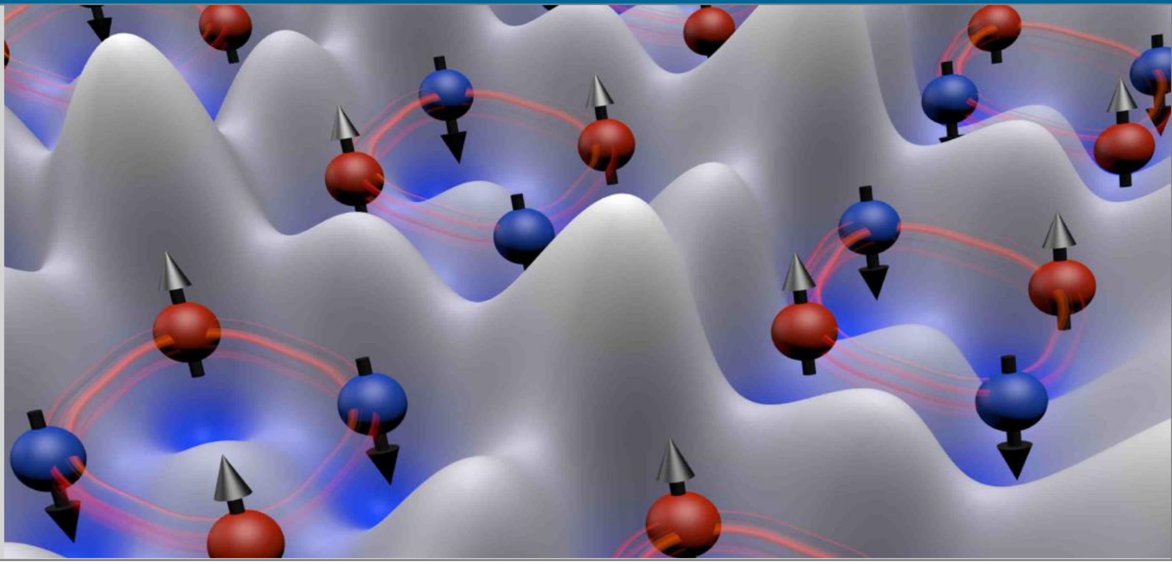

Atomic Spin Entanglement and Anyonic Statistics in Optical Lattices

Zhen-Sheng Yuan （中国科大 苑震生）

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University of Science and Technology of China (USTC)

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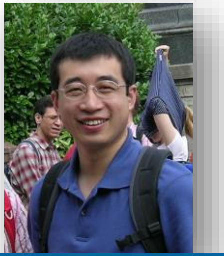
The team, QPQI @ USTC

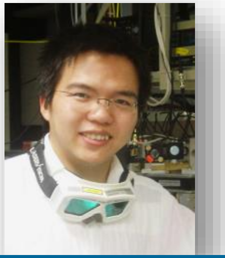
The team, QPQI @ USTC


Jian-Wei Pan


包小辉

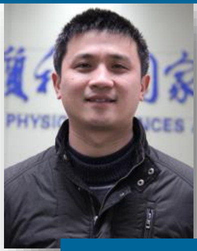

陈凯


Shuai Chen

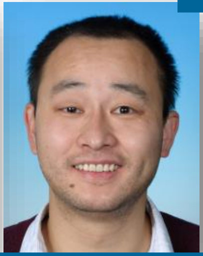

Yu-Ao Chen


陆朝阳


徐飞虎




Zhen-Sheng Yuan


Bo Zhao

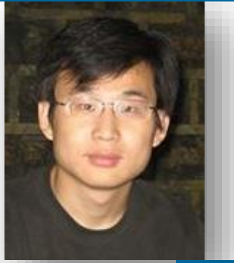

You-Jin Deng


张强

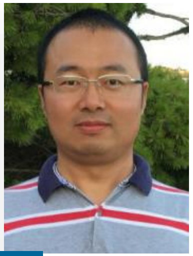

张军


刘乃乐


朱晓波


霍永恒


Xing-Can Yao


王喜林


郁司夏


Hanning Dai


陈腾云


江晓


印娟


任继刚

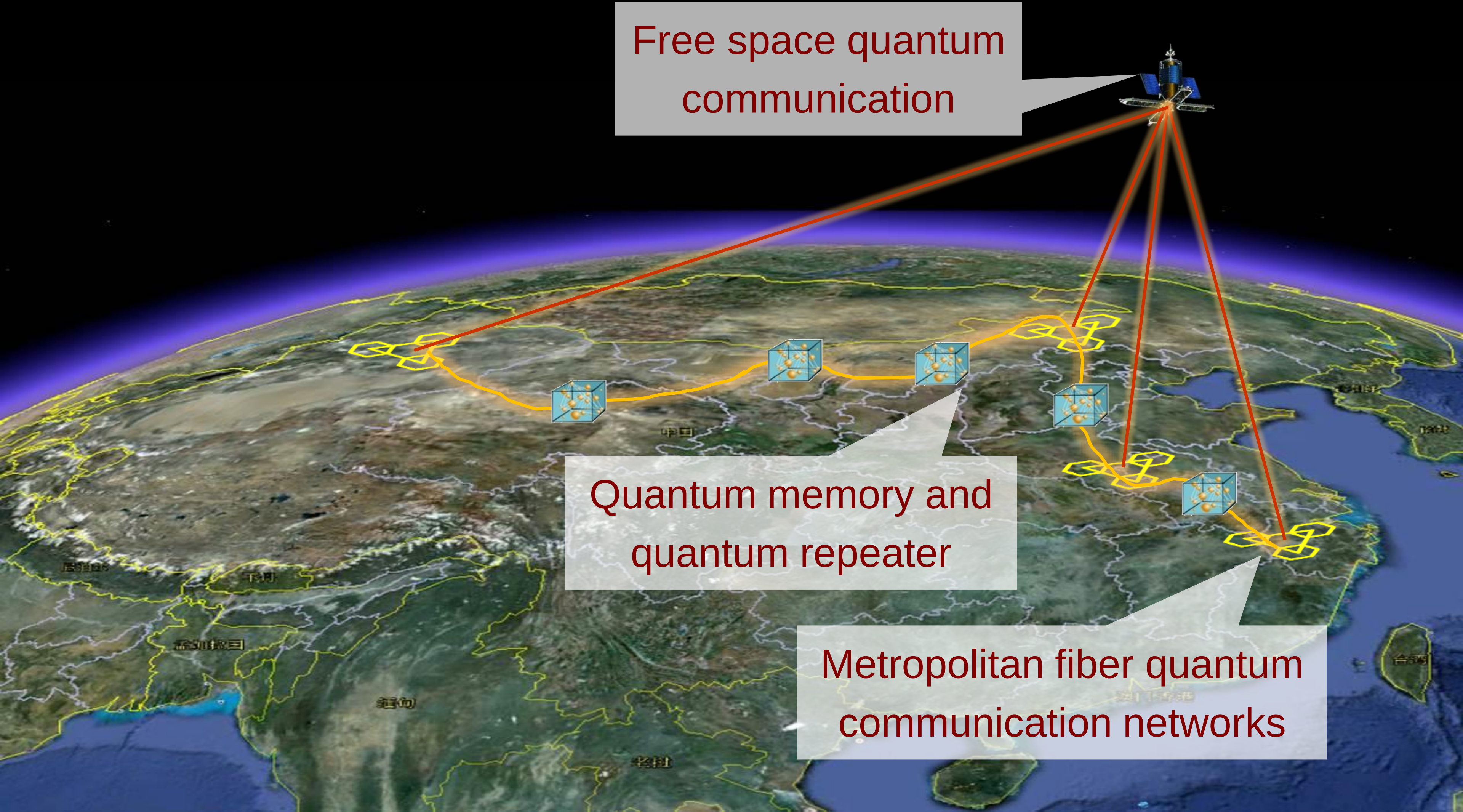

廖胜凯


李力

Introduction to our team

Research field: quantum information processing with photons and atoms

- Quantum communication



Free space quantum communication

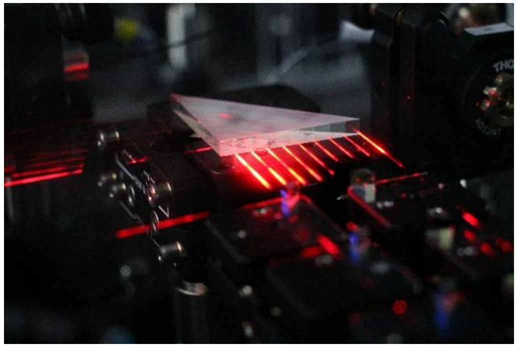
Quantum memory and quantum repeater

Metropolitan fiber quantum communication networks

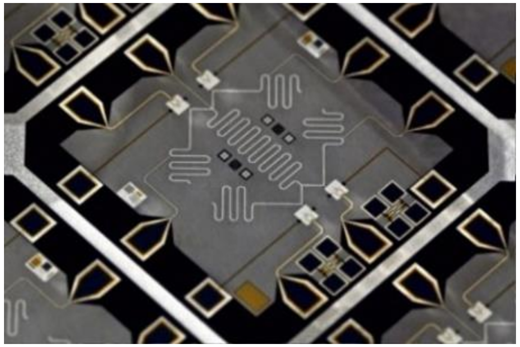
Introduction to our team

Research field: quantum information processing with photons and atoms

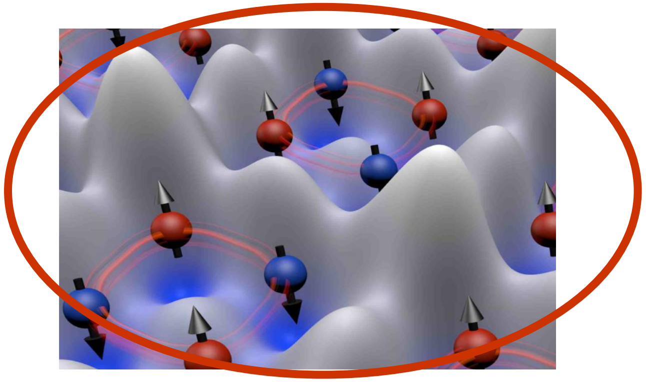
- Quantum computation and simulation with



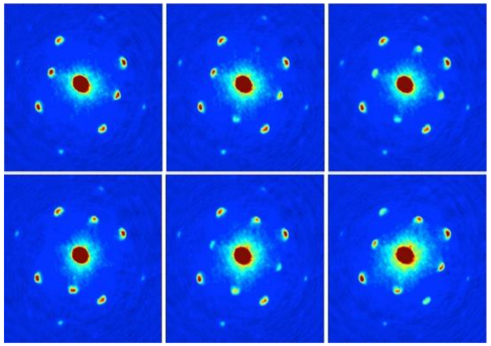
Multi-photon entanglement



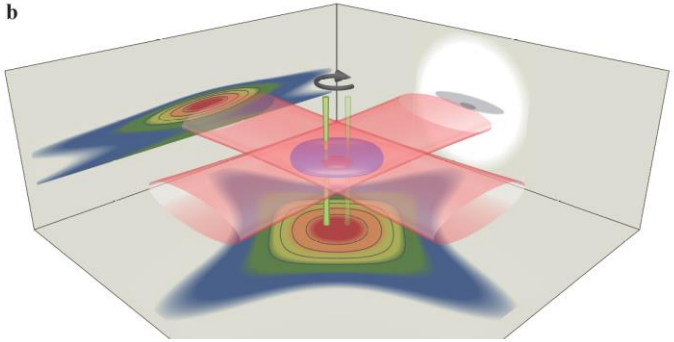
Superconducting qubit



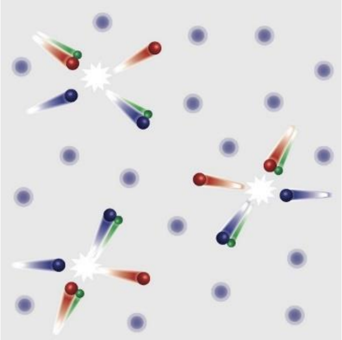
Atom-atom entanglement



Ultracold Bose gases (SOC)



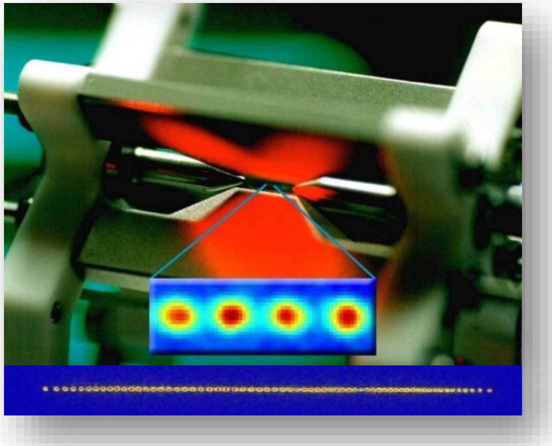
Ultracold Fermion mixture



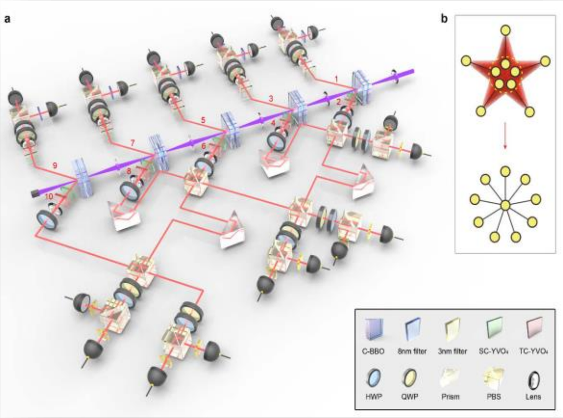
Ultracold molecule

Motivation: Quantum Information Processing

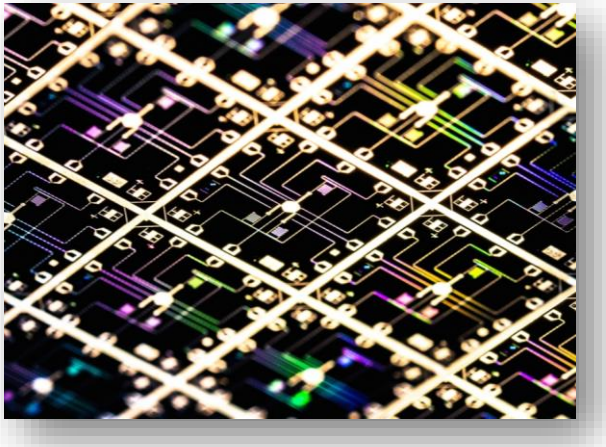
Resource for QIP, Entangled states



Ions: R. Blatt, C. Monroe



Photons: Jian-Wei Pan



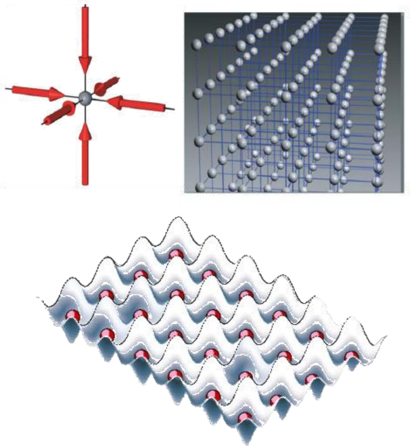
Superconducters: Google, IBM, Intel

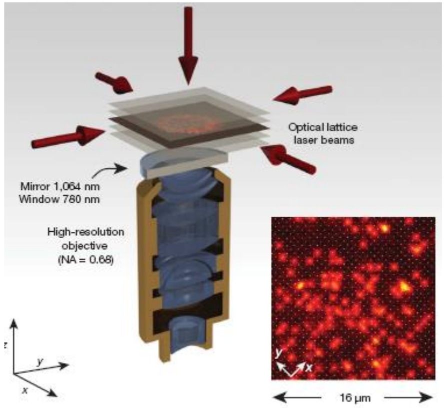
Ions: Monz et al, PRL **106**, 130506 (2011); N. Friis et al, PRX 8, 021012 (2018);
J Zhang et al, Nature 551, 601 (2017)

