QUANTUM SIMULATION IN OPTICAL SUPERLATTICE

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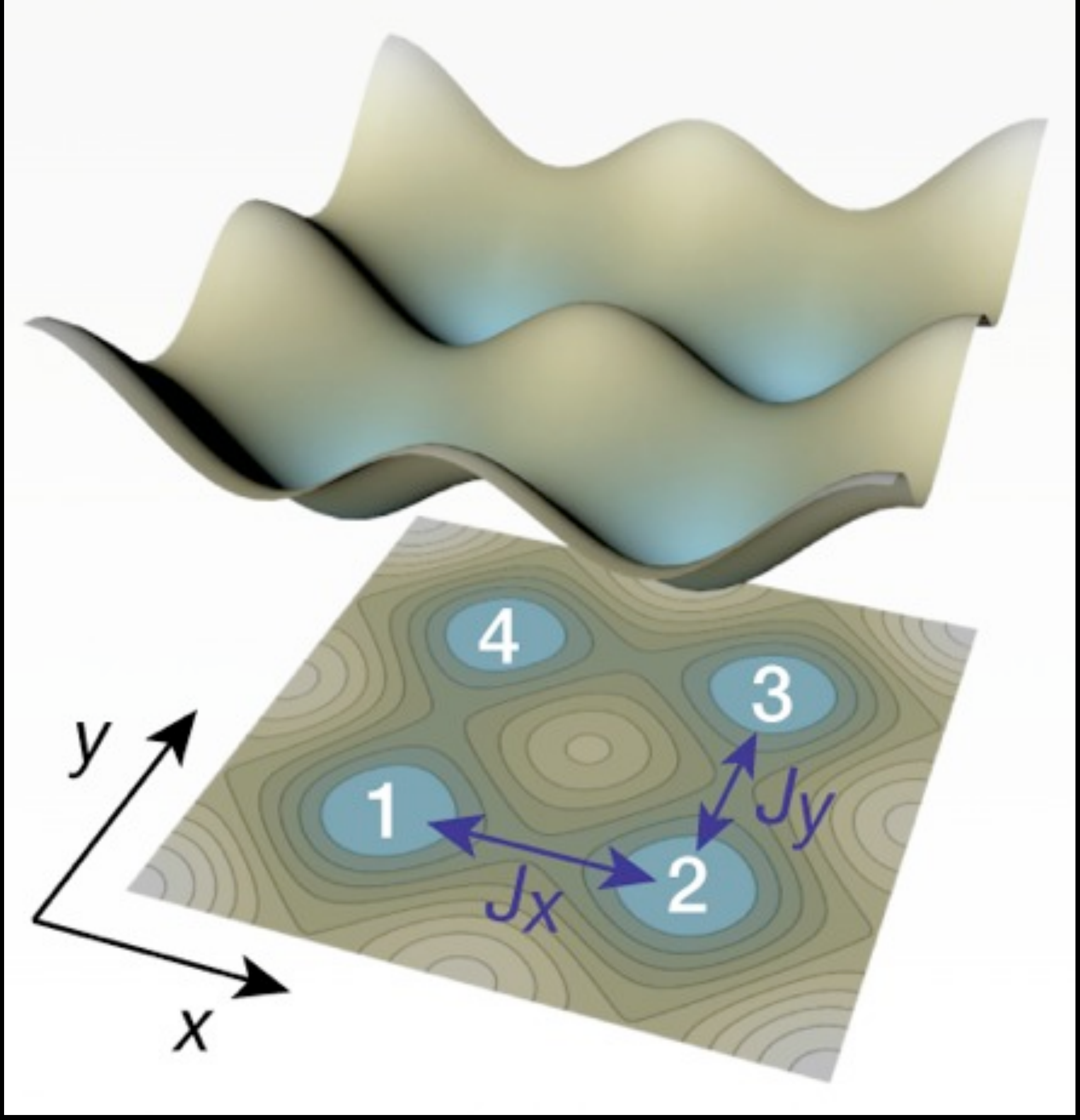

Quantum Physics & Quantum Information

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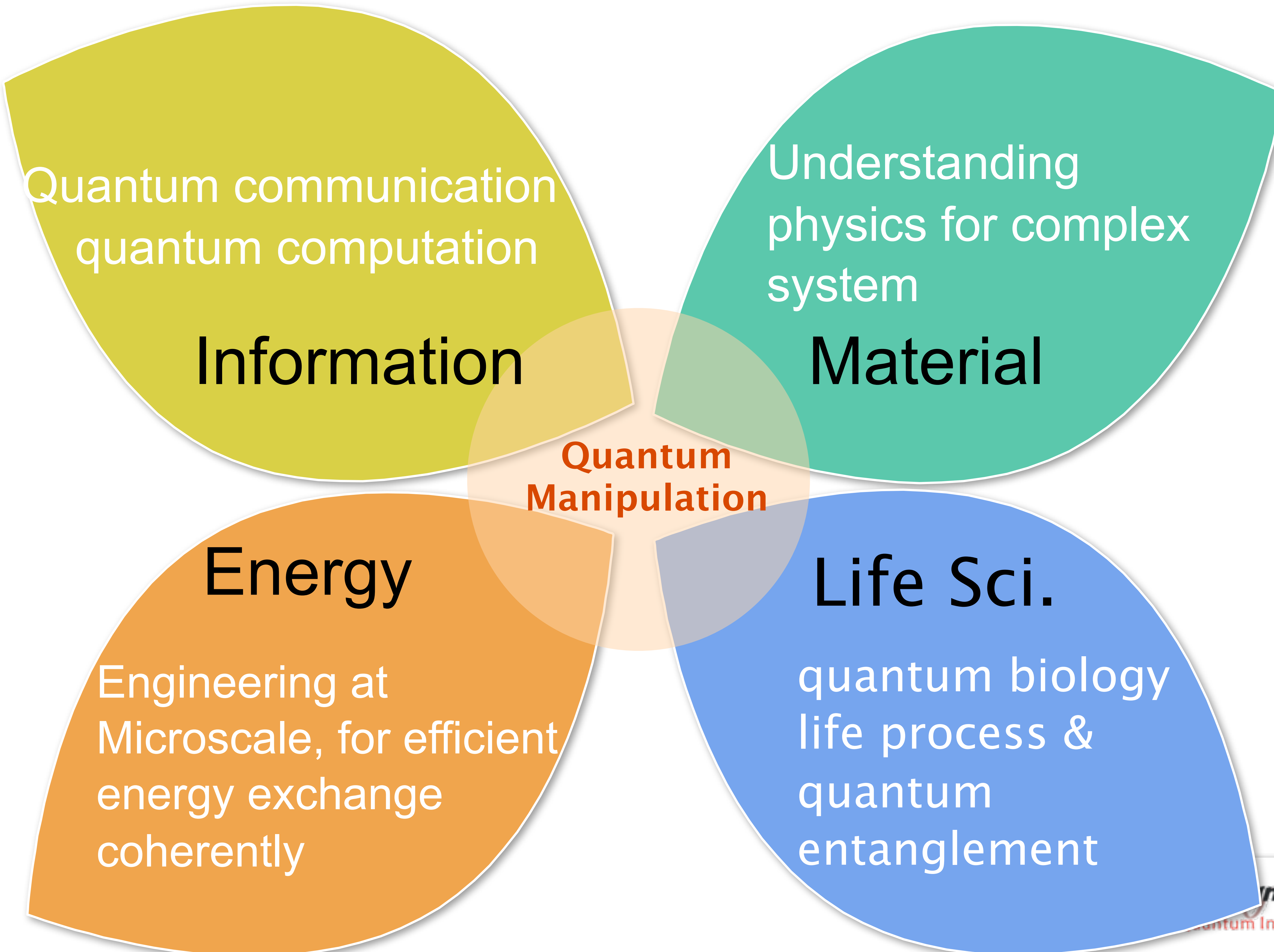
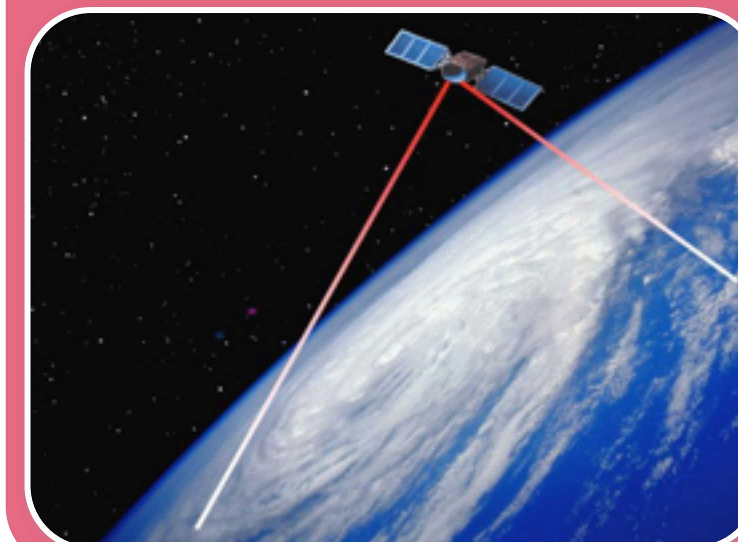
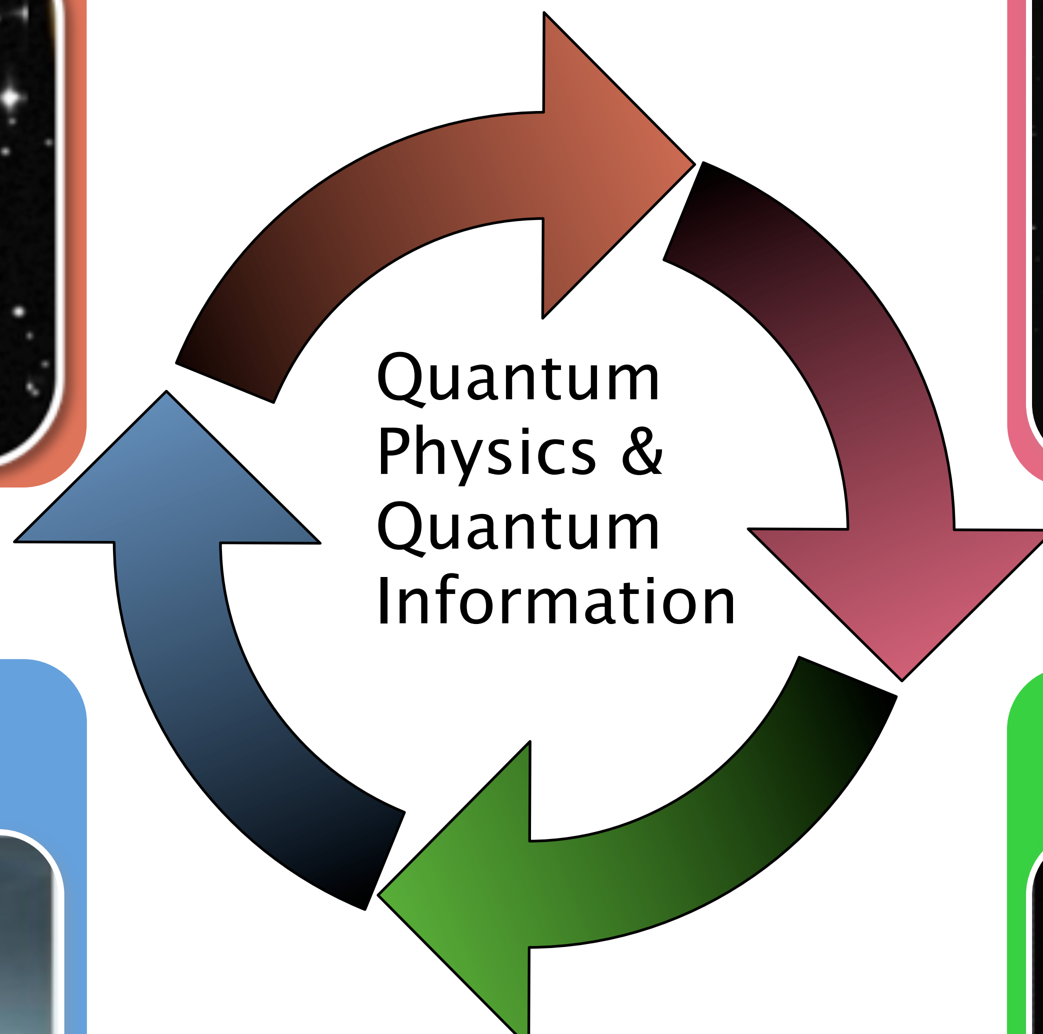


Division of Quantum Physics & Quantum Information

Fundermantal test of quantum machanics

Quantum Communication





Quantum Simulation

Quantum Computation

Quantum
Physics & Quantum Information

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(内蒙古)
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(吉)
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辽宁
(辽)
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肃
呼和浩特
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天津
(津)
石家庄
渤海
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(晋)
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银川
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(浙)
东海
南昌
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长沙
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(湘)
贵州
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(滇、云)
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(桂)
南宁
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澳门
(澳)
东沙群岛