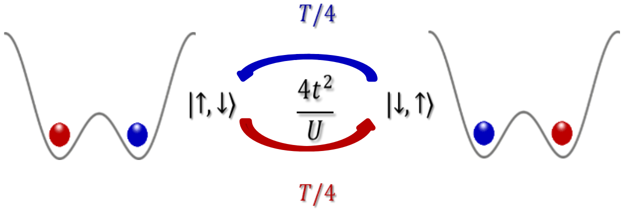
Photons: X-L Wang et al, PRL 117, 210502 (2016); arXiv:1801.04043

Superconducting qubits: P. Roushan et al, Science 358, 1175 (2017) Google;
N. Kalb et al, Science 356, 928 (2017), intel Qutech; IBM 49 qubits; Yale;

Scalability: atoms in optical lattice





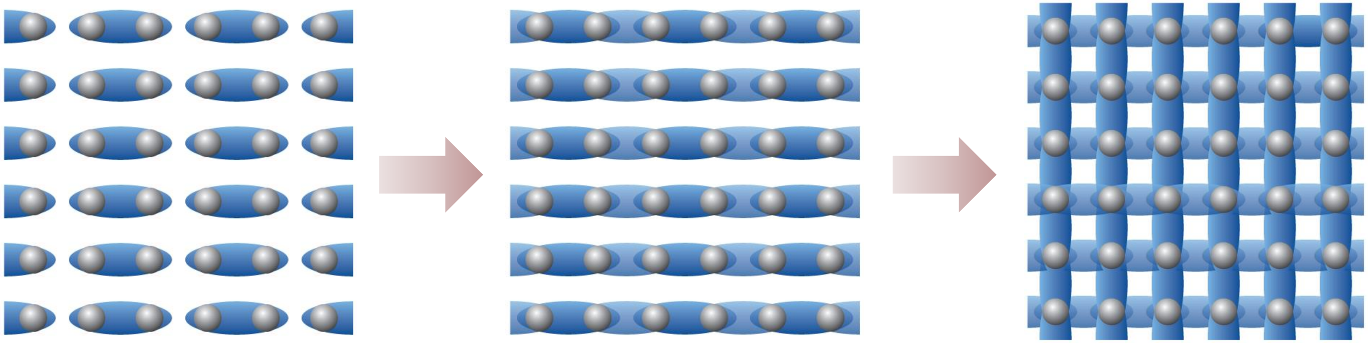


Optical lattice: an array of well coherently controlled cold atoms

in-situ imaging: only one atom trapped in a lattice

Spin exchange interaction: generate spin-spin entanglement

Multi-atom entanglement!



Vaucher *et al*, NJP (2008)

Scalability: fault tolerable qubits

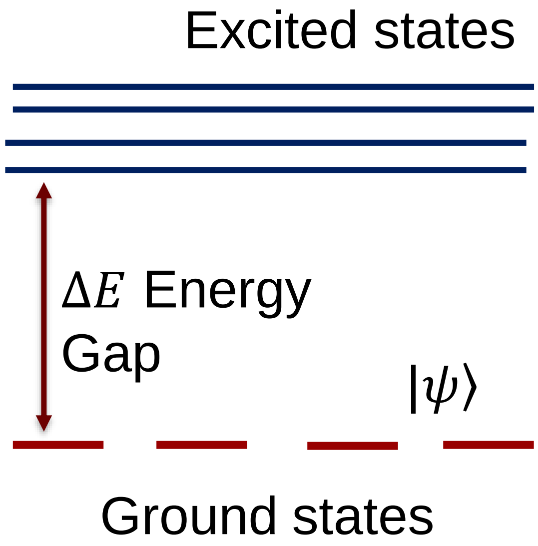
To overcome qubit errors in quantum computing

- Error-correcting code
  - Shor, PRA 52, R2493 (1995) 9qubits
  - Steane, PRL 77, 793 (1996) 7qubits
  - Laflamme *et al*., PRL 77, 198 (1996) 5qubits
  - ☒ Traditional concatenated codes require error rate $< 2\times10^{-5}$!

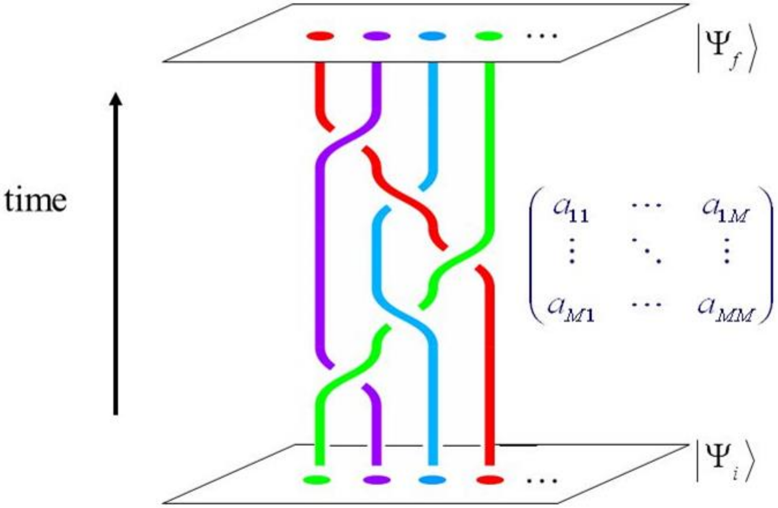
- Protect quantum bits/gates at the physical level -- topological quantum computing
  - Kitaev, Ann. Phys. 303, 2 (2003); Ann. Phys. 321, 2 (2006)
  - Raussendorf *et al*., Ann. Phys. 321, 2242 (2003)
  - Nayak *et al*., RMP 80 (3): 1083 (2008)
  - ☑ Relax the error threshold rate from 10^{-5} to 10^{-2}

Scalability: fault tolerable qubits

Topological Quantum Computation



Protect qubits with energy gap



Quantum gates--Braiding Anyons

- **Anthony James Leggett:** …no naturally occurring system is likely to have a Hamiltonian (for topological computing); Purpose-engineered systems of optical lattices or Josephson junction arrays (are promising candidates)

Kitaev Model: Toric code

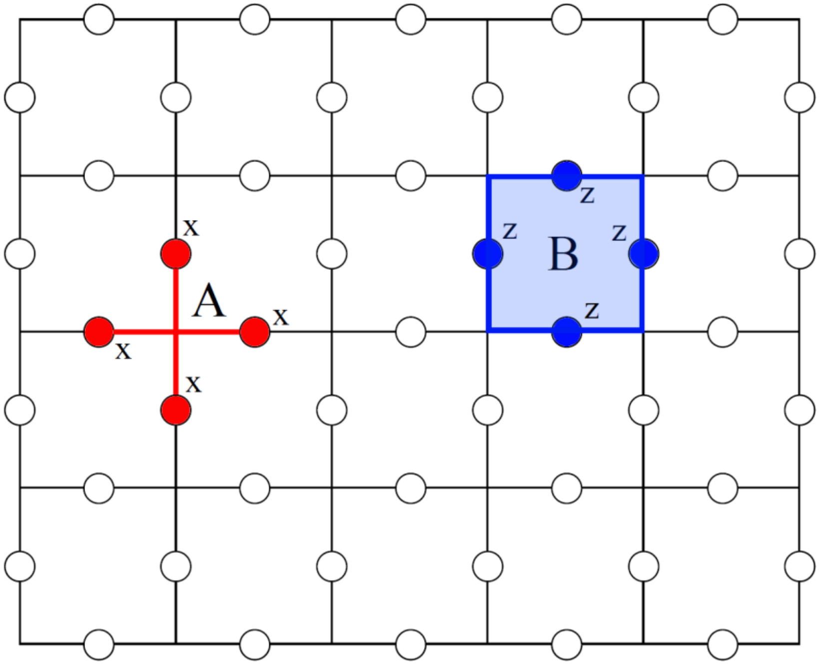
Protecting qubits with energy gap

Hamiltonian:

$$H_0 = -\sum_s A_s - \sum_p B_p$$

$$A_s = \prod_{j\in \mathrm{star}(s)} \sigma_j^x$$

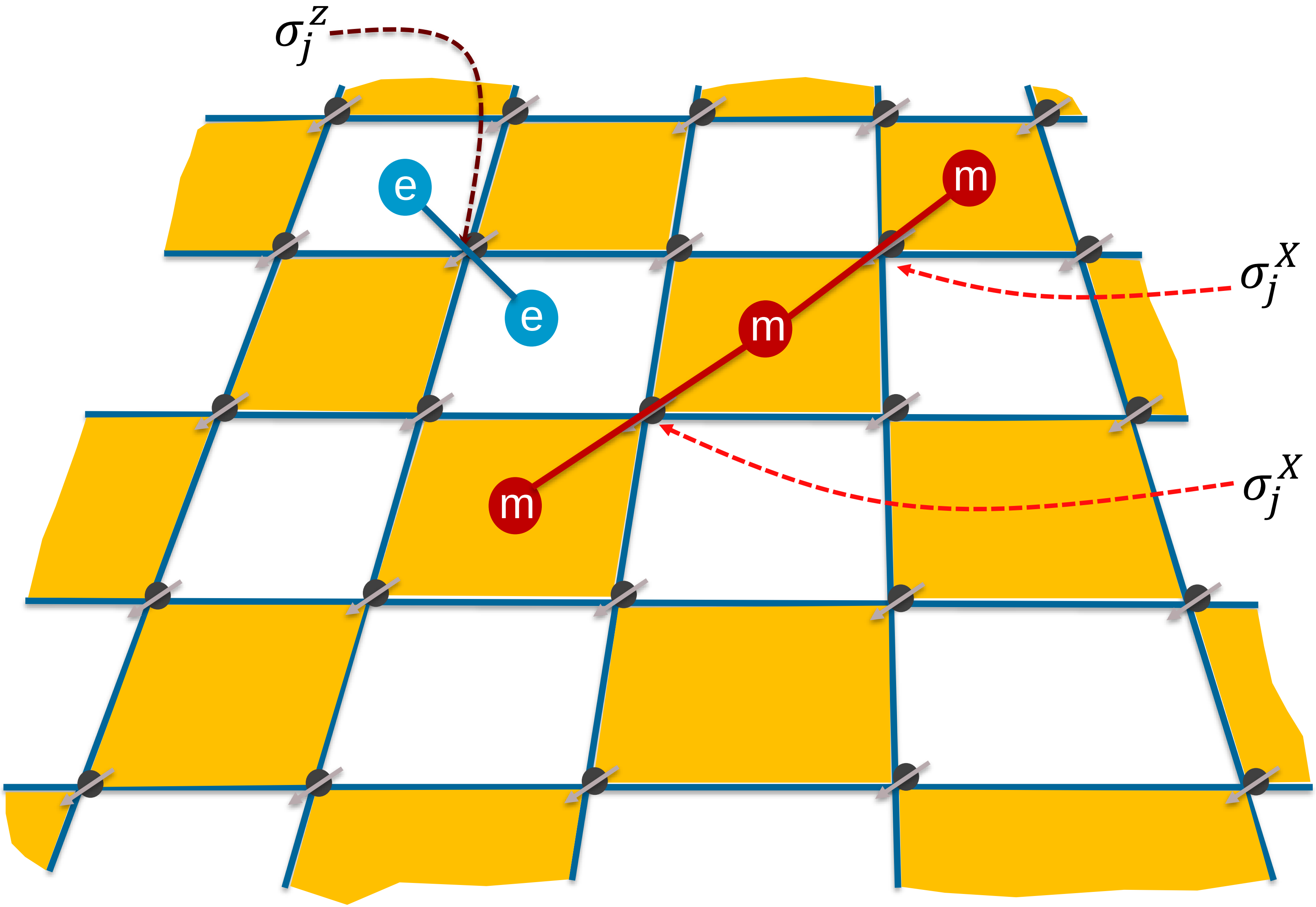
$$B_p = \prod_{j\in \mathrm{boundary}(p)} \sigma_j^z$$



- Four-body interaction
- Abelian Anyons: *e*, *m* excitaions

Kitaev, Annals of Physics 303, 2 (2003)

Toric code -- Braiding



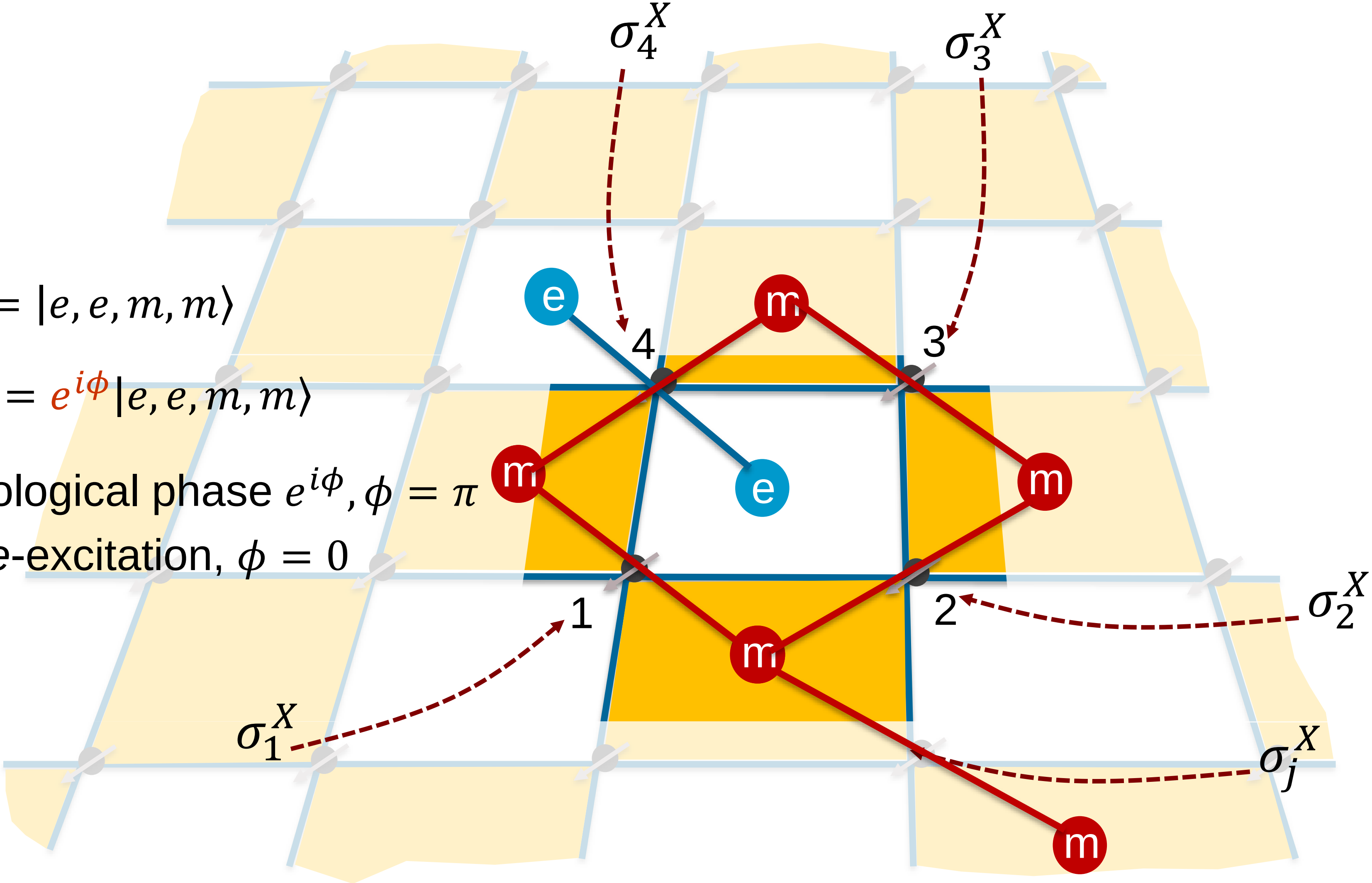
Toric code -- Braiding

$|\varphi\rangle = |e, e, m, m\rangle$

$|\varphi'\rangle = e^{i\phi}|e, e, m, m\rangle$

Topological phase $e^{i\phi}, \phi = \pi$

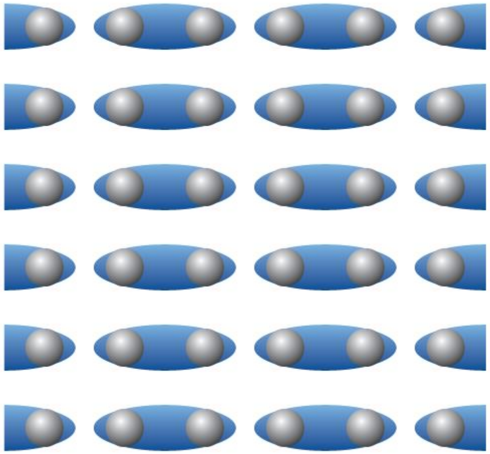
No *e*-excitation, $\phi = 0$



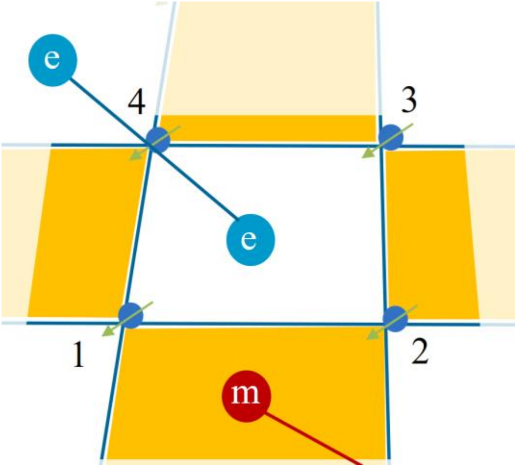
Spin entanglement and anyonic statistics in OL

Our experiment:

- Manipulating superexchange in optical lattice
- Creating entangled atom pairs
- Manipulating four-body interaction, four-atom entanglement
- Demonstrating anyonic statistics with plaquette units



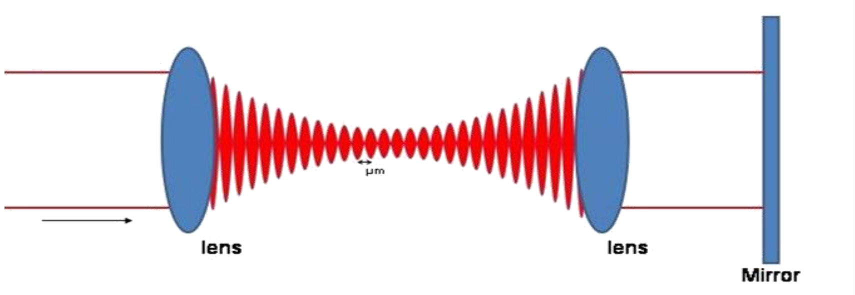
Entangled atom pairs



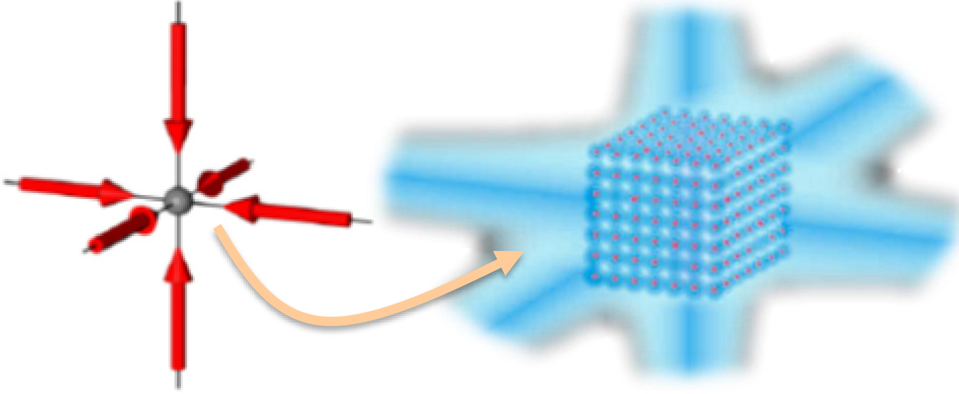
Ring exchange and Toric code

Atoms in optical lattices

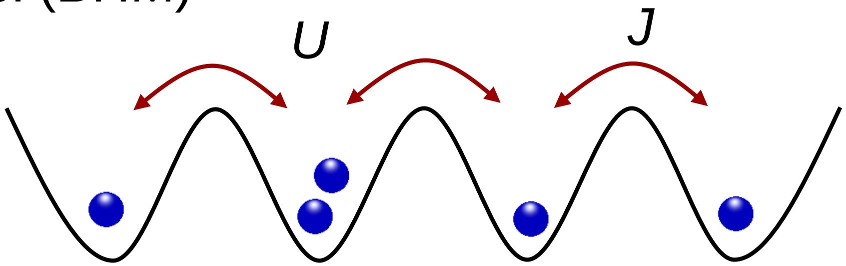
Standing wave of light



3D optical lattice



Bose-Hubbard model (BHM)

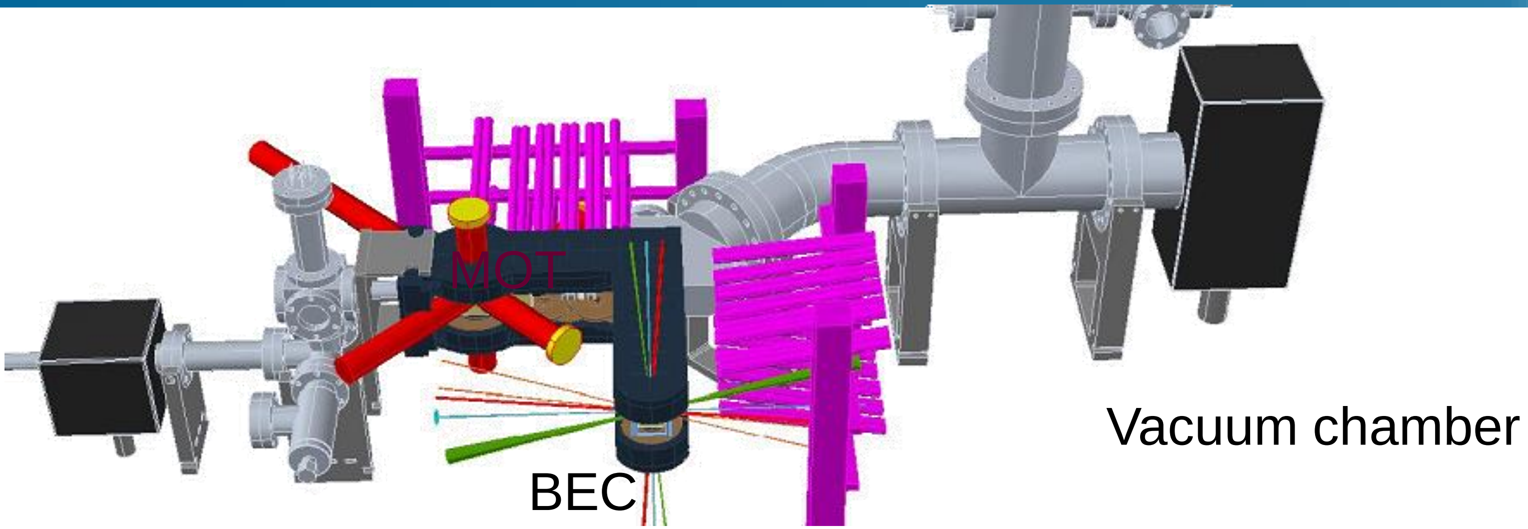


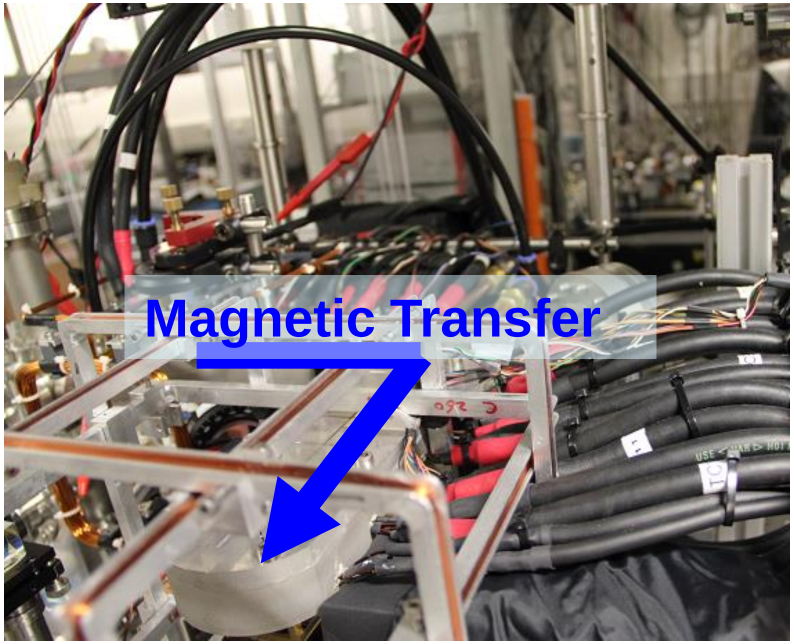
$$\hat{H} = -J\sum_{\langle i,j\rangle}\hat{a}_i^\dagger\hat{a}_j + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i-1) - \sum_i \mu_i\hat{n}_i,$$

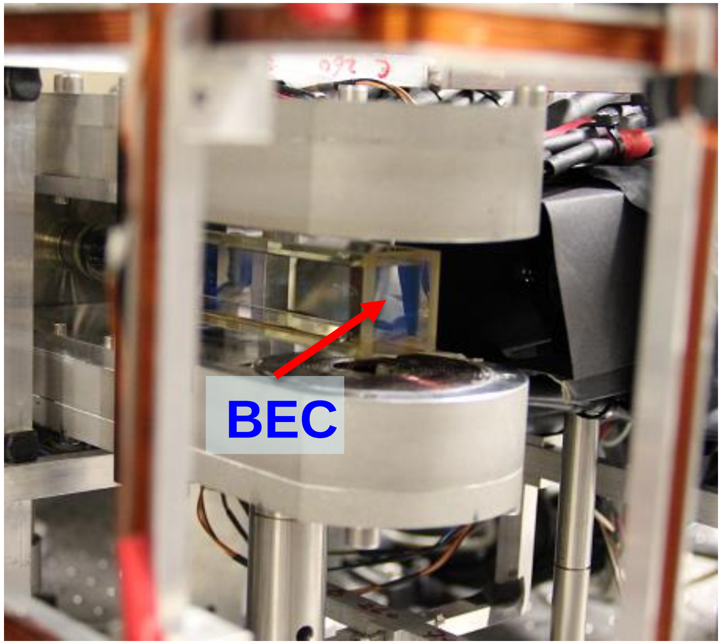
J: nearest-neighbor tunneling

U: onsite interactions

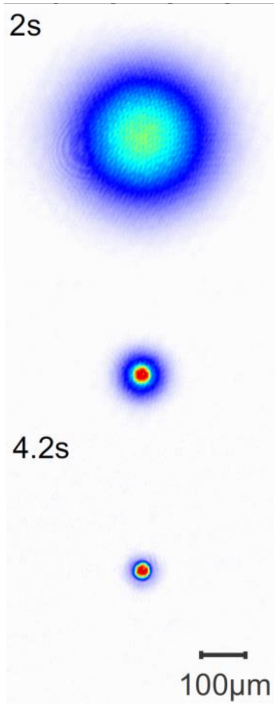
Experimental setup



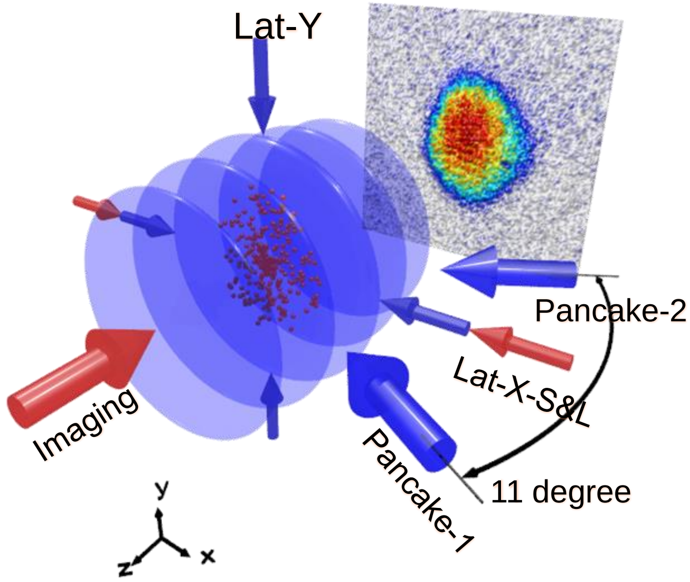




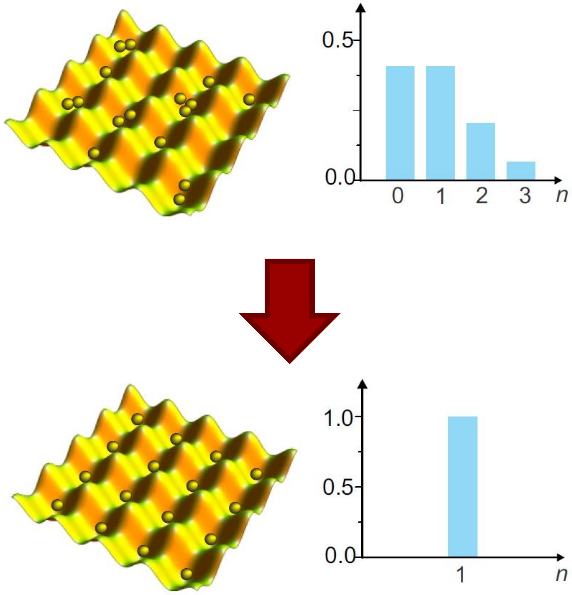
Prepare a 2D quantum gas with in-situ imaging