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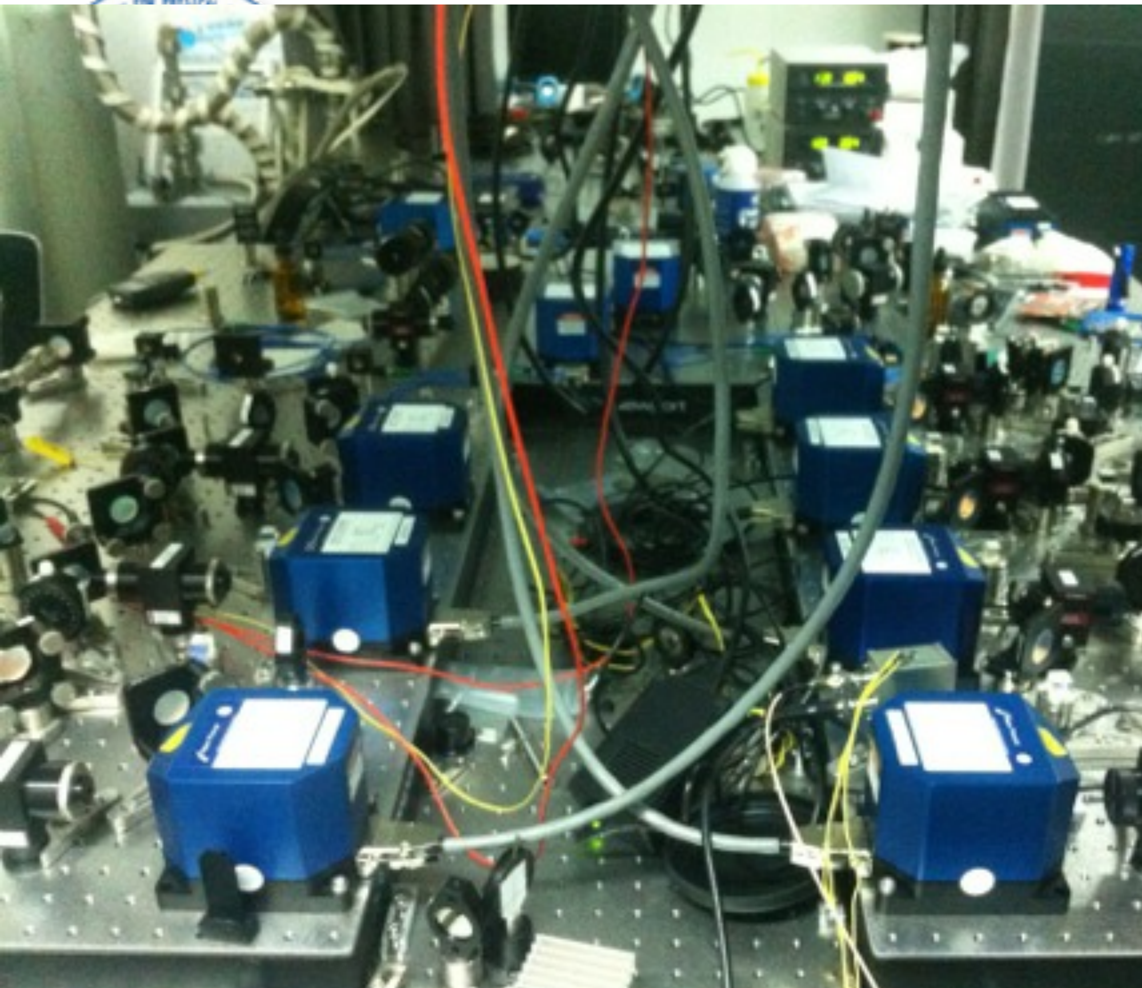
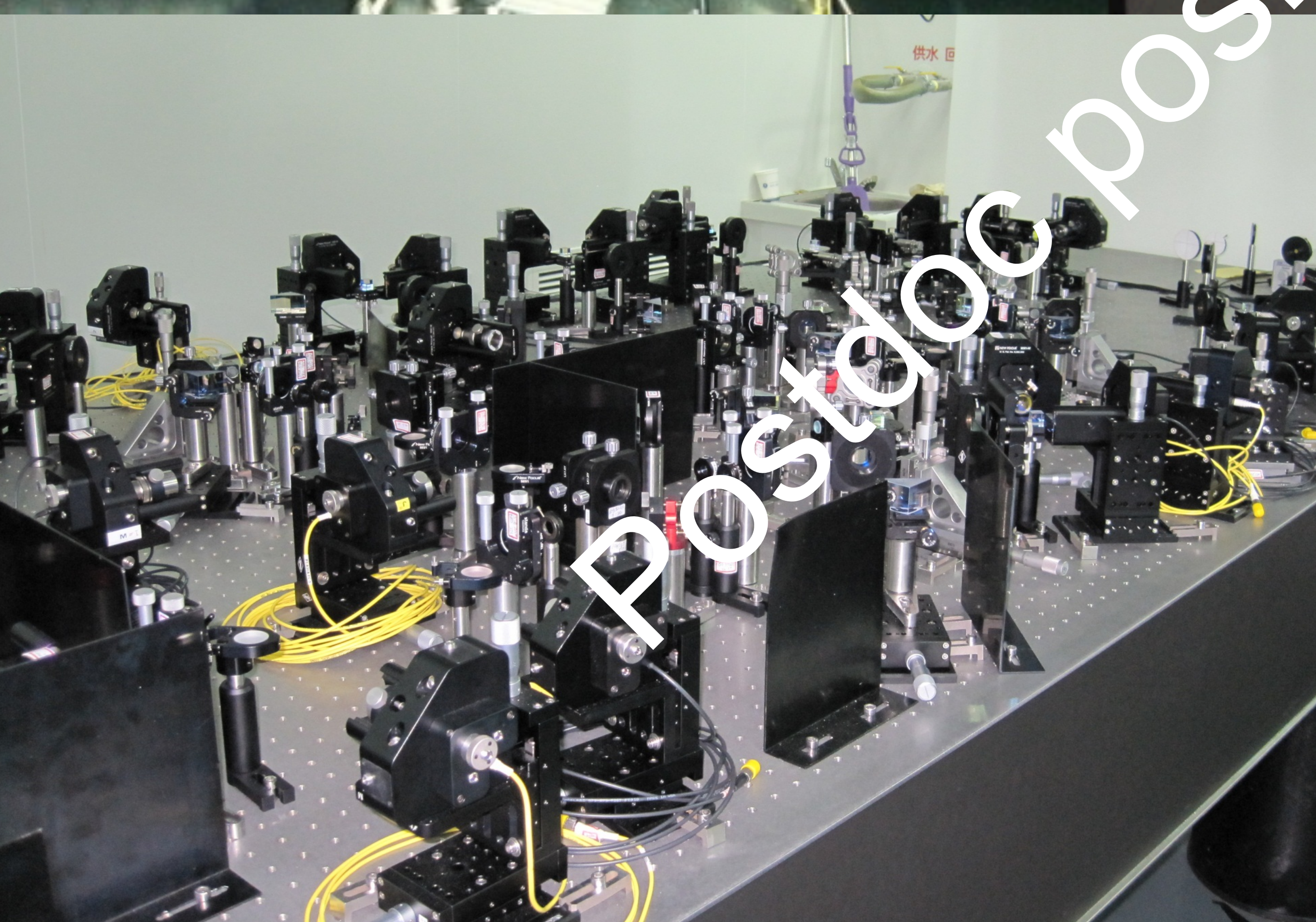
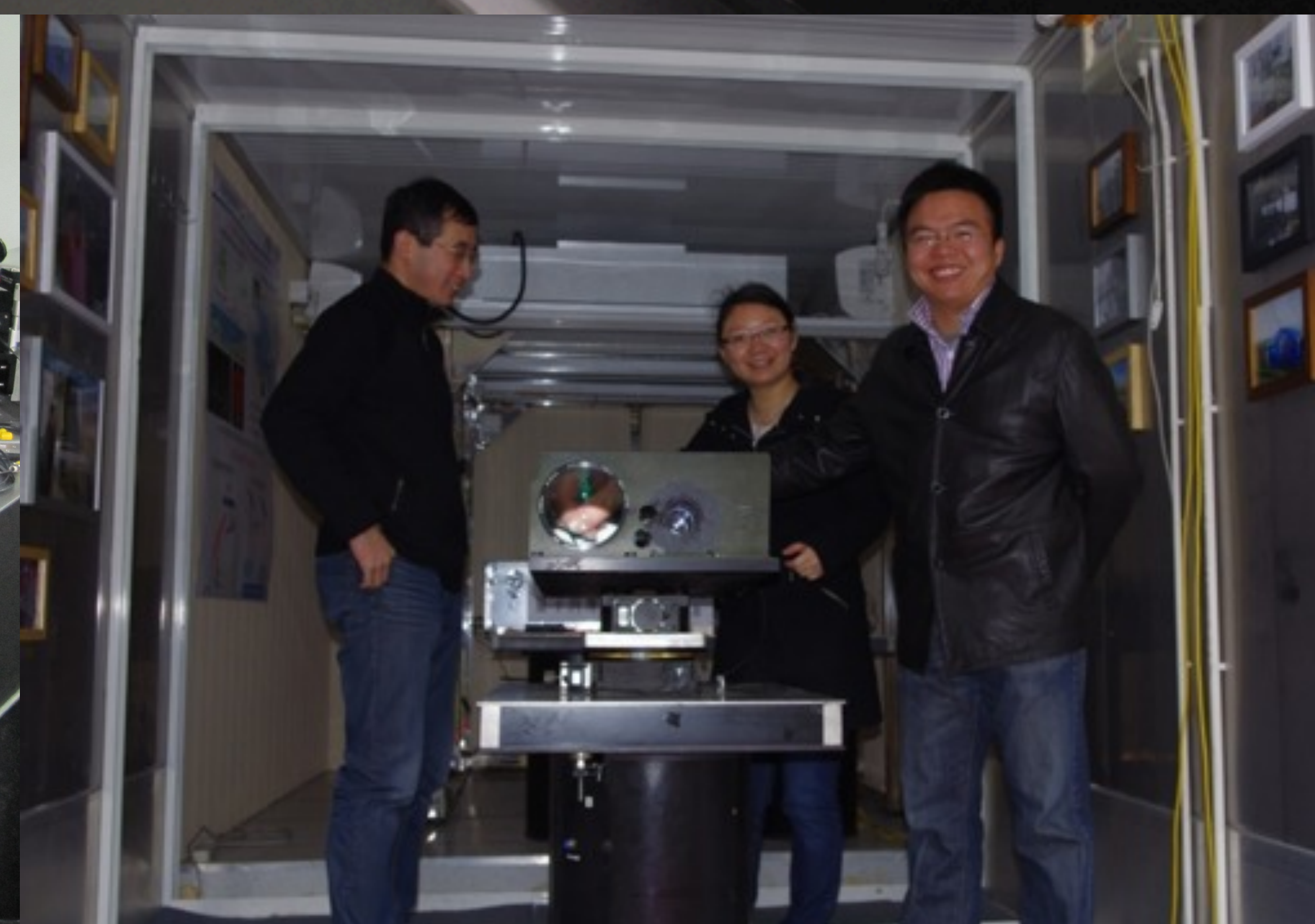
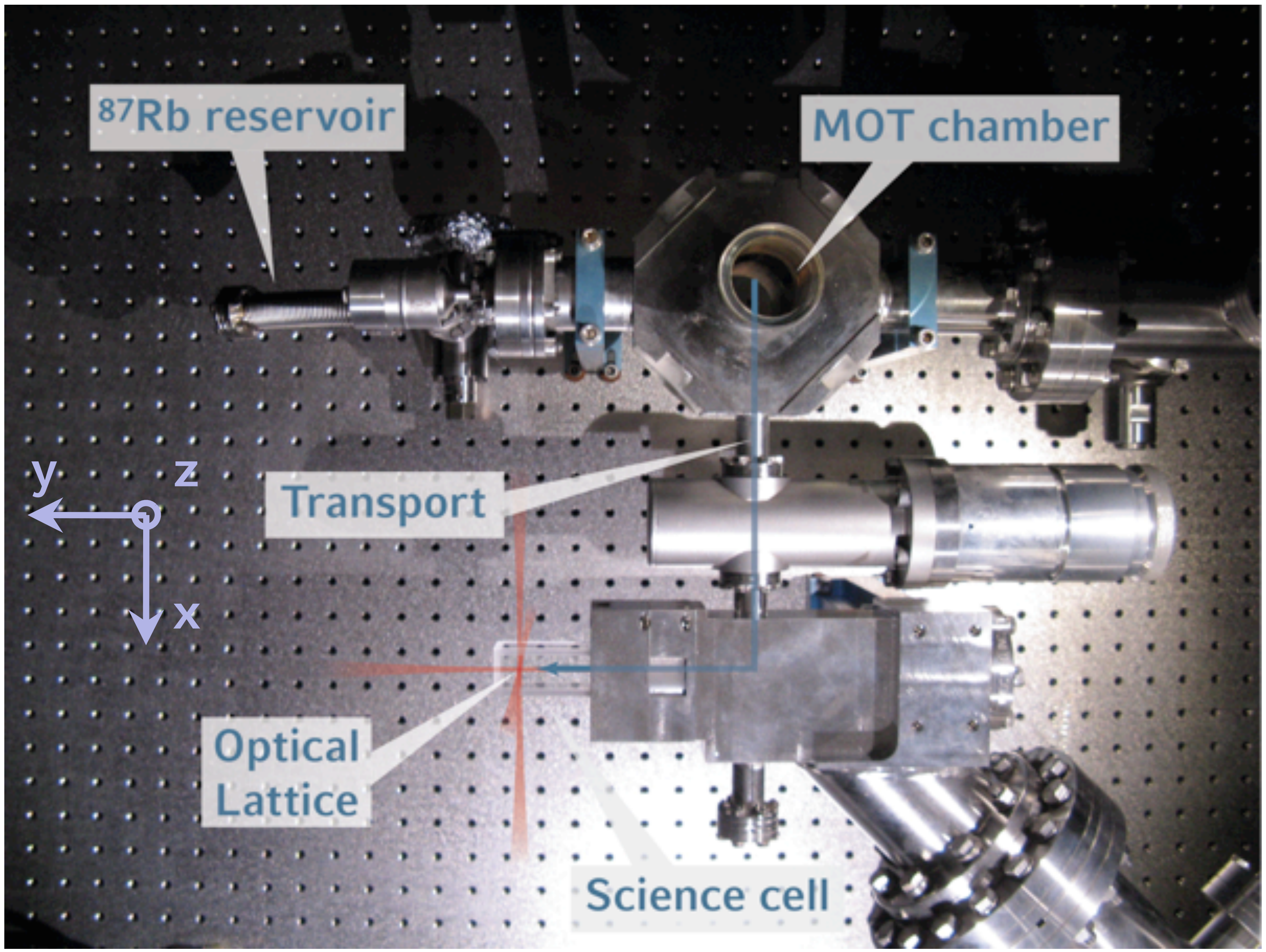