^{87}Rb: $|F=1, m_F=-1\rangle$
BEC 2×10^5 atoms



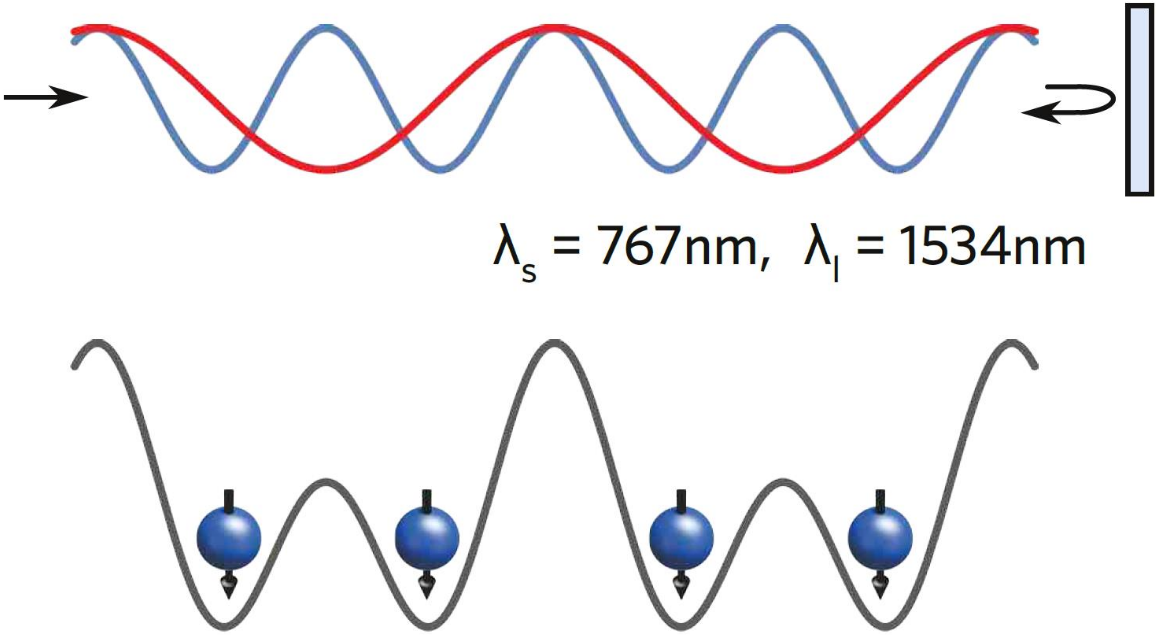
Load into a pancake trap
N_{2D}~15000, T_{2D}=23(3) nK



SF to MI transition by ramping up lattice depth

- Objective: NA=0.48, resolution 2 μm

Optical super-lattice



● $|\downarrow\rangle = 5S_{1/2}|F=1, m_F=-1\rangle$ ● $|\uparrow\rangle = 5S_{1/2}|F=2, m_F=-2\rangle$

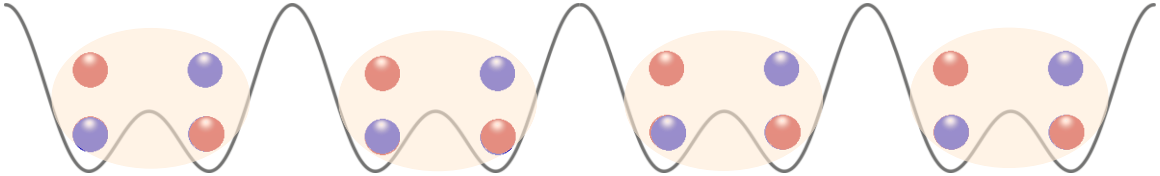
Isolated double wells: $V(x) = V_s \cos^2(2kx + \phi_x) + V_l \cos^2(kx)$

Theory: Duan *et al.*, PRL 91, 090402 (2003)

Experiment: Trotzky *et al.*, Science 319, 295 (2008)

Spin super-exchange: generating spin entanglement

Interaction dominated $(U \gg J)$, with pseudo spins:



$$\hat{\mathrm{H}} = -J_{ex}\,\hat{\mathrm{S}}_L \cdot \hat{\mathrm{S}}_R \qquad J_{ex} \sim 4J^2/U$$

Initial state: $|\uparrow\downarrow\rangle$ is degenerate with $|\downarrow\uparrow\rangle$

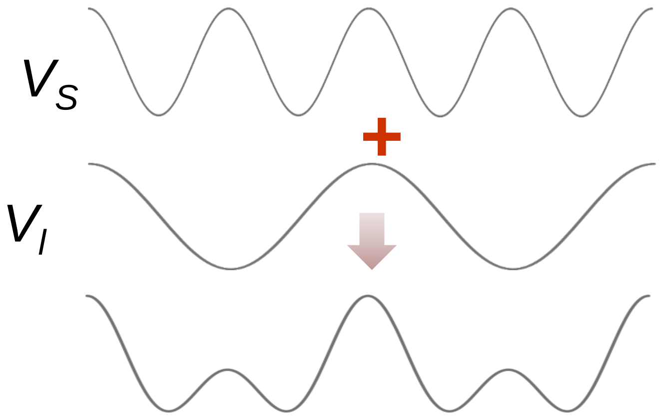
The spins will oscillate between the two configurations with a period of $1/J_{ex}$

Stop the oscillation by increasing the barrier to create spin entanglement

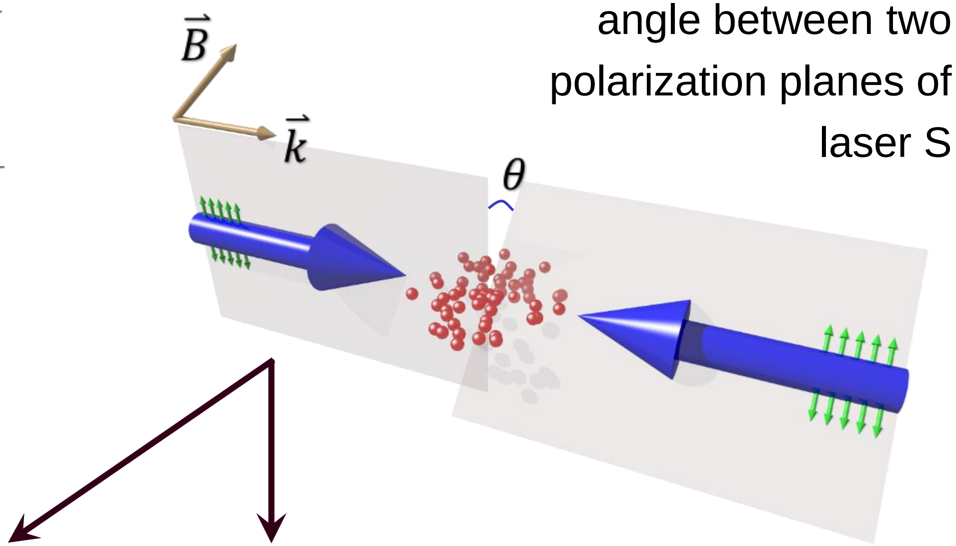
$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

Spin-dependent superlattices

Normal super-lattice



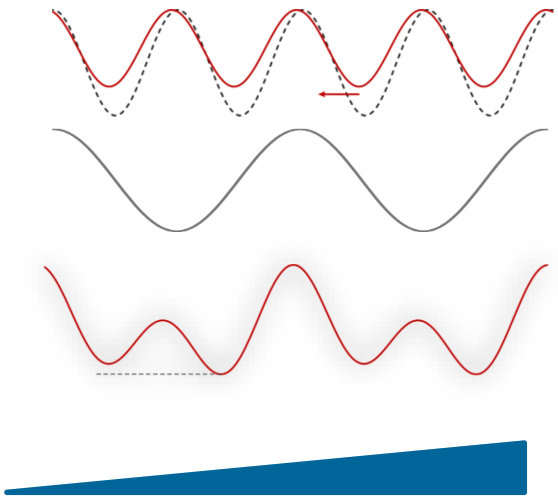
Spin-dependent superlattice



angle between two polarization planes of laser S

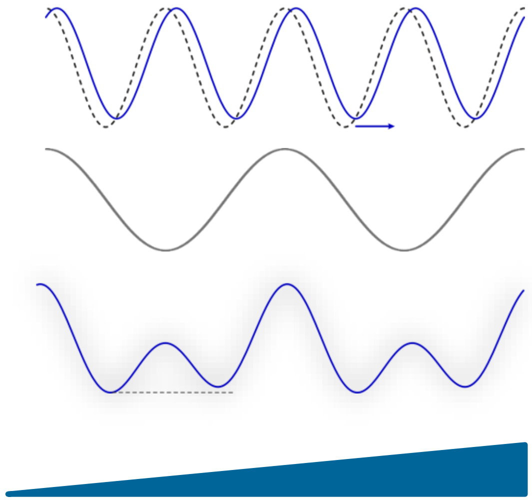
● $|\uparrow\rangle = 5S_{1/2}|F = 2, m_F = -2\rangle, g_F = 1/2$

● $|\downarrow\rangle = 5S_{1/2}|F = 1, m_F = -1\rangle, g_F = -1/2$



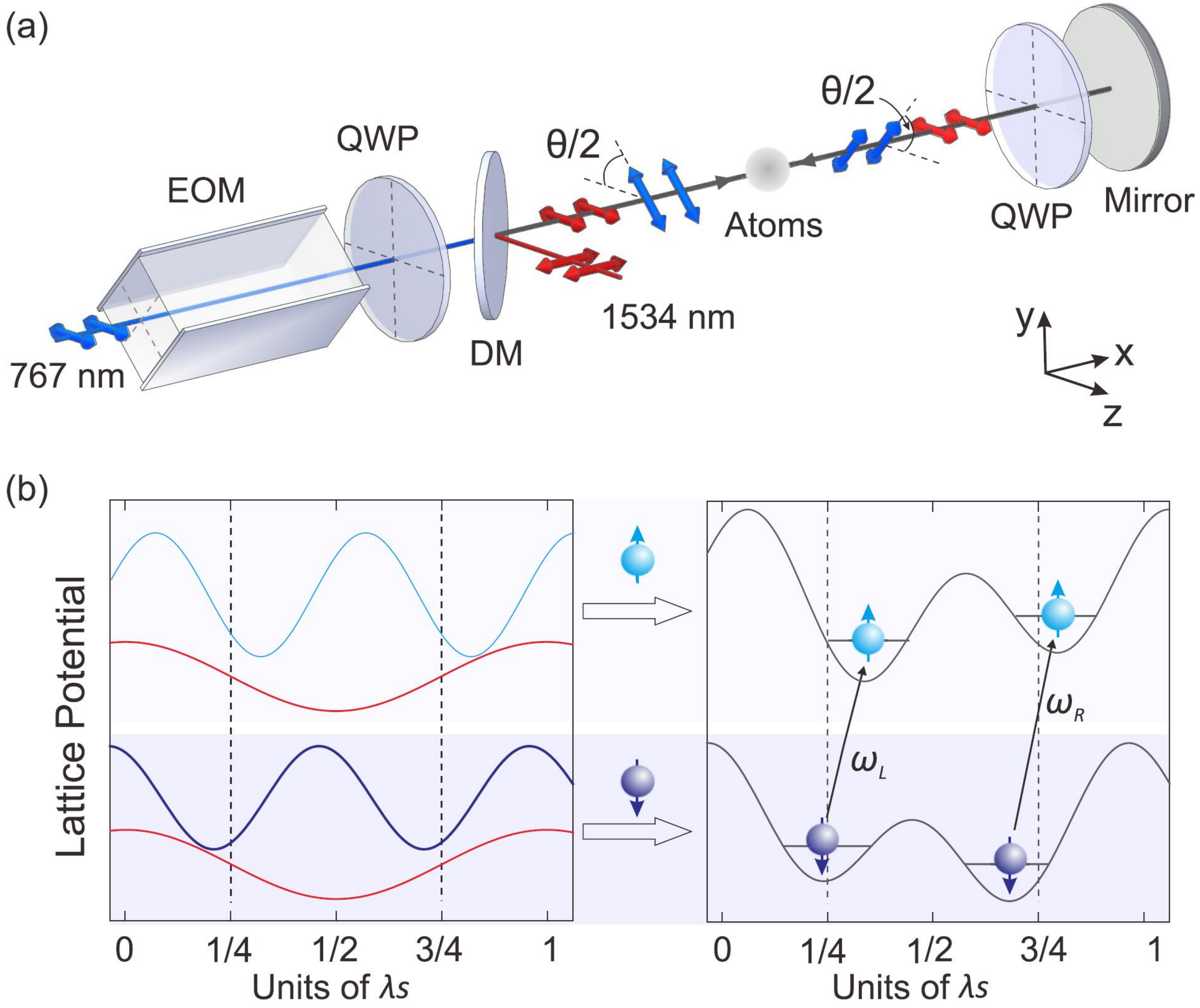
Left well is higher

∇B



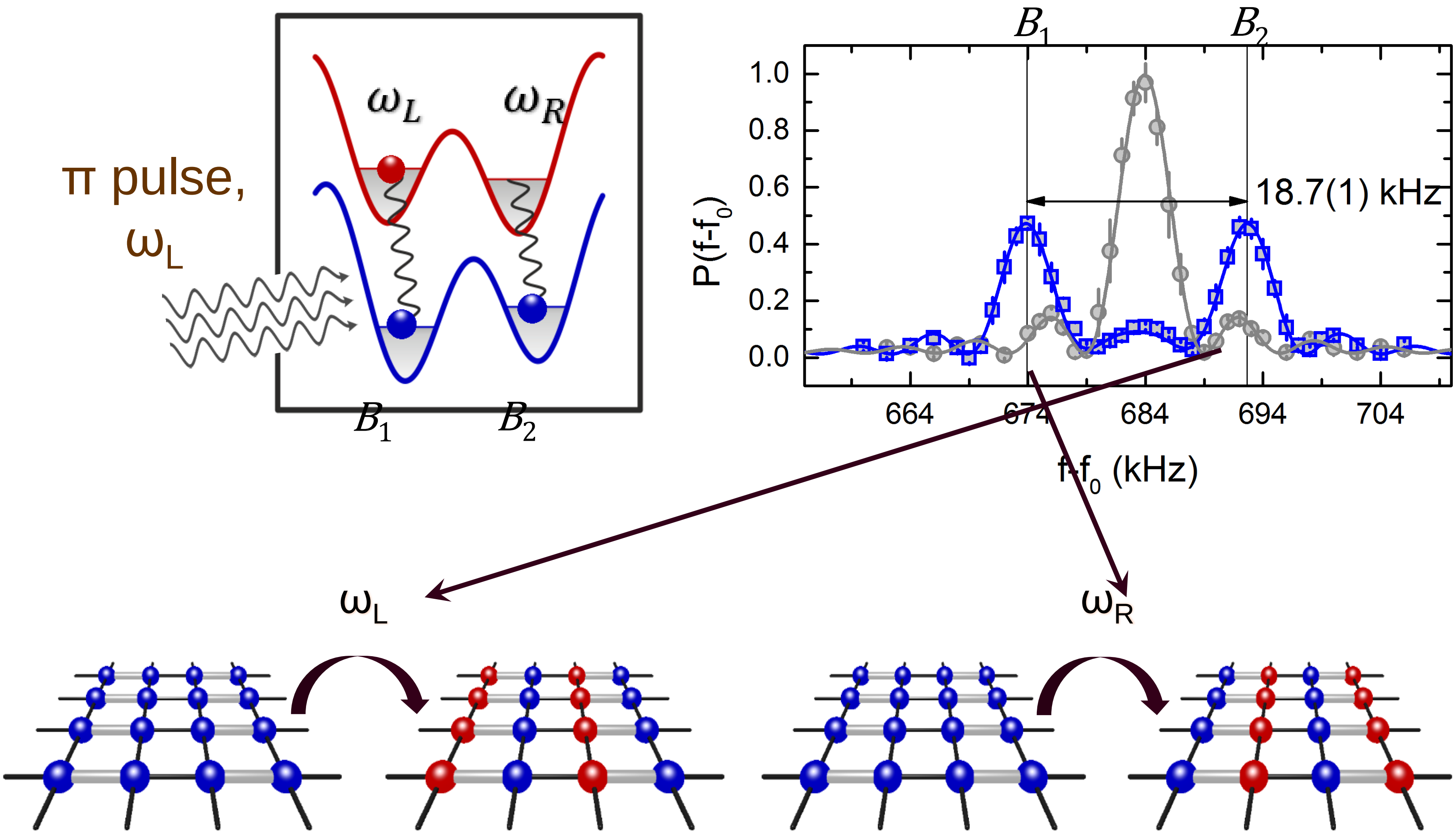
Right well is higher

Spin-dependent superlattices

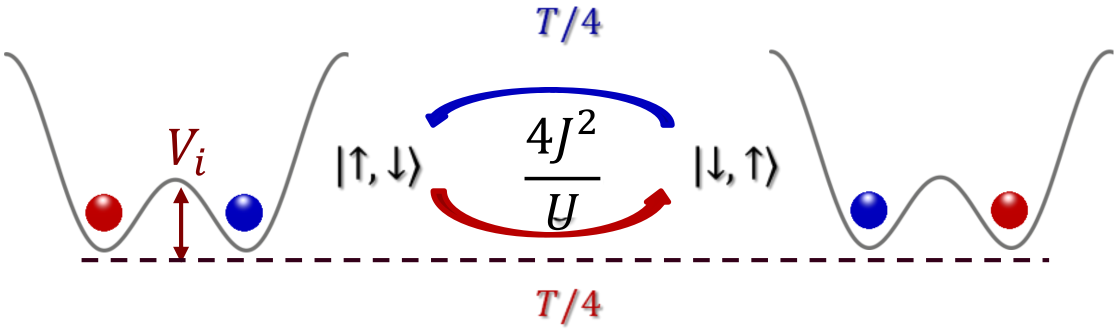


Spin-dependent superlattices

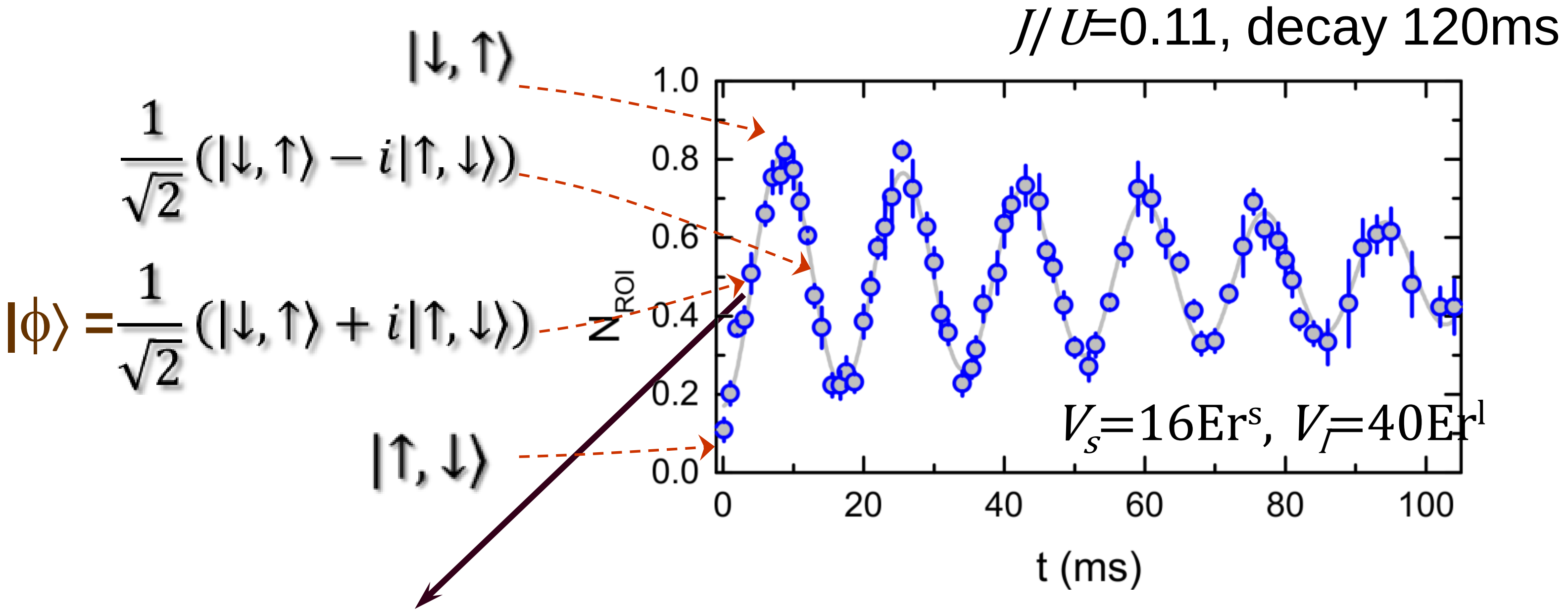
effective magnetic gradient caused by spin-dependent superlattice



Spin super-exchange: generating spin entanglement



- Switch off effective magnetic gradient, $|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$ degenerate
- Decrease V_i → spin oscillation



- Increase V_i → Freeze entangled state

How to detect entanglement?

Entanglement detection

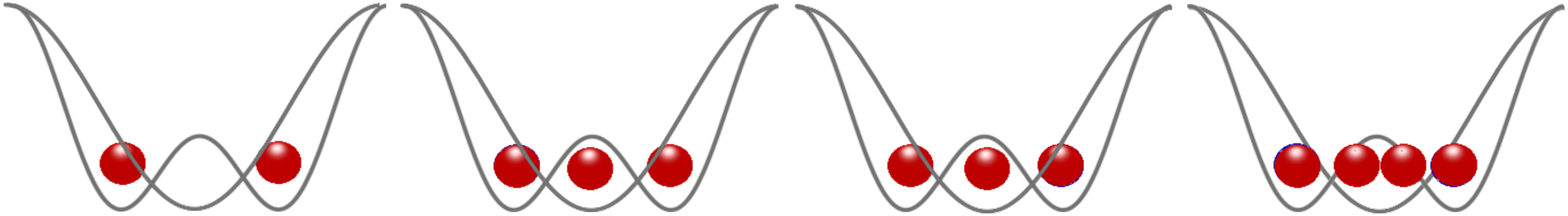
Entangled state: $|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle)$

Spin-dependent collisional loss: identify $|\downarrow\downarrow\rangle$ from 4 spin basis

- Imaging spin-up atoms
- Merging and killing

- Count N_1
- Count N_2

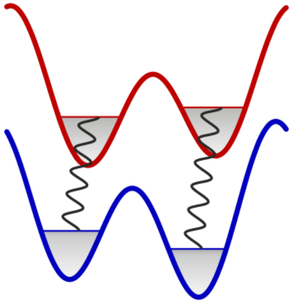
- π pulse



$$N_{\downarrow\downarrow} = N_{Total} - N_1 - N_2$$

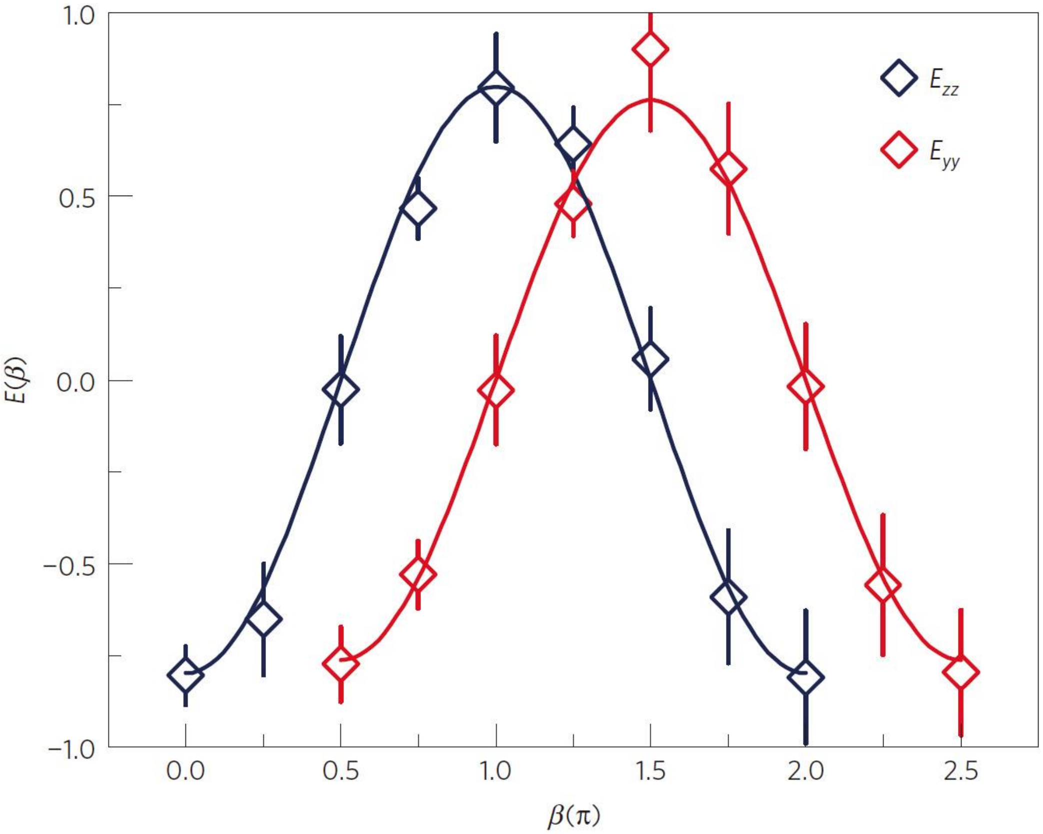
Identify $|\uparrow\downarrow\rangle$, $|\downarrow\uparrow\rangle$, $|\uparrow\uparrow\rangle$:

transfer to $|\downarrow\downarrow\rangle$ by left/right π pulse



Detection of entanglement

Spin correlation curve



Violation of CHSH type Bell's inequality $S = 2.21 \pm 0.08$

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

2D-optical superlattice

BHM：

$$\hat{H} = -J\sum_{\langle i,j\rangle}\hat{a}_i^{\dagger}\hat{a}_j + \frac{U_0}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) - \sum_i \mu_i\hat{n}_i,$$