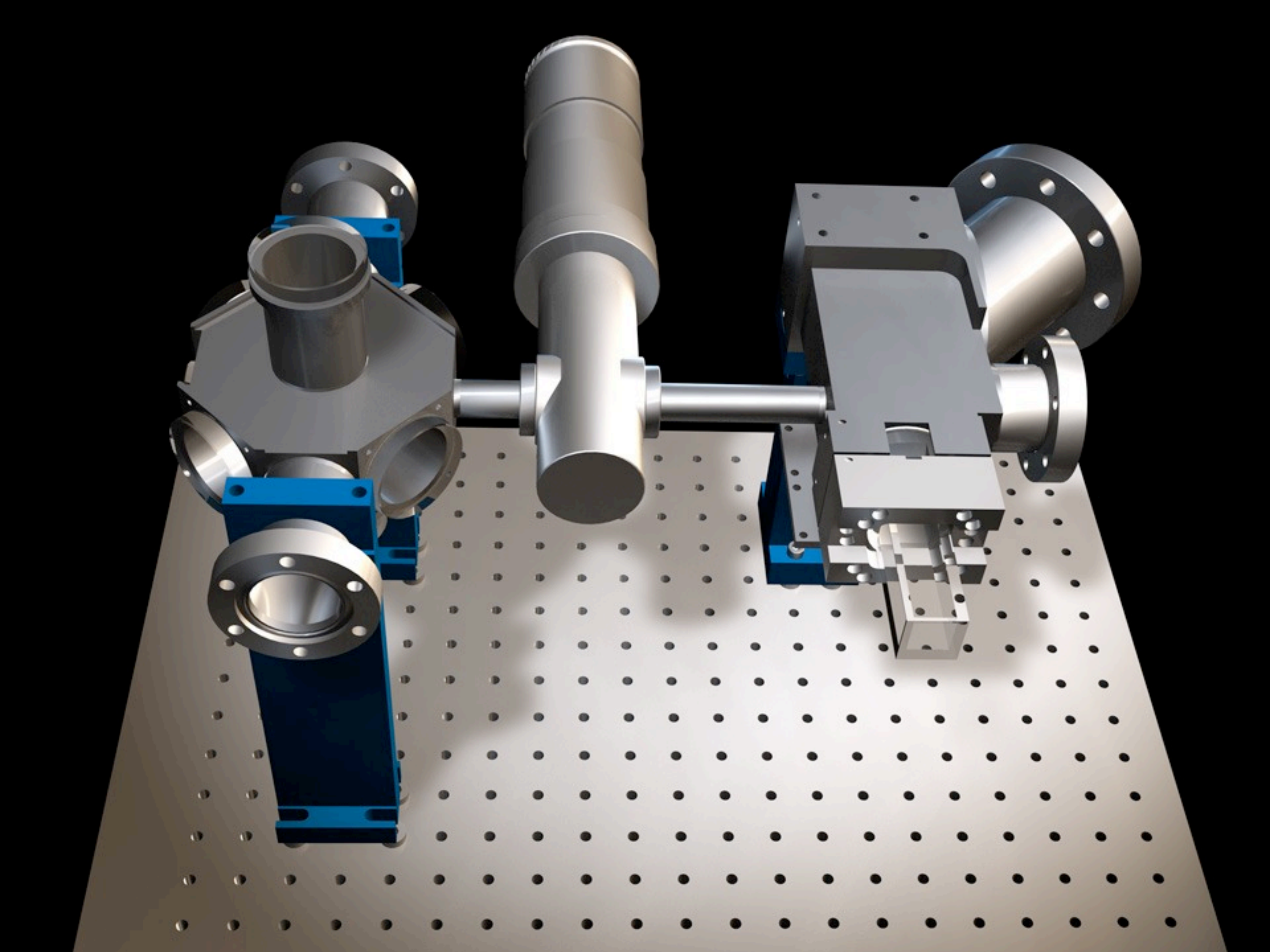
Postdoc positions available

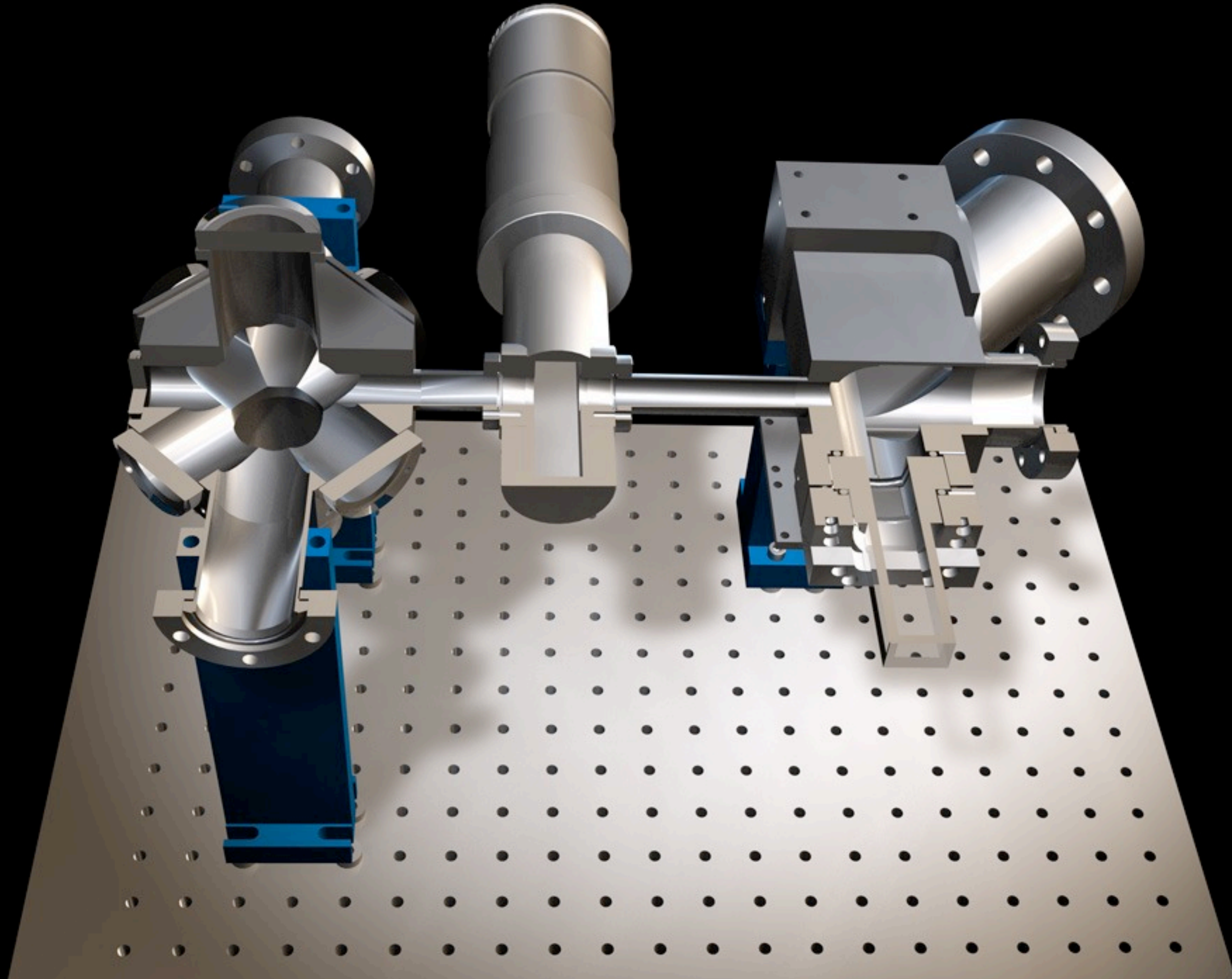
The Boson Experiment in Munich

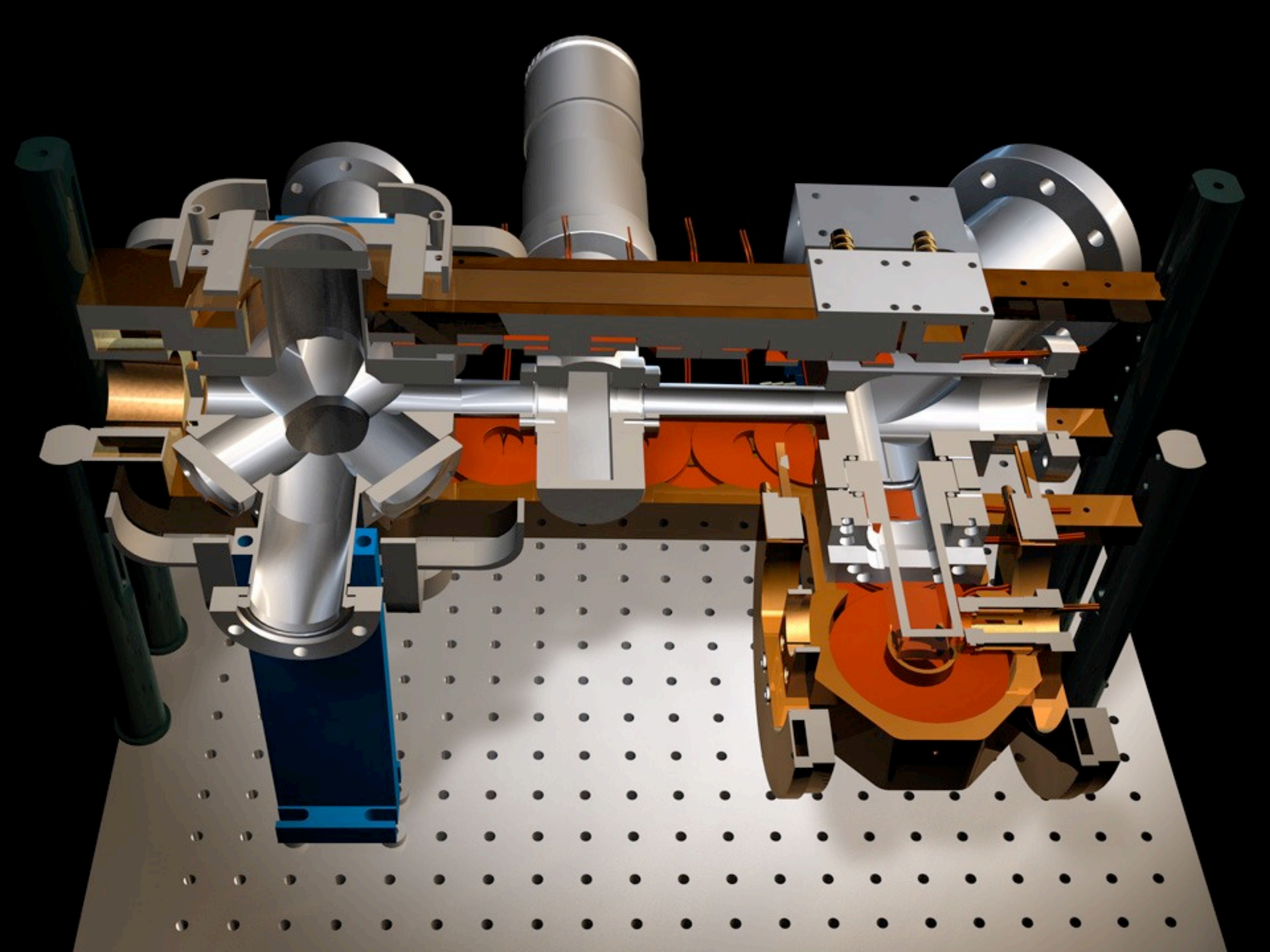


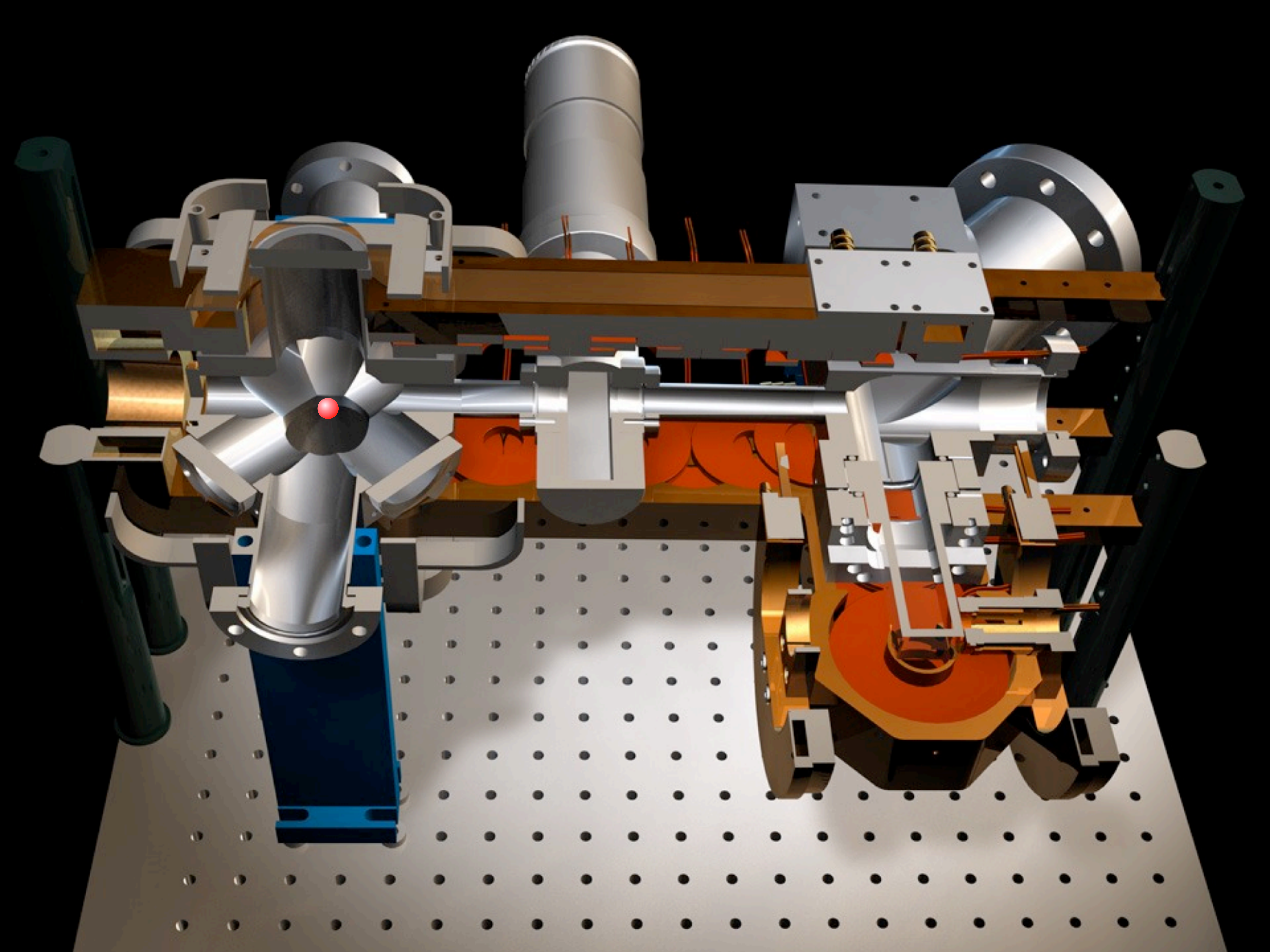
Bare chamber (no magnetic coils, no optics, etc.)

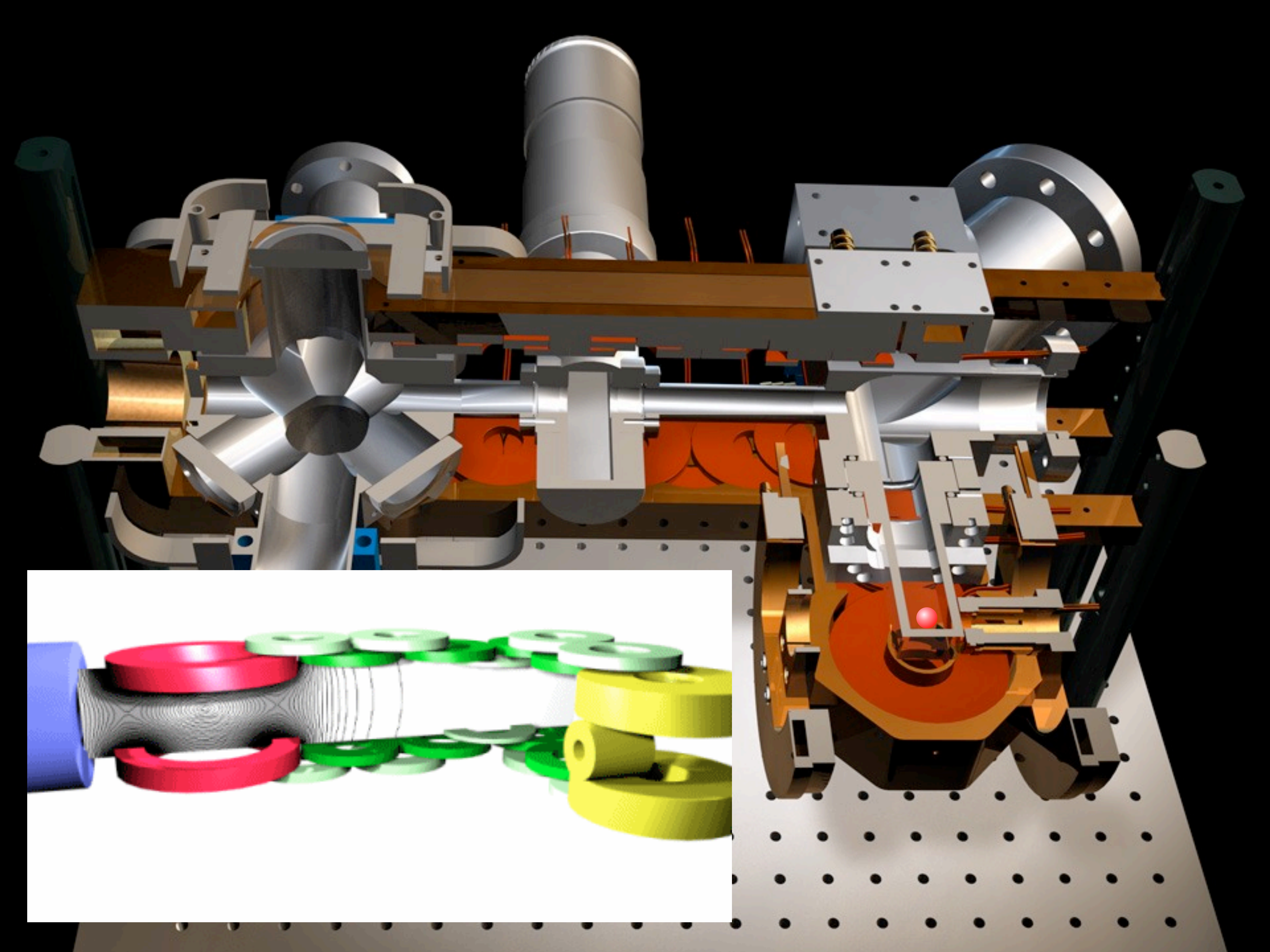
- ^{87}Rb (bosons)