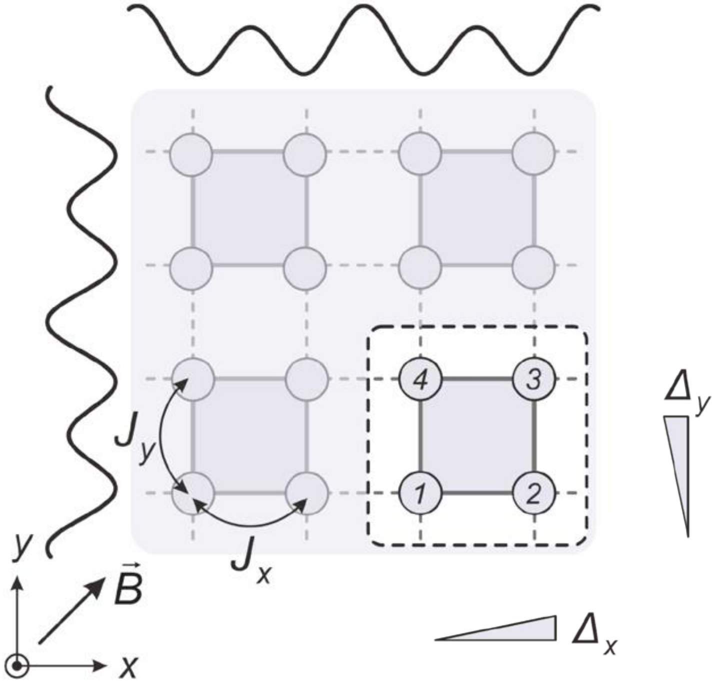
J<<U

Super-exchange:

$$\hat{\mathbf{H}} = -J_{ex}\,\hat{\mathbf{S}}_L\cdot\hat{\mathbf{S}}_R$$

Ring-exchange:

$$\mathbf{H}=J_{\square}S_1S_2S_3S_4$$



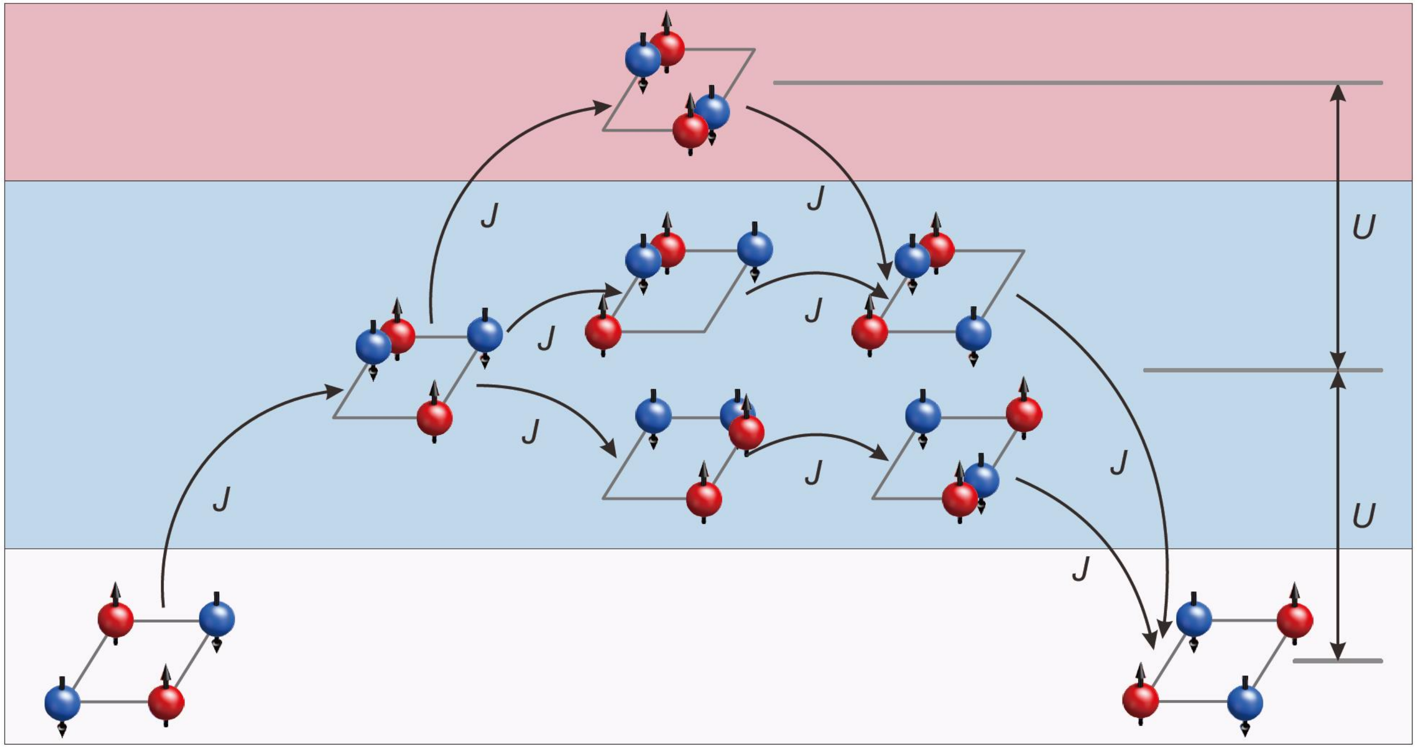
isolated plaquettes

B.Paredes & I.Bloch, PRA77,23603 (2008).

Ring-exchange interaction

$$A_s = -\sigma_1^x \sigma_2^x \sigma_3^x \sigma_4^x$$

4th order perturbation to the BHM



$$\hat{H}^{(4)} = {\color{red}40}\, {}^{J^4}\!/_{U^3} \longrightarrow \sim\mathrm{Hz}$$

2D-optical superlattice

BHM

$$\hat{H}: = -J\sum_{\langle i,j\rangle}\hat{a}_i^{\dagger}\hat{a}_j + \frac{U_0}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) - \sum_i \mu_i \hat{n}_i,$$

J=200 Hz, *U*=2 kHz

Super-exchange:

$$\hat{\mathbf{H}} = -J_{ex}\,\hat{\mathbf{S}}_L \cdot \hat{\mathbf{S}}_R$$

$$J_{ex} \sim \frac{J^2}{U} = 20\ \mathrm{Hz} \sim 1\ \mathrm{nK}$$

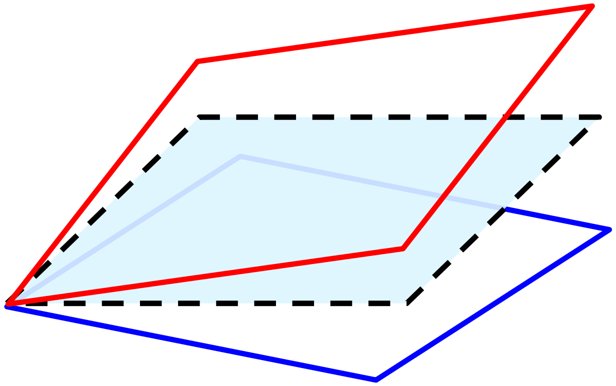
Ring-exchange:

$$\mathbf{H} = J_{\square} S_1 S_2 S_3 S_4$$

$$J_{\square} \sim \frac{J^4}{U^3} = 0.2\ \mathrm{Hz} \sim 0.01\ \mathrm{nK}$$

Minimum toric code Hamiltonian

ring exchange



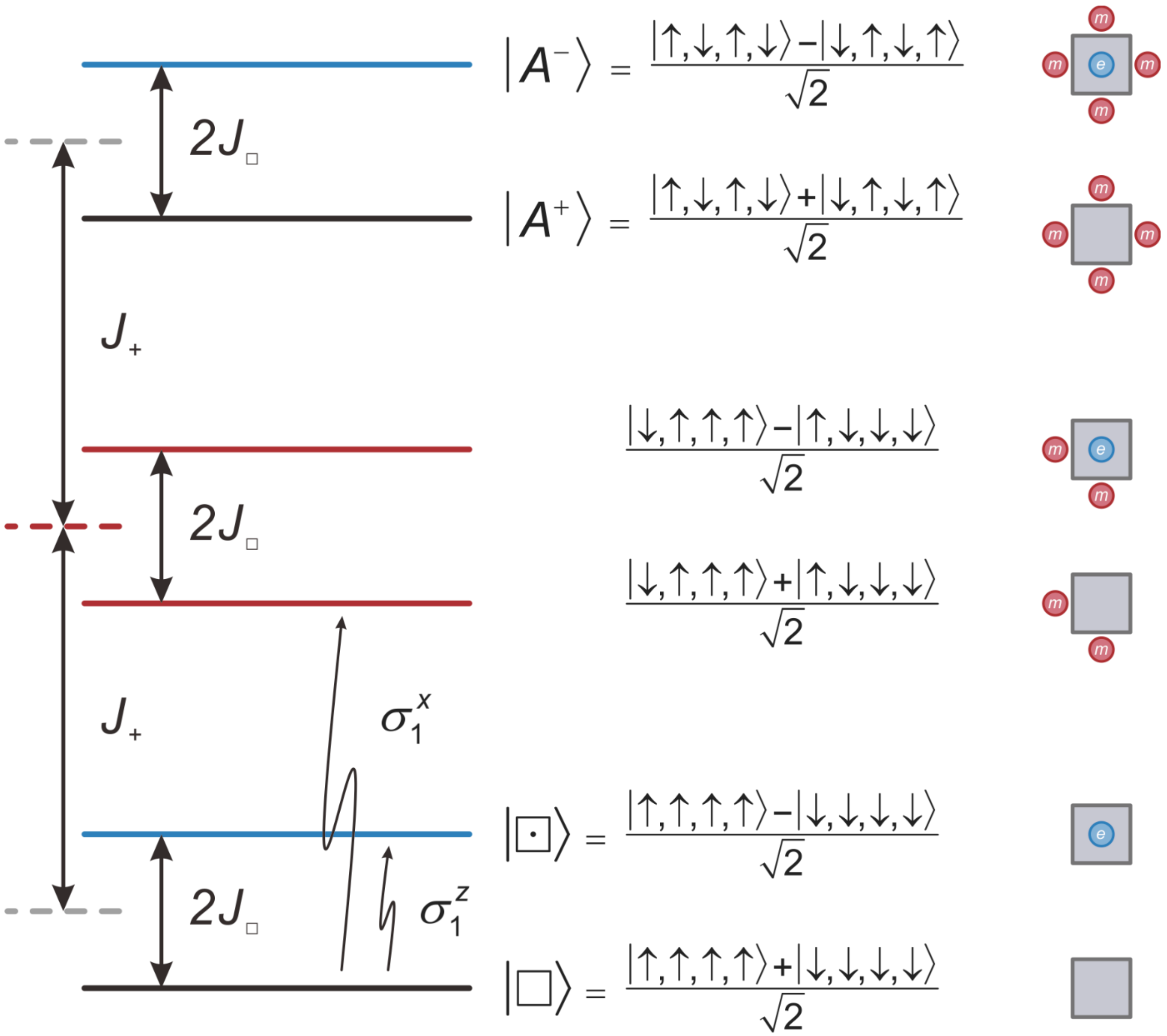
- *the Toric code model*:

$$\hat{H}_{\mathrm{T}} = -\hat{\sigma}_1^x\hat{\sigma}_2^x\hat{\sigma}_3^x\hat{\sigma}_4^x - \sum_{<i,j>} \hat{\sigma}_i^z\hat{\sigma}_j^z$$

Toric code model in subspace

$$\mathbb{H} = \{|\uparrow,\downarrow,\uparrow,\downarrow\rangle, |\downarrow,\uparrow,\downarrow,\uparrow\rangle\}$$

Spectrum of the plaquette model



$$|A^-\rangle = \frac{|\uparrow,\downarrow,\uparrow,\downarrow\rangle - |\downarrow,\uparrow,\downarrow,\uparrow\rangle}{\sqrt{2}}$$

$$|A^+\rangle = \frac{|\uparrow,\downarrow,\uparrow,\downarrow\rangle + |\downarrow,\uparrow,\downarrow,\uparrow\rangle}{\sqrt{2}}$$

$$\frac{|\downarrow,\uparrow,\uparrow,\uparrow\rangle - |\uparrow,\downarrow,\downarrow,\downarrow\rangle}{\sqrt{2}}$$

$$\frac{|\downarrow,\uparrow,\uparrow,\uparrow\rangle + |\uparrow,\downarrow,\downarrow,\downarrow\rangle}{\sqrt{2}}$$

$$|\boxdot\rangle = \frac{|\uparrow,\uparrow,\uparrow,\uparrow\rangle - |\downarrow,\downarrow,\downarrow,\downarrow\rangle}{\sqrt{2}}$$

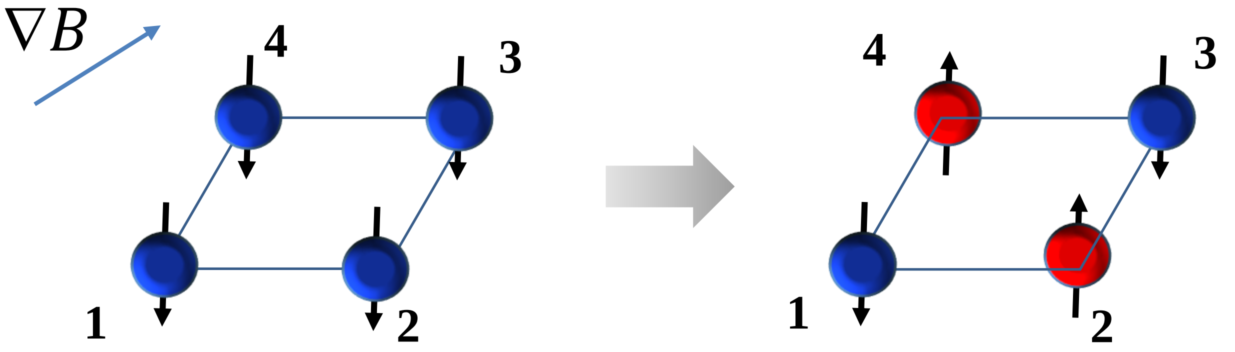
$$|\Box\rangle = \frac{|\uparrow,\uparrow,\uparrow,\uparrow\rangle + |\downarrow,\downarrow,\downarrow,\downarrow\rangle}{\sqrt{2}}$$

Site-resolved addressing: state initialization

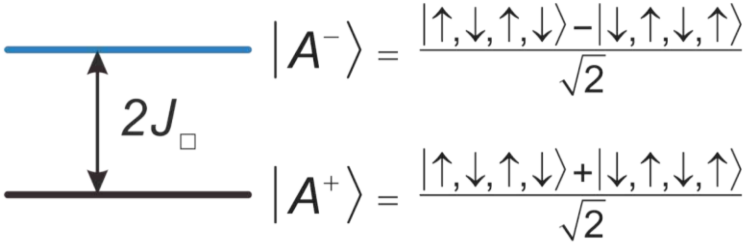
Effective magnetic gradient created by the spin-dependent superlattices