- $N_{BEC} \sim 10^5$
- $T \sim 10$nK
- 3D optical lattice
  $\lambda_z = 843$nm
  $\lambda_{xs,ys} = 767$nm
- **1D Superlattice**
  $+\lambda_{xl} = 1534$nm
- **Another Superlattice**
  $+\lambda_{yl} = 1534$nm

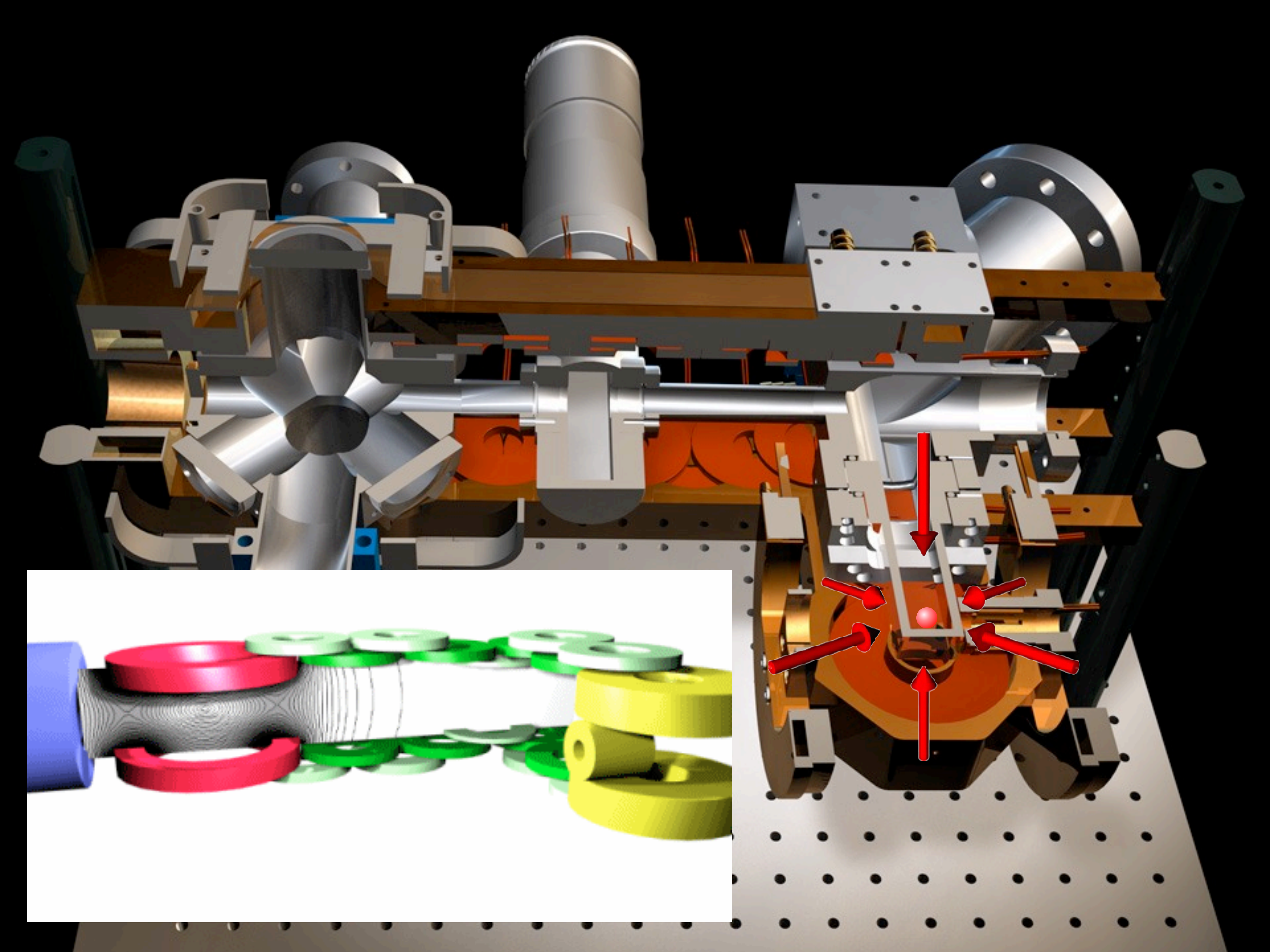


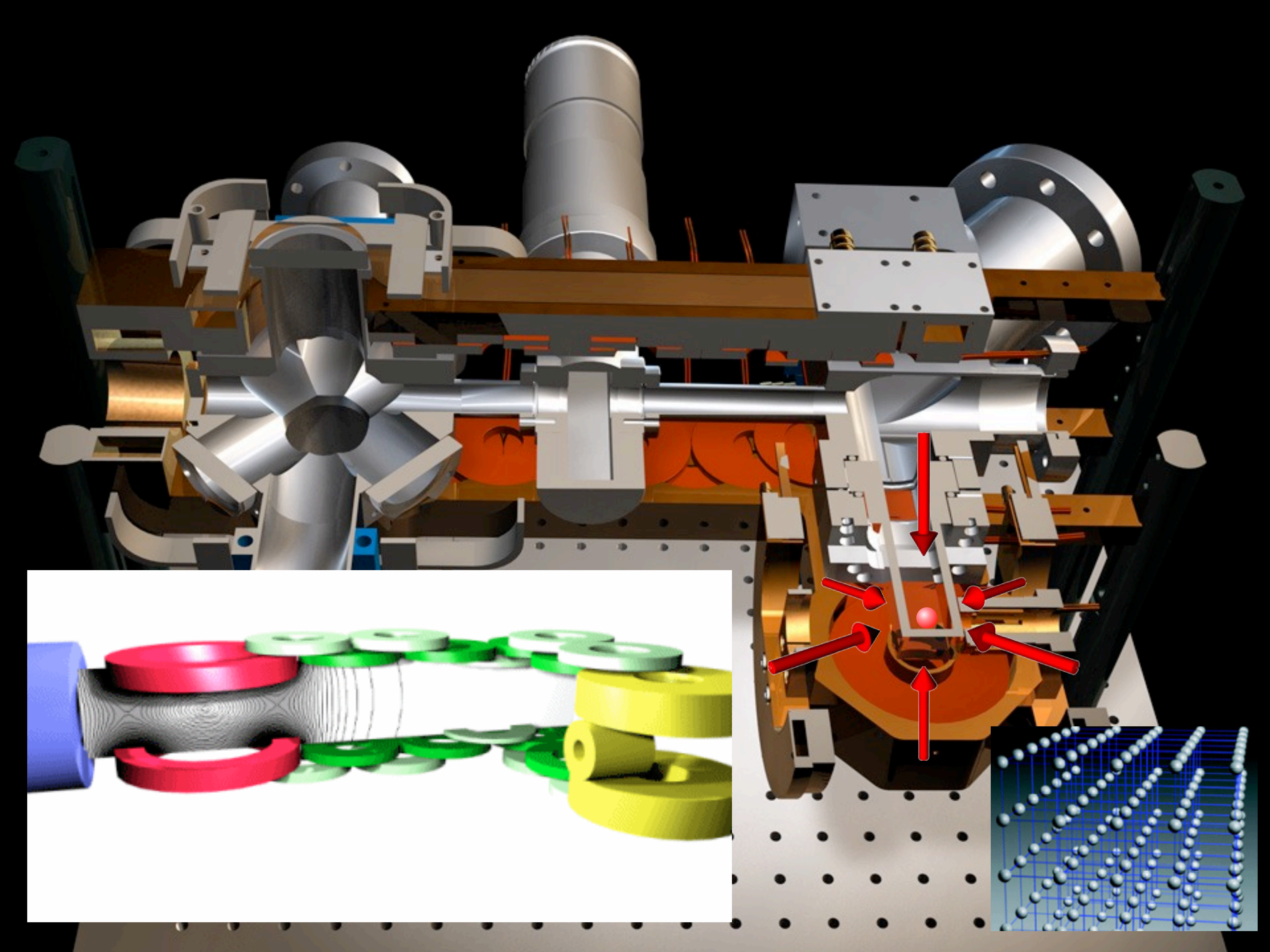












And a lot of optics and electronics !