Sawtooth-like, period of OL

$$B_3 > B_4 = B_2 > B_1$$

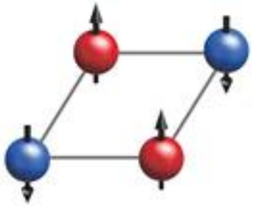


Ring Exchange Driven Oscillation



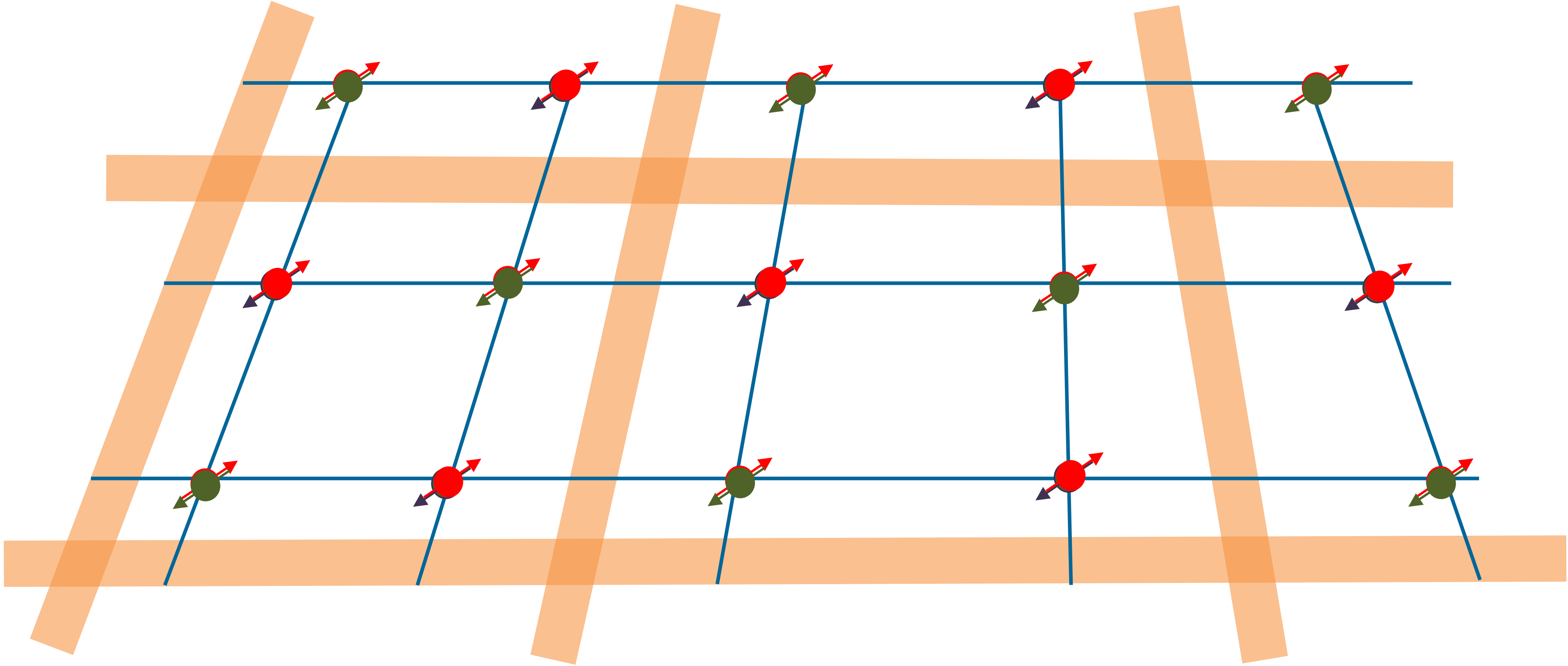
$$|A^-\rangle = \frac{|\uparrow,\downarrow,\uparrow,\downarrow\rangle - |\downarrow,\uparrow,\downarrow,\uparrow\rangle}{\sqrt{2}}$$

$$|A^+\rangle = \frac{|\uparrow,\downarrow,\uparrow,\downarrow\rangle + |\downarrow,\uparrow,\downarrow,\uparrow\rangle}{\sqrt{2}}$$



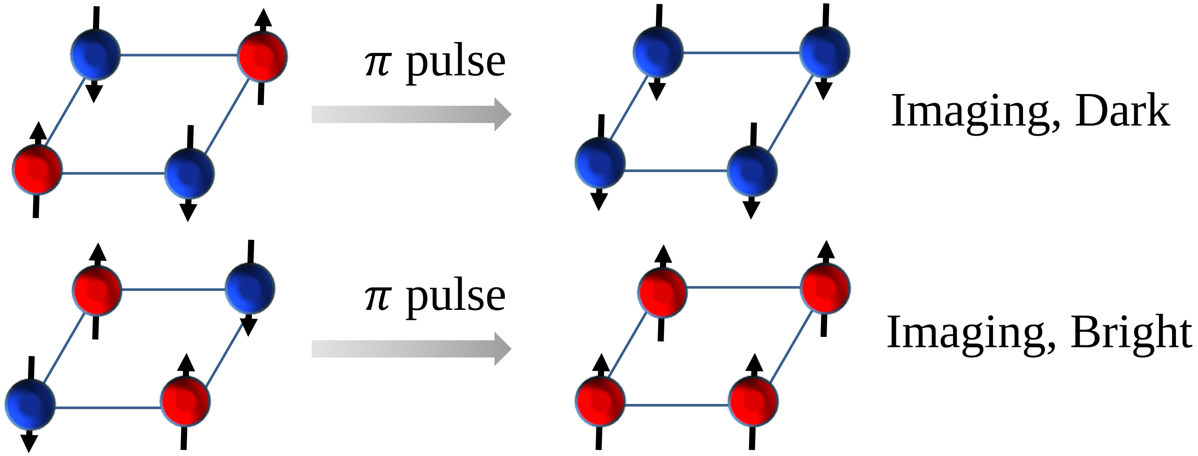
Initial state

$$= \frac{1}{\sqrt{2}}(|A^-\rangle + |A^+\rangle)$$



Observation of ring exchange driven oscillation

Count the populations of different states

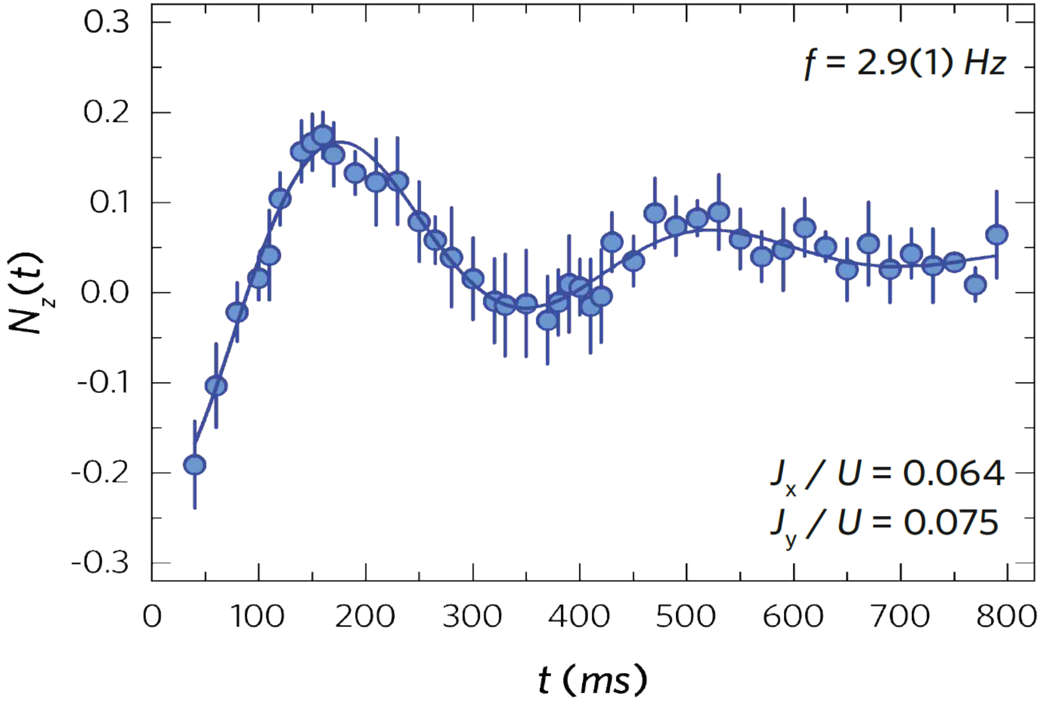


π pulse

Imaging, Dark

π pulse

Imaging, Bright



Settings:

$V_{xl} = V_{yl} = 10\ E_r$

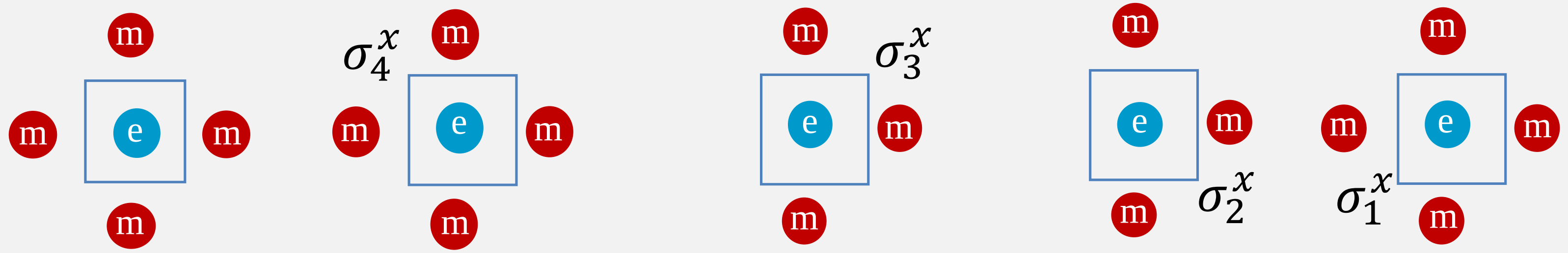
$\Delta_x = 115(1)\ Hz$

$V_{ys} = 18.2(1)\ E_r$

$V_{xs} = 19.2(1)\ E_r$

$\Delta_y = 145(1)\ Hz$

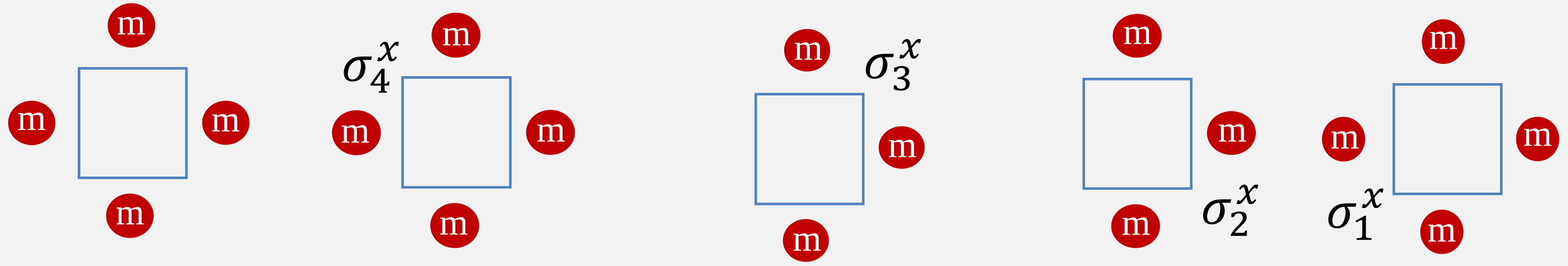
Topological phase of Abelian anyons, θ =π /2



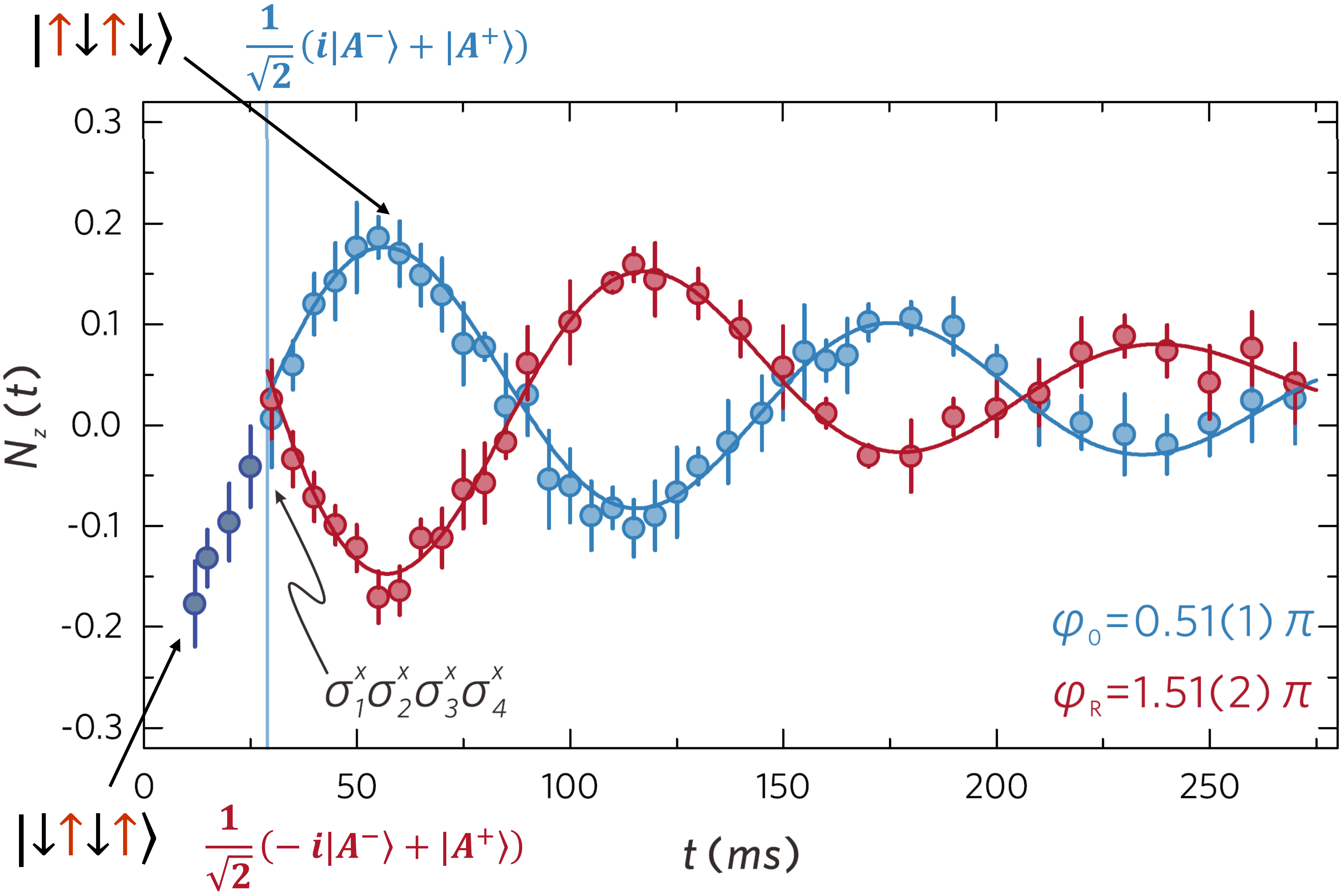
$|A^-\rangle$ $-|A^-\rangle$

$$\psi_i = \frac{1}{\sqrt{2}}(i|A^-\rangle + |A^+\rangle) \longrightarrow \psi_f = \frac{1}{\sqrt{2}}(-\,i|A^-\rangle + |A^+\rangle)$$

$|A^+\rangle$ $+|A^+\rangle$



Observation of Anyonic Fractional Statistics

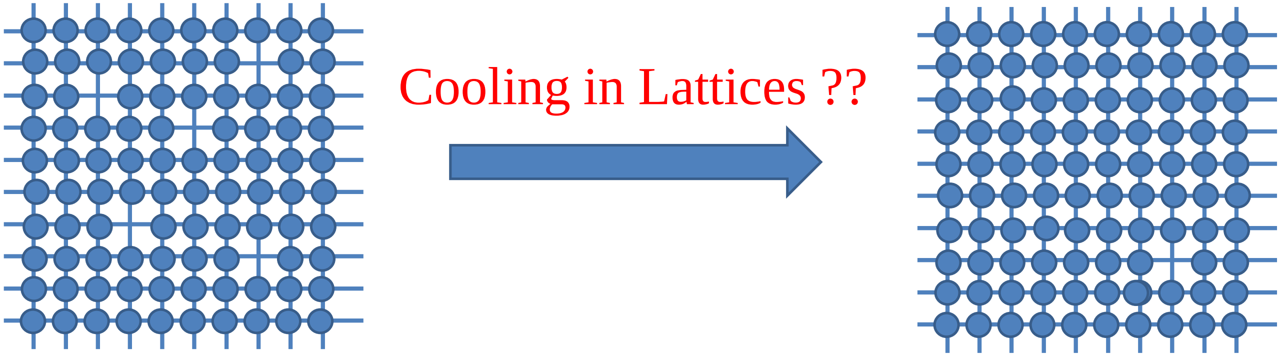


Dai *et al*, Nature Physics 13, 1195 (2017)

Outlook- towards large entangled state

- For a large entangled state: remove defects, connect the atom pairs

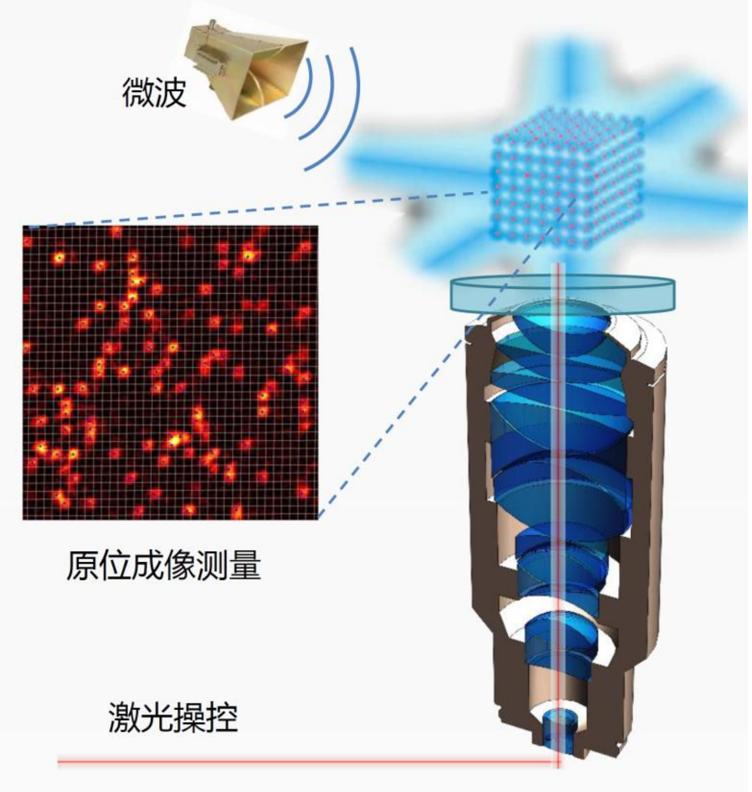
  Challenge: cool the atoms in lattices?

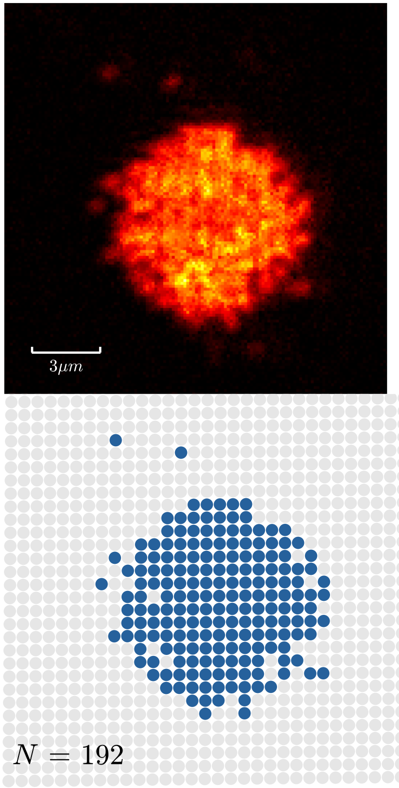


Cooling in Lattices ??

Outlook- towards large entangled state

- High-resolution imaging system



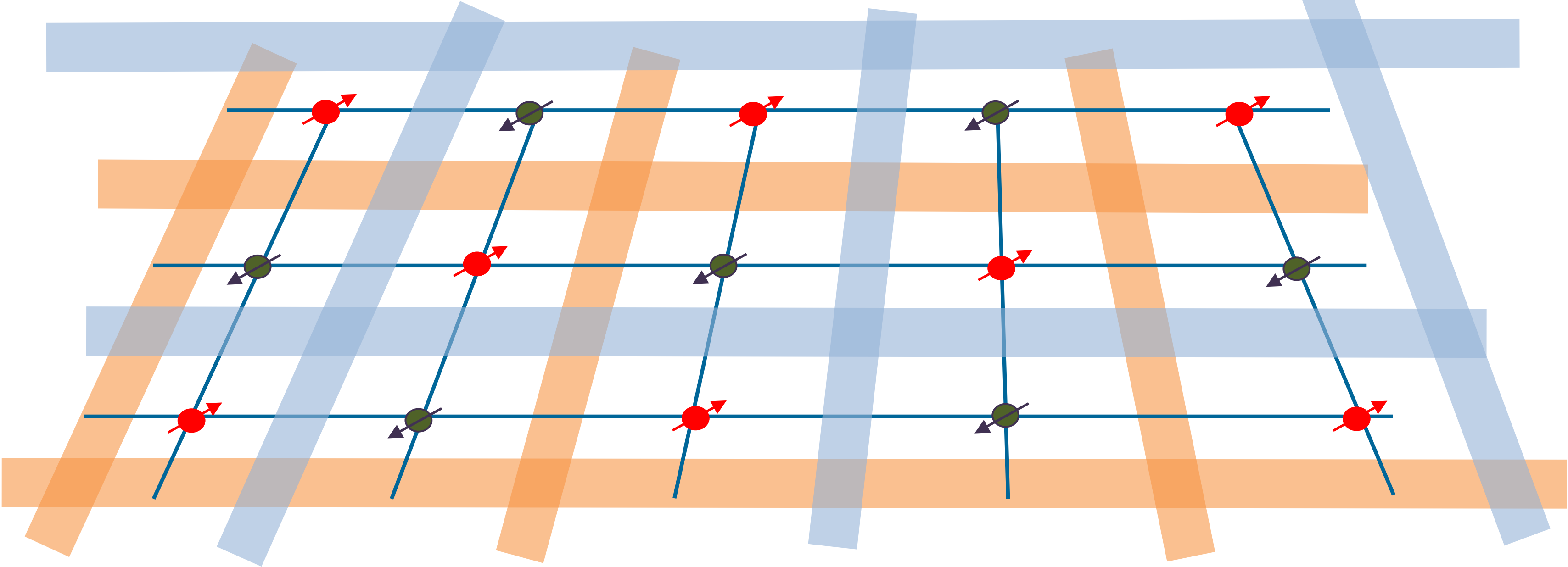


Numerical aperture: NA=0.8; Resolution: 690 nm

- Challenge theoreticians at an unprecedented level

Outlook- simulating topological materials

- Couple the plaquettes; strongly correlated topological system

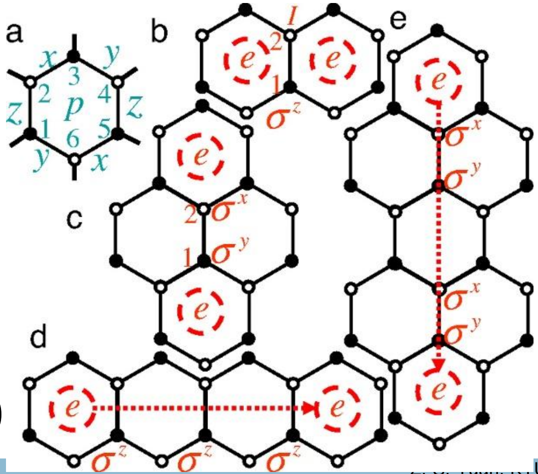


Reviews on topological matters with ultracold atoms:

Goldman, Budish&Zoller, Nat. Phys. (2016)

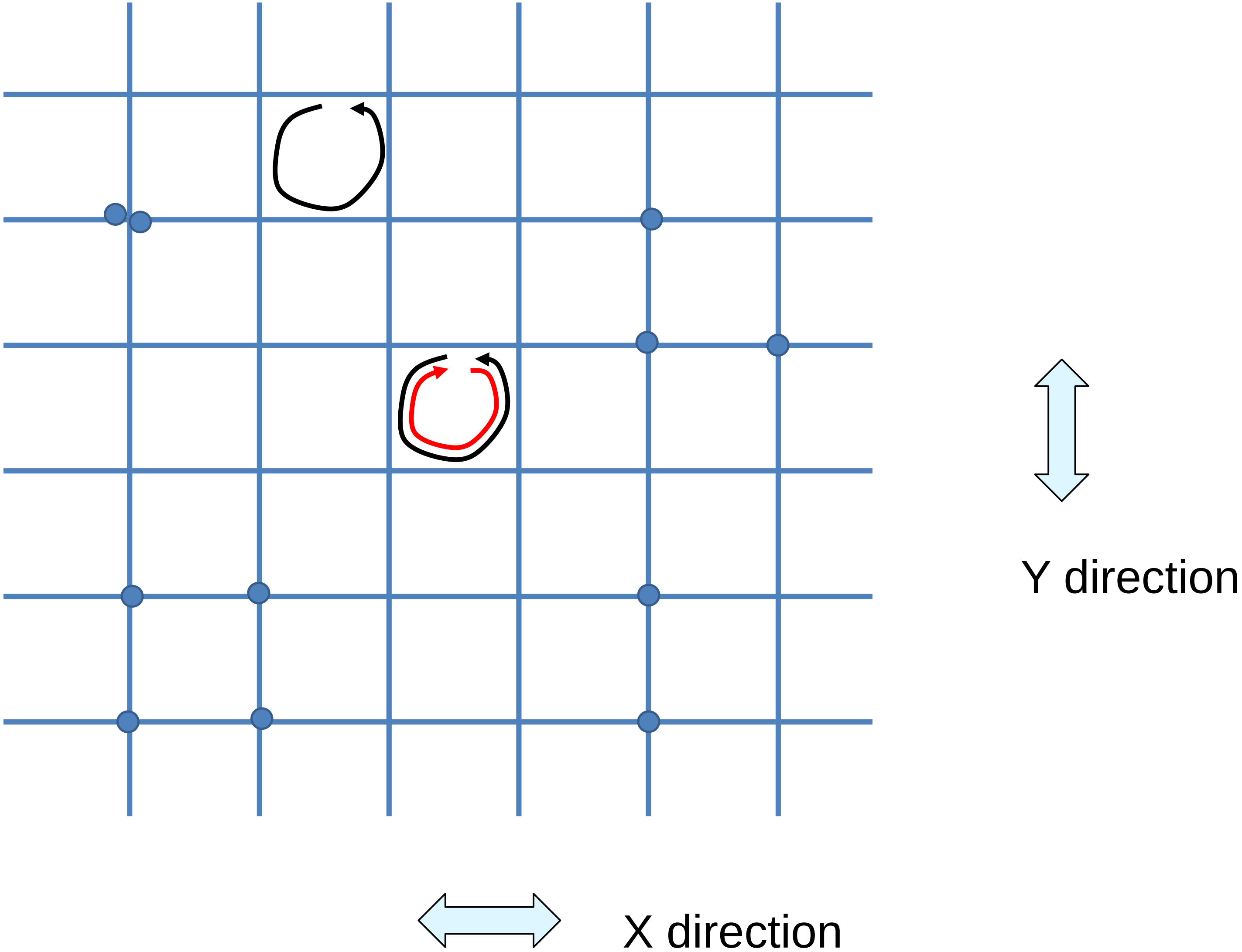
Zohar et al. Rep. Prog. Phys. (2016)

- Extend to fermionic systems; non-Abelian ...

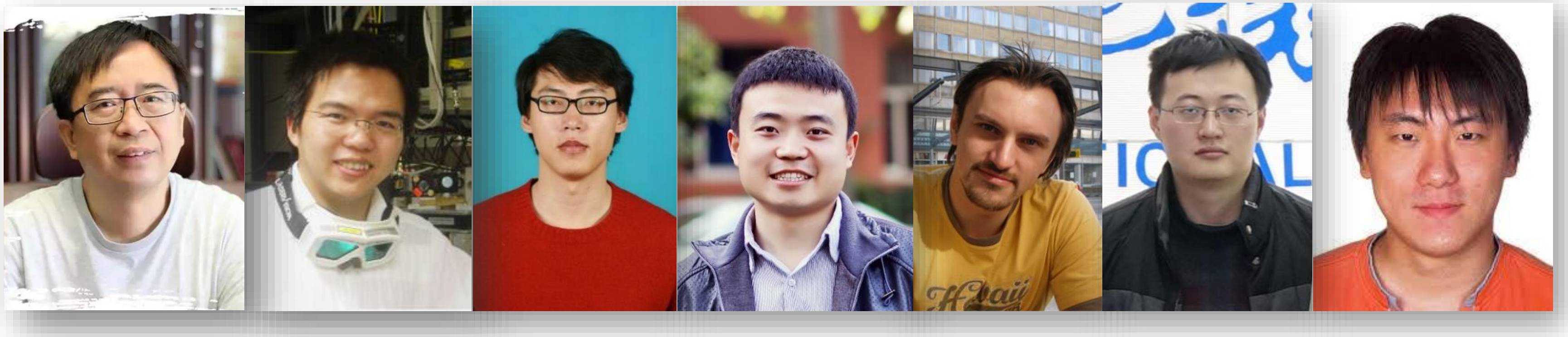


Theo: CW Zhang et al, PNAS (2007)

Shaking, spin dependent shaking



The team members



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