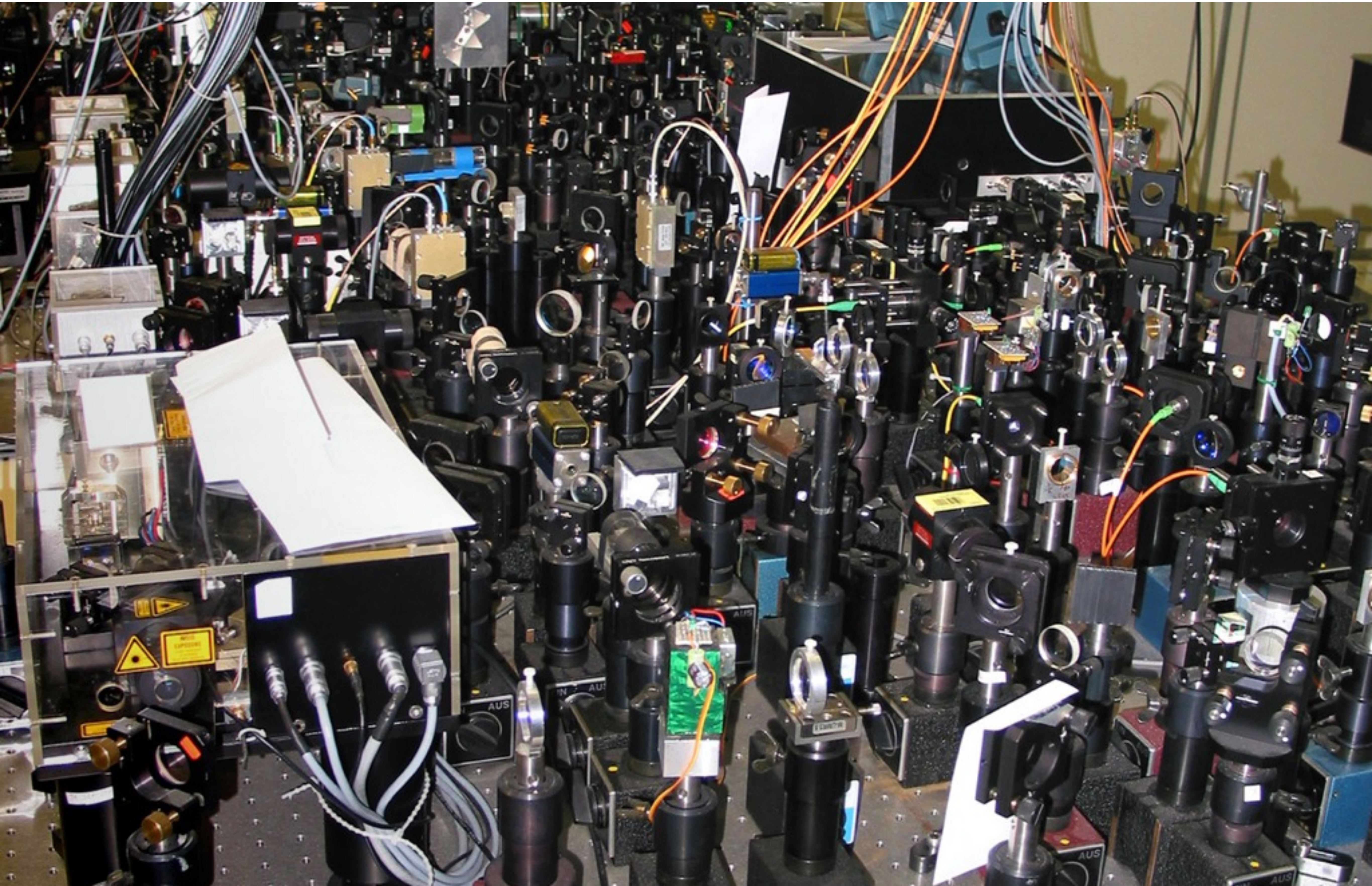
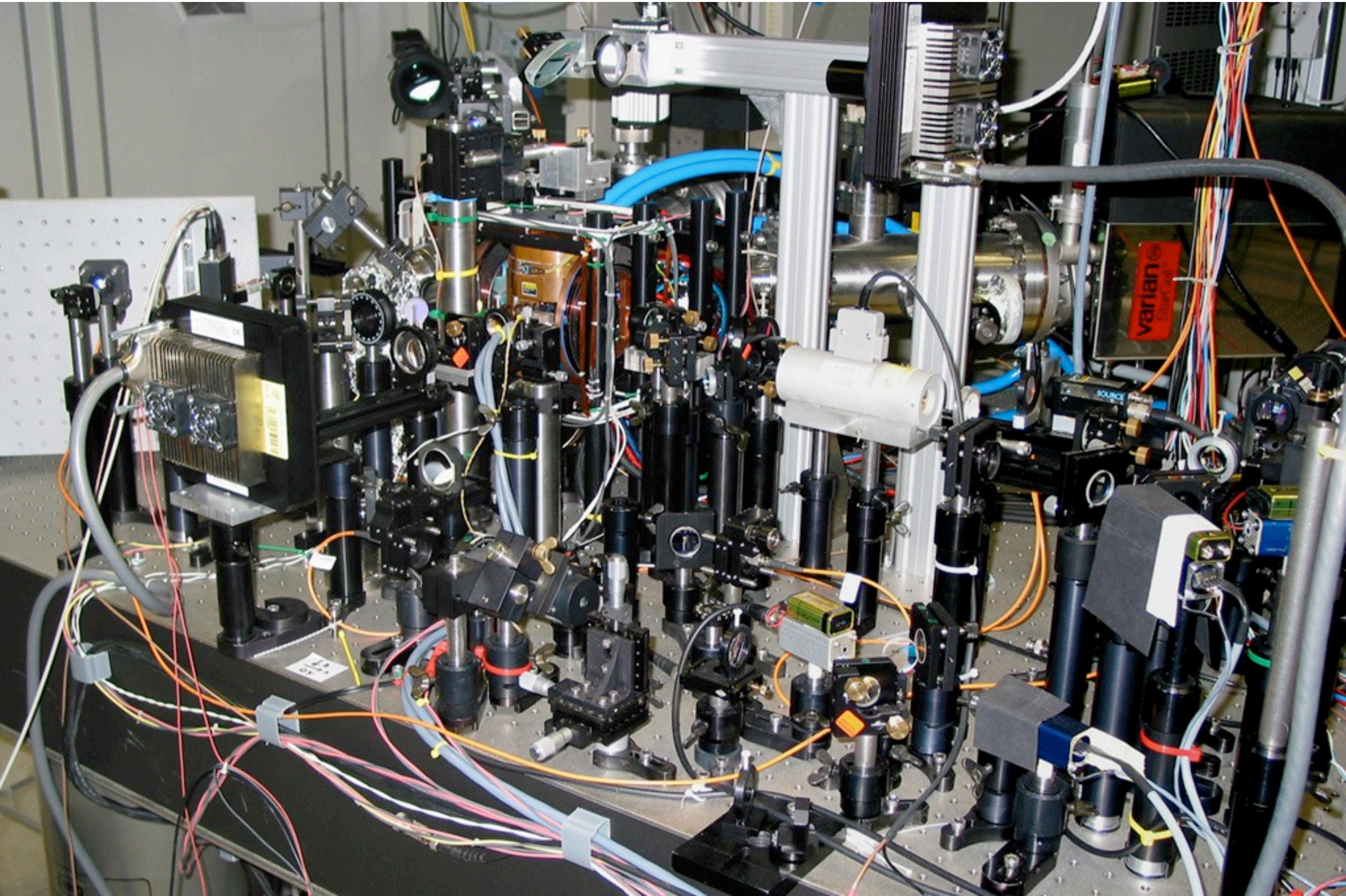
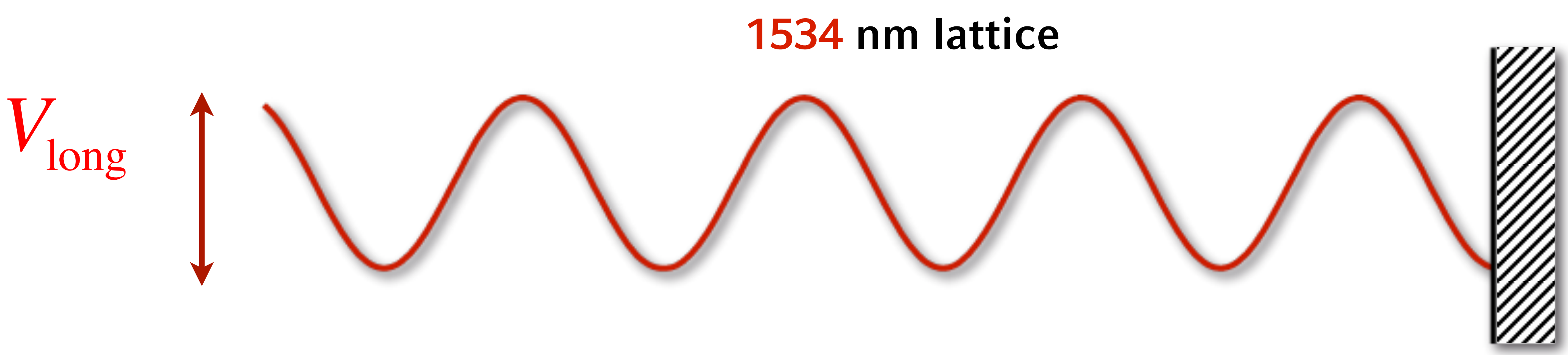


Table 2

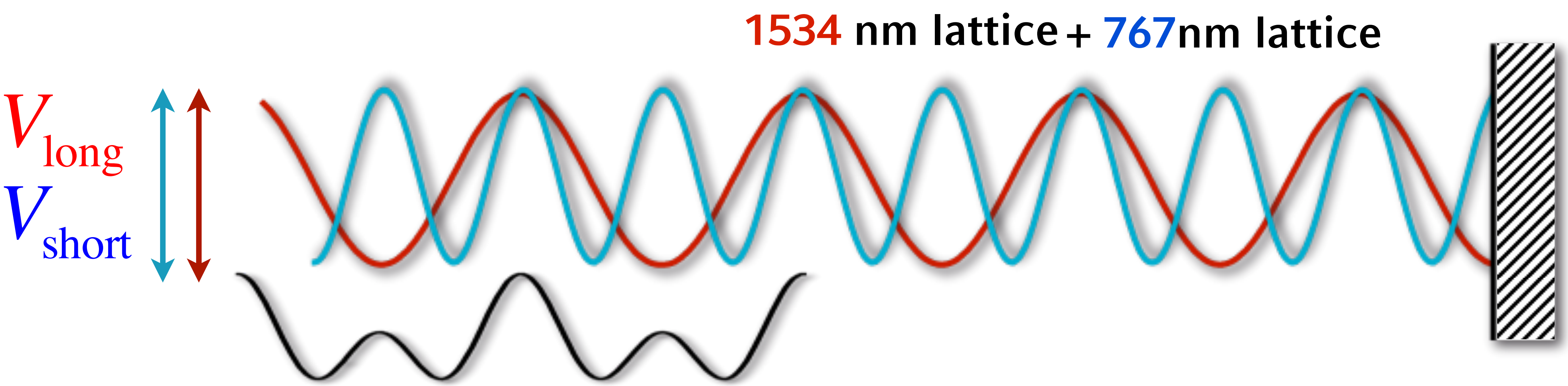


The Bichromatic Superlattice

The Bichromatic Superlattice

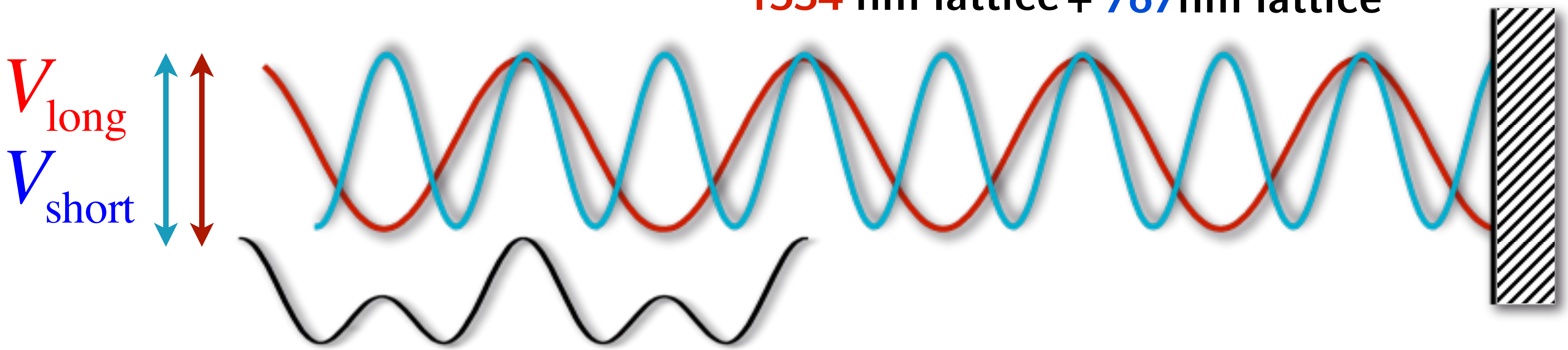


The Bichromatic Superlattice

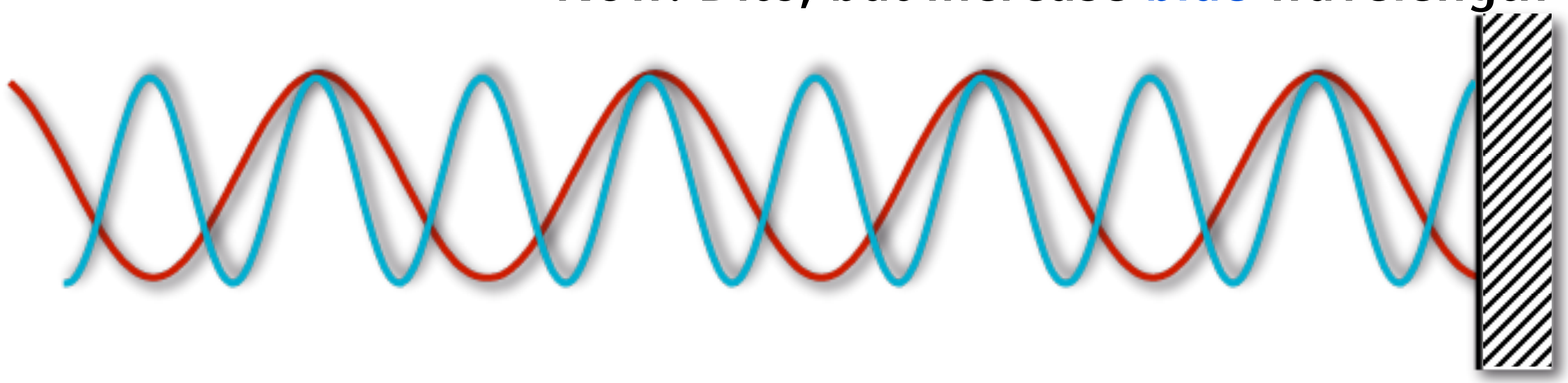


The Bichromatic Superlattice

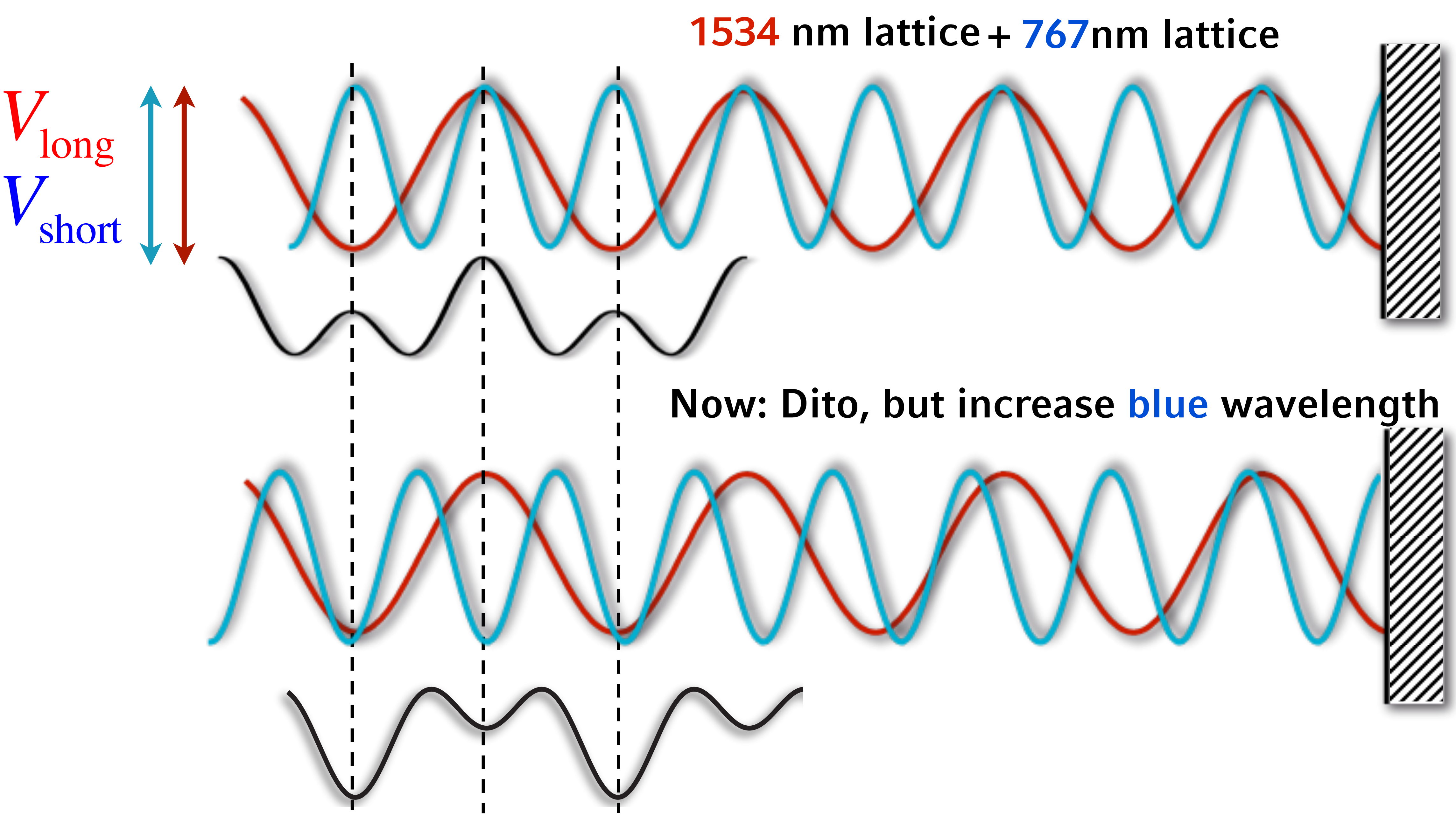
1534 nm lattice + 767nm lattice



Now: Dito, but increase blue wavelength

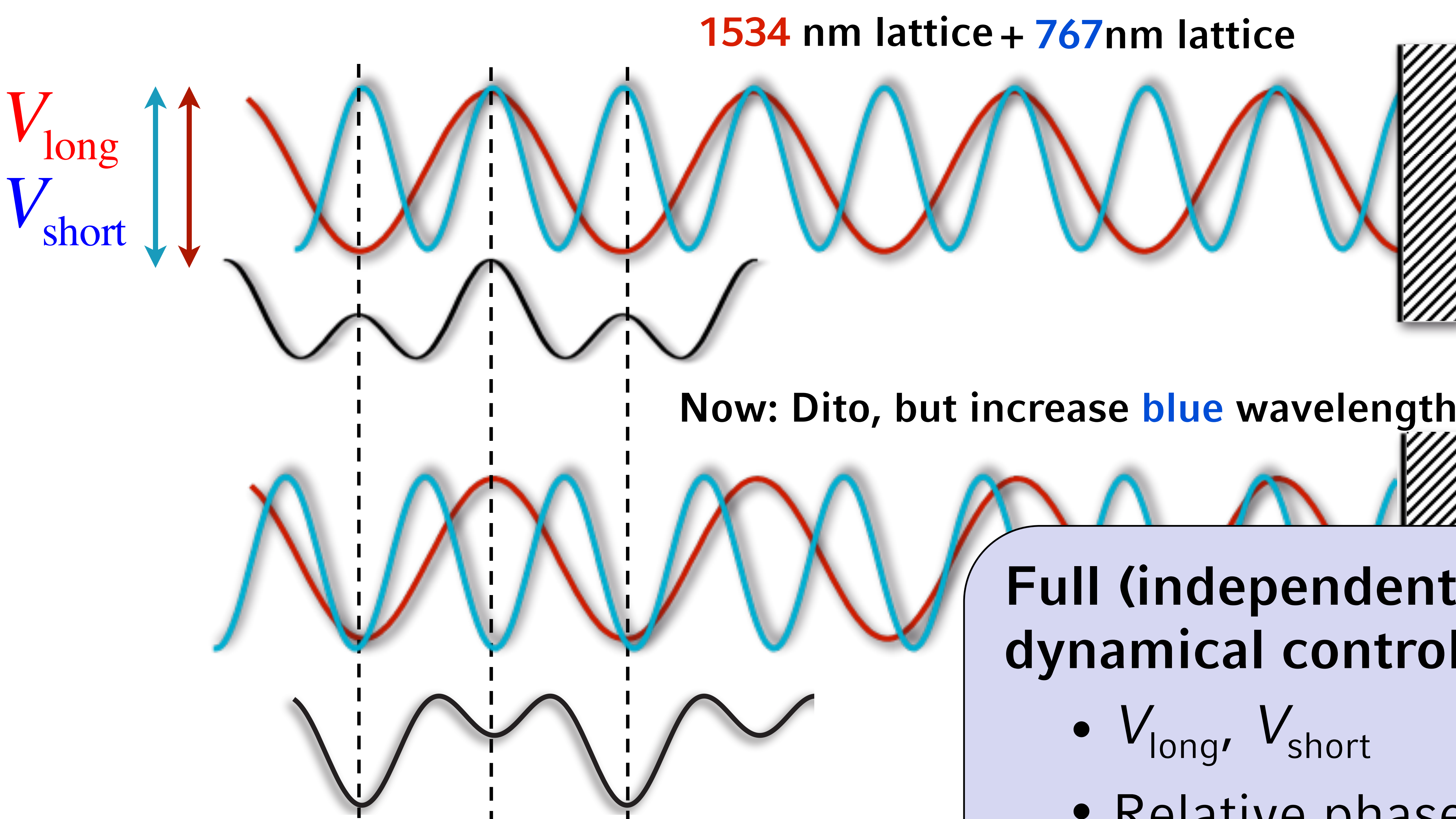


The Bichromatic Superlattice



$$V(x) = V_l \cos(2k_l x) + V_s \cos(4k_l x + \varphi)$$

The Bichromatic Superlattice

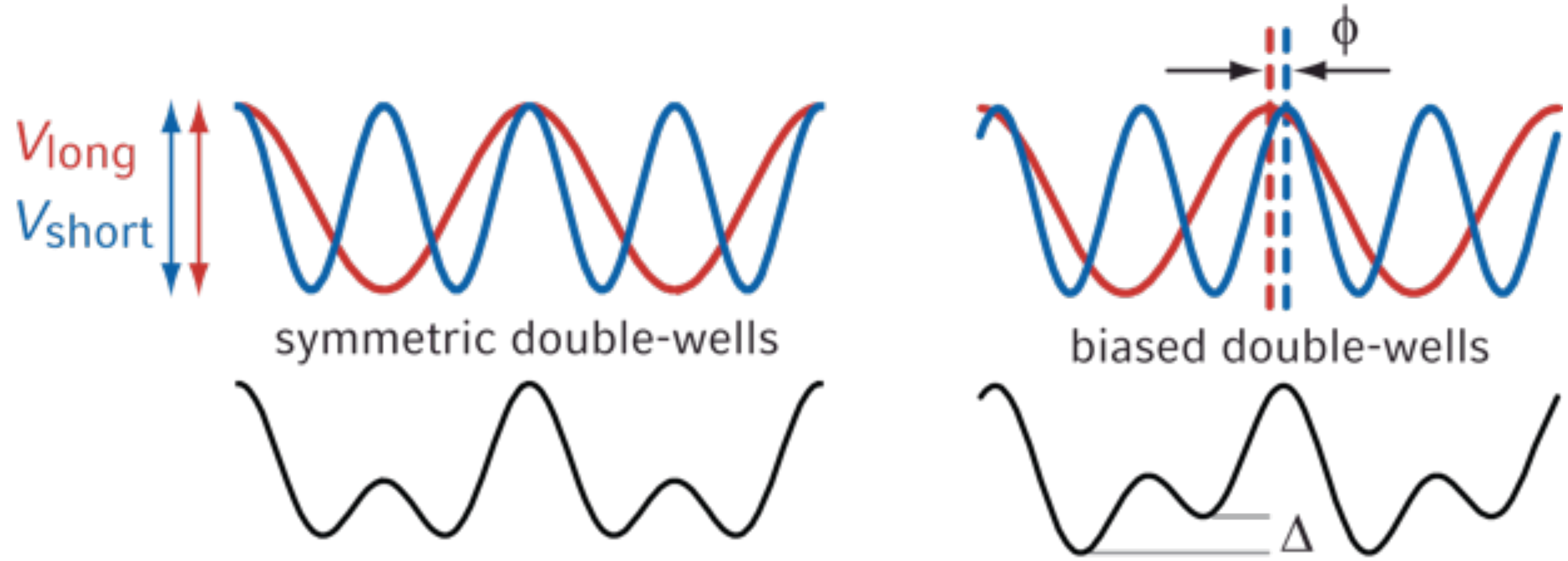


$$V(x) = V_l \cos(2k_l x) + V_s \cos(4k_l x + \varphi)$$

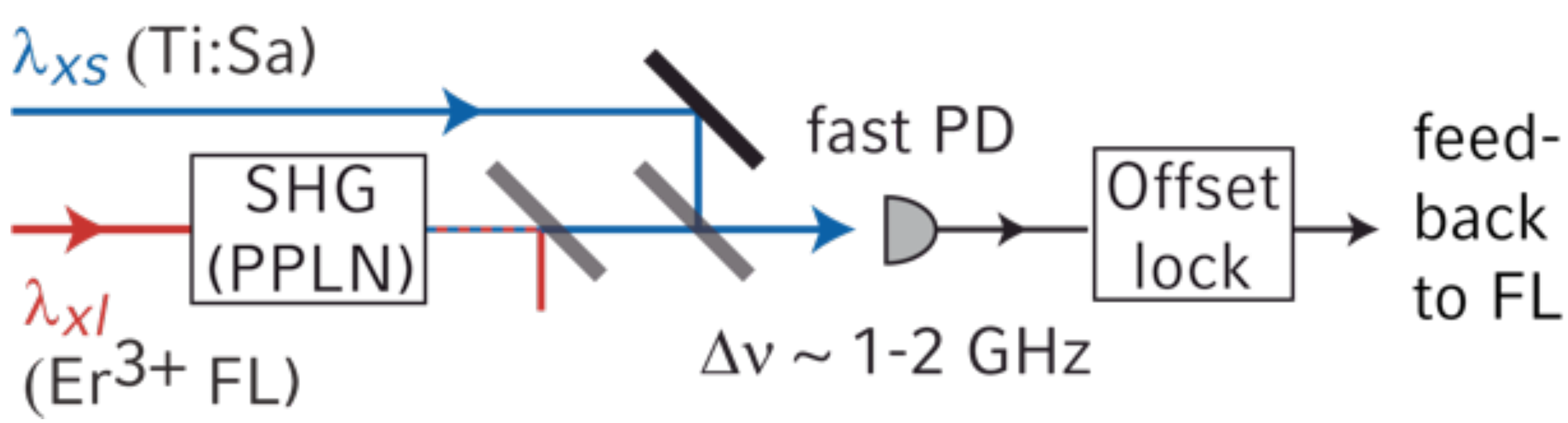
Full (independent) dynamical control over:

- V_{long}, V_{short}
- Relative phase φ
- Transverse lattices

The Bichromatic Superlattice



- Adjusting φ by fine-tuning λ_l
- Offset-locking frequency-doubled fiber-laser to Ti:Sa-laser

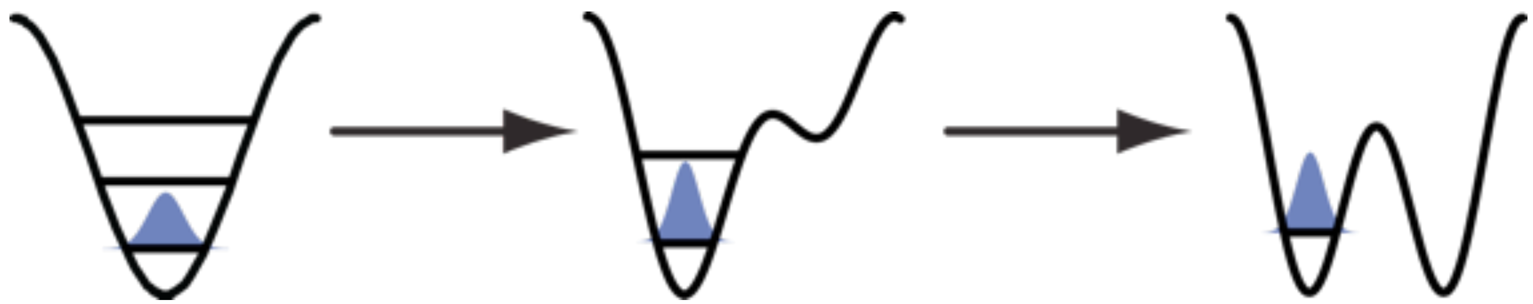


- Offset-frequency Δν = 1 - 2GHz

  → Tuning range φ = 0…2π

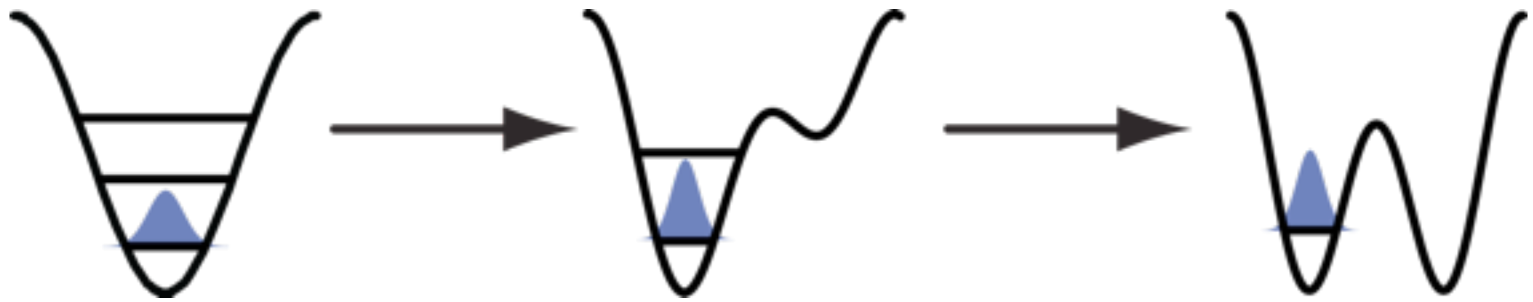
The Bichromatic Superlattice

- Novel *state preparation* techniques, e.g. **patterned loading**

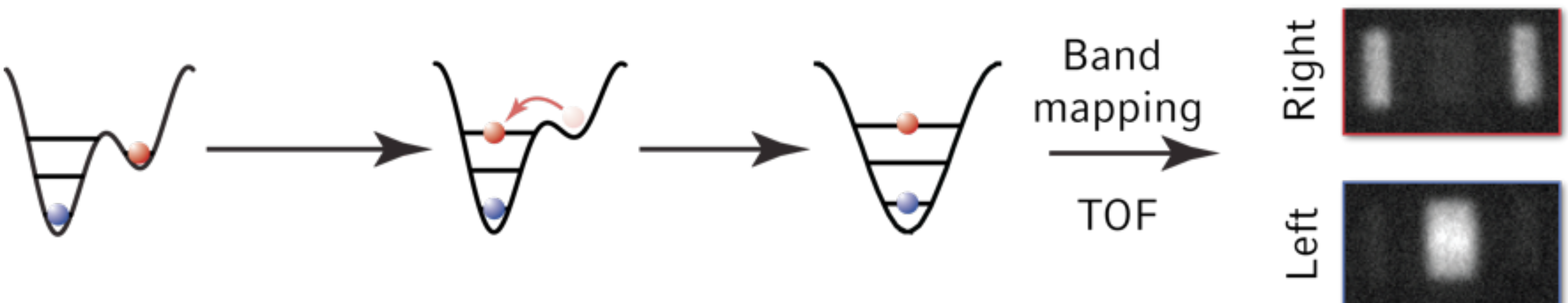


The Bichromatic Superlattice

- Novel *state preparation* techniques, e.g. **patterned loading**



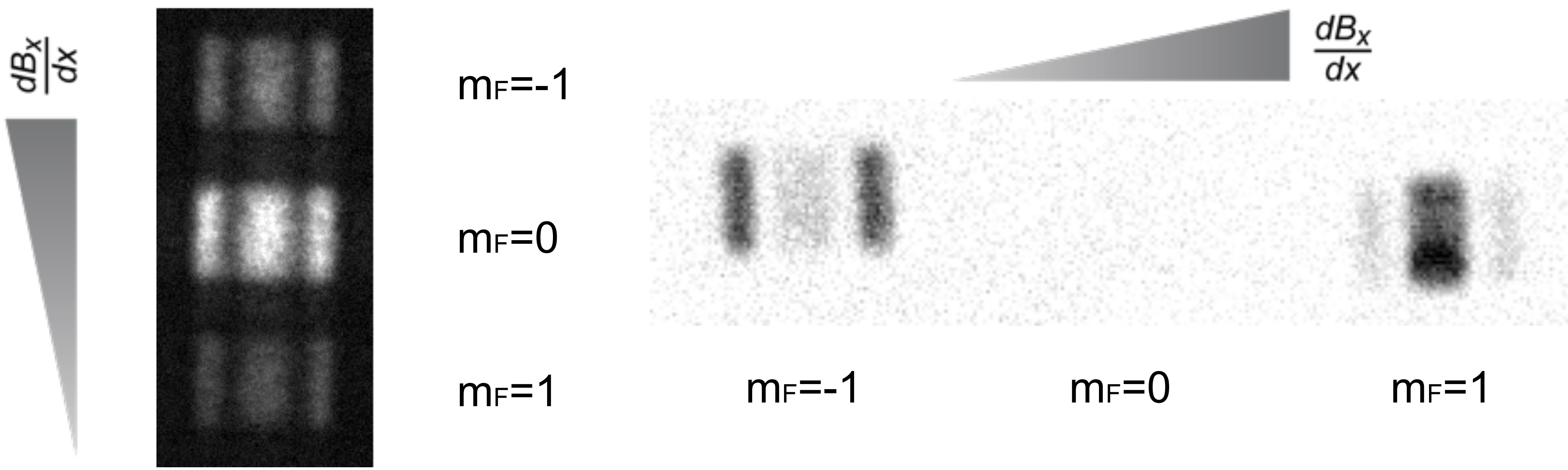
- Novel *read-out* methods, e.g. **sub-lattice resolved detection**



(Alternative: Raman-spectroscopy)

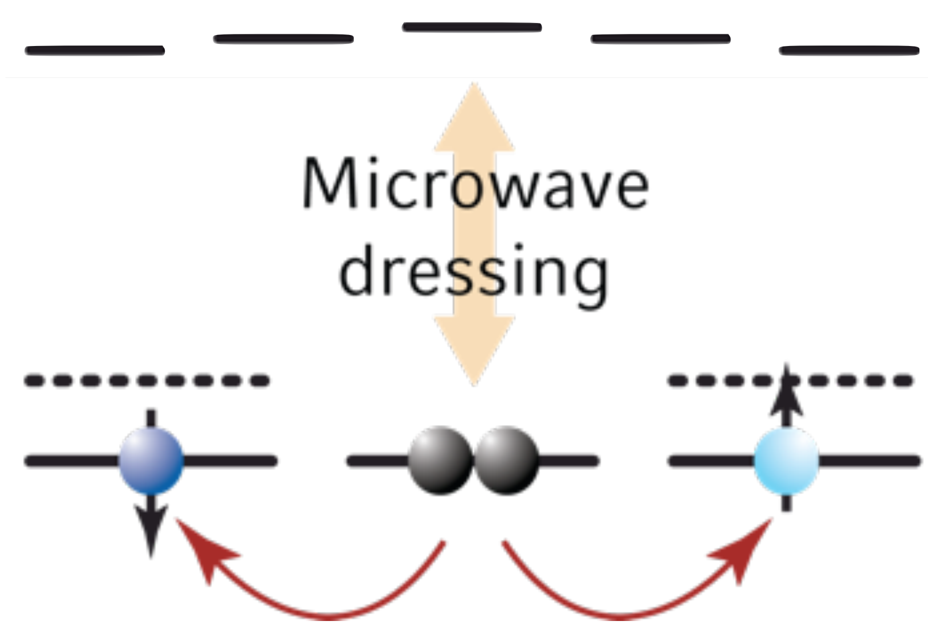
The Bichromatic Superlattice

- Novel *state read out* techniques, e.g. **Stern-Gerlach**



Preparing Spin Singlets

- Atom pairs in long-lattice wells $|F = -1, m_F = 0\rangle$
- Initialize in $|F = 1, m_F = 0\rangle$
- Microwave-dressed spin-changing collisions
  → **Spin-pairs** in $|F = 1, m_F = \pm 1\rangle$



Collisionally driven
Rabi-oscillations

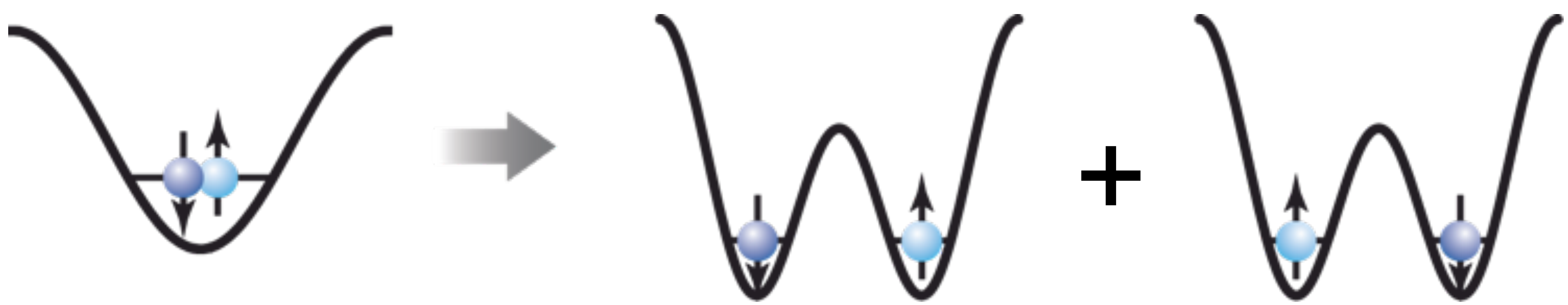
A. Widera et al., PRL **95** (2005), F. Gerbier et al., PRA **73** (2006)

Preparing Entangled Spin Singlets

- **Spin pairs** in $|F=1, m_F=\pm1\rangle \equiv |\uparrow\rangle, |\downarrow\rangle$
- Barrier raised *slowly* to split

  → Crossing a miniature Mott-transition: $n_{\mathrm{Left}} = n_{\mathrm{Right}}$

J. Sebby-Strabley et al., PRL **98** (2007)



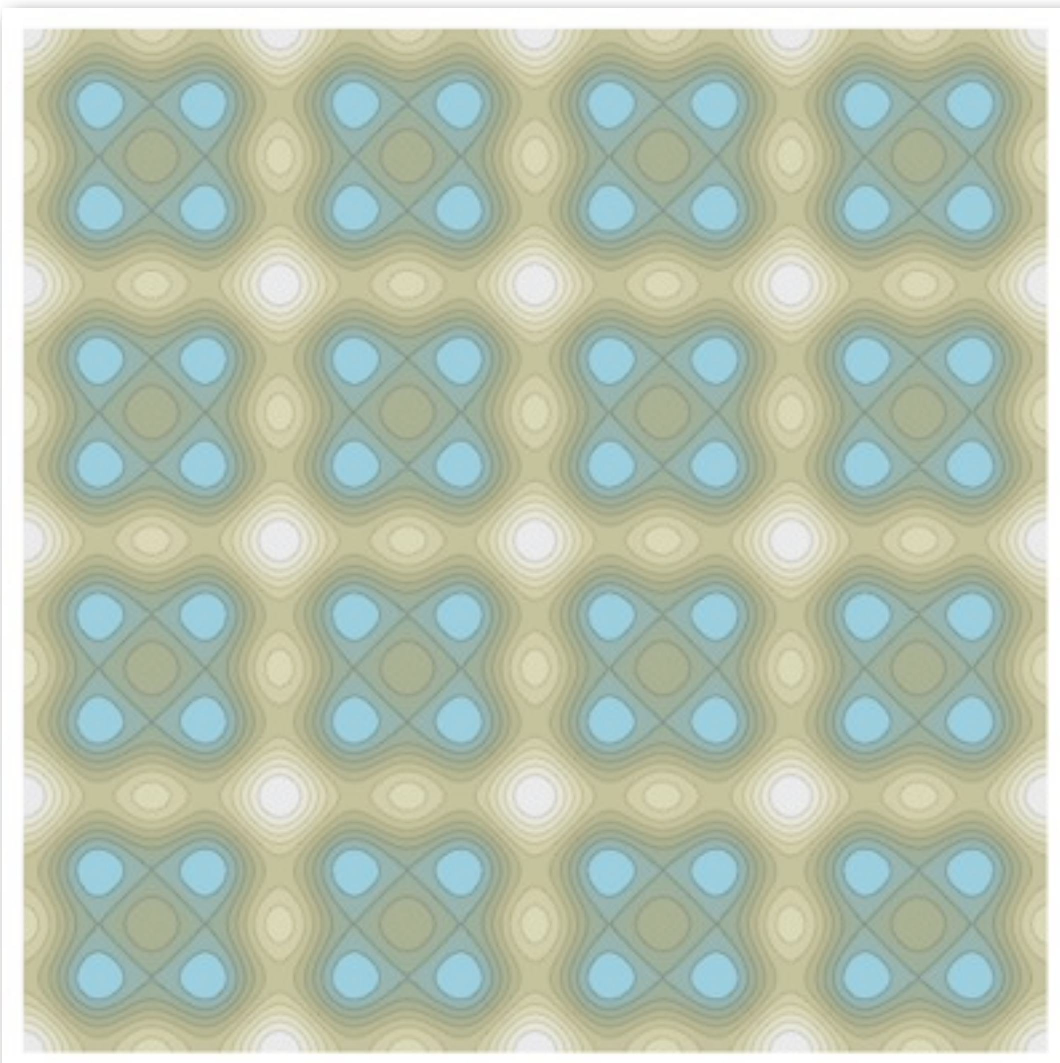
- **Bosons**: Symmetric wavefunction → Triplet $|t_0\rangle$

  (Fermions: Antisymmetric wavefunction → Singlet $|s_0\rangle$)

Details on the loading of the Spin-pairs:

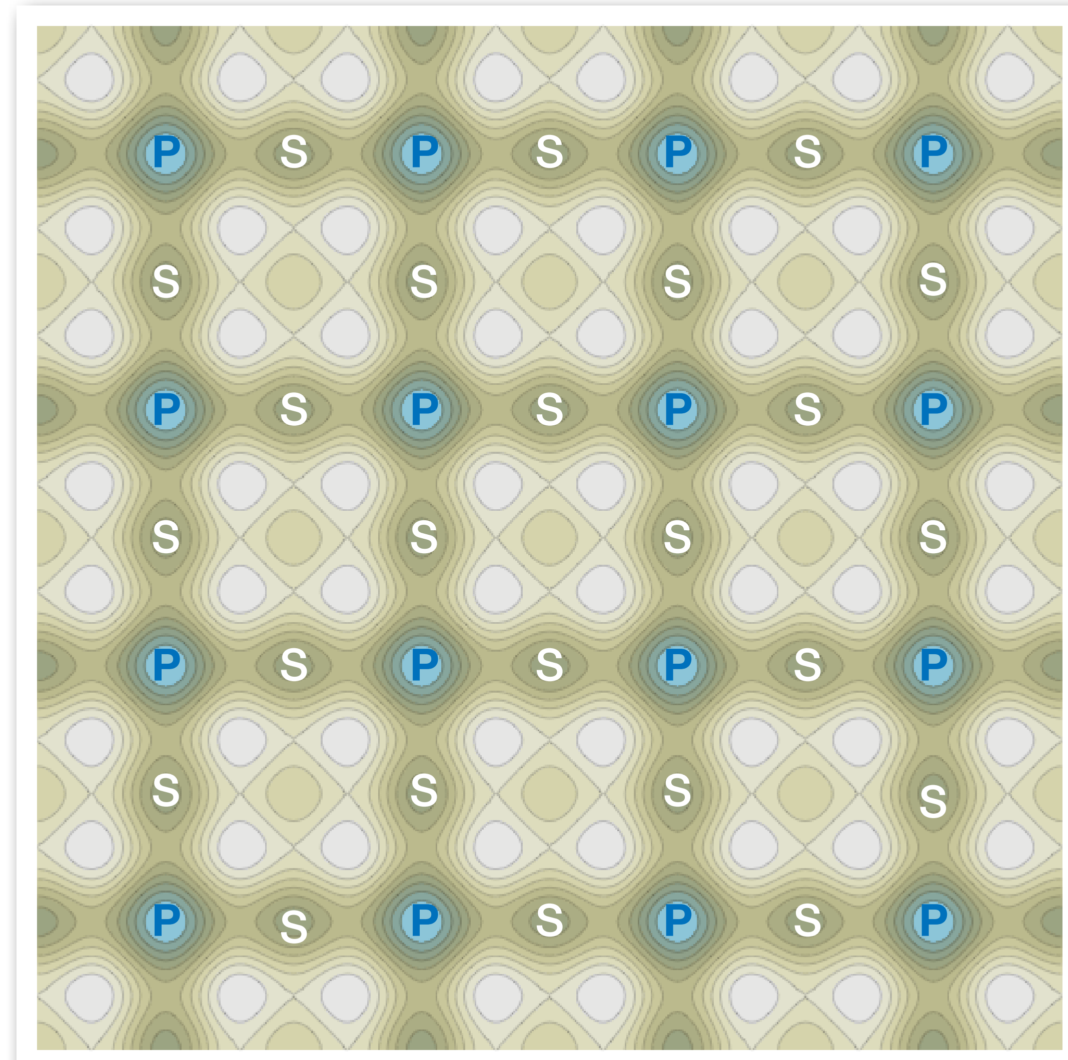
S. Trotzky et al., Science **319** (2008), A.-M. Rey at al., PRL **99** (2007)

2D Superlattice Geometries (2 SL)



Coupled Plaquette Systems

see B. Paredes & I. Bloch, PRA **77**, 23603 (2008)
S. Trebst et al., PRL **96**, 250402 (2006)



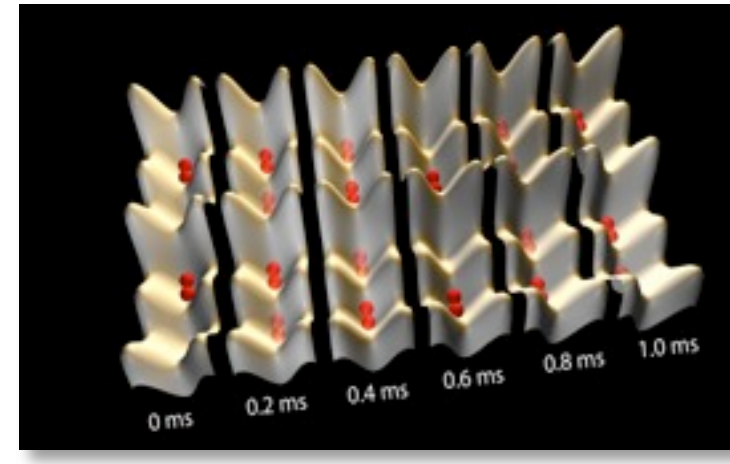
Higher Lattice Orbital Physics

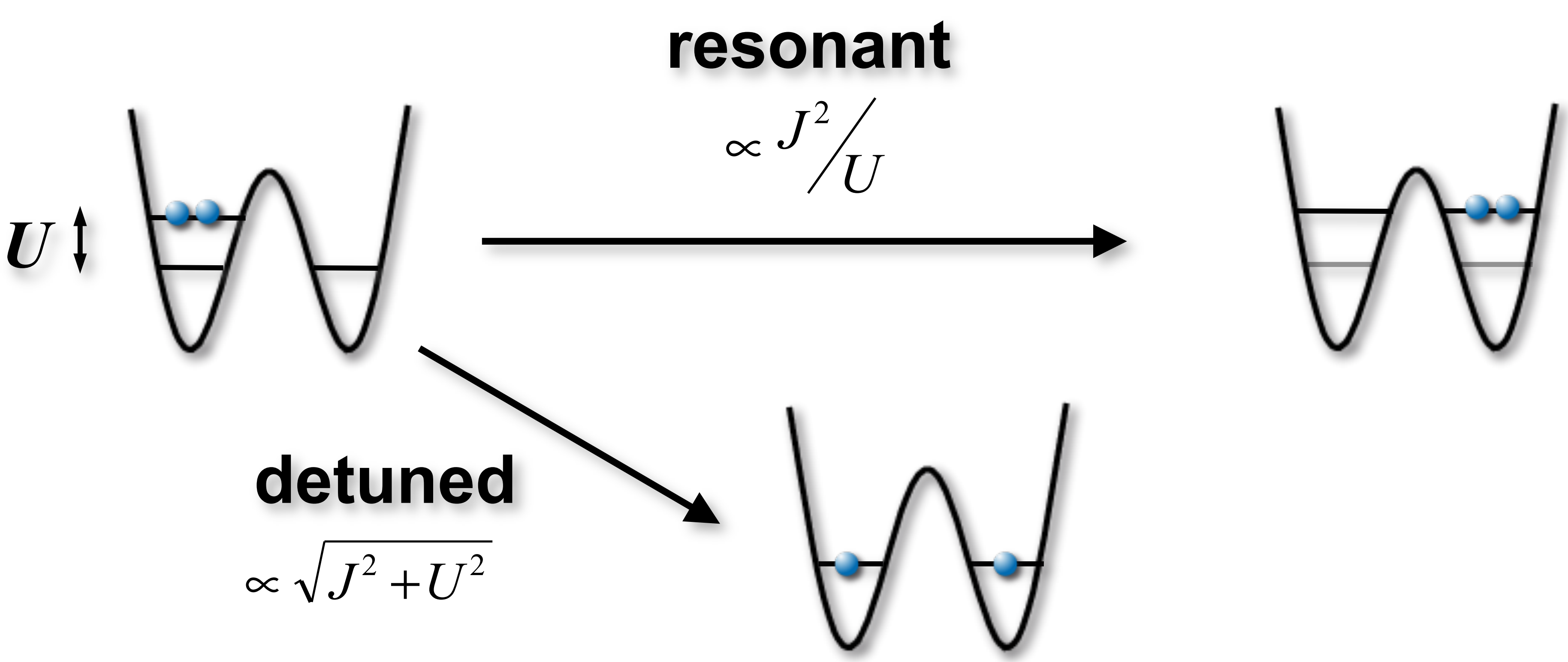
see V. Liu, A. Ho, C. Wu and others work
exp: related to A. Hemmerich's exp.

Quantum
Physics & Quantum Information

Experiments in the Superlattice

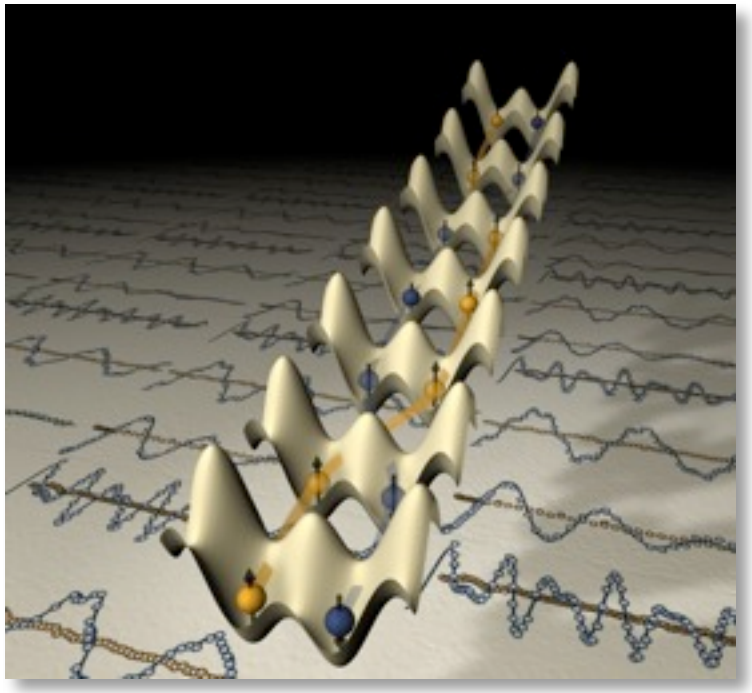
- **Isolated double-wells:**
  - Correlated tunneling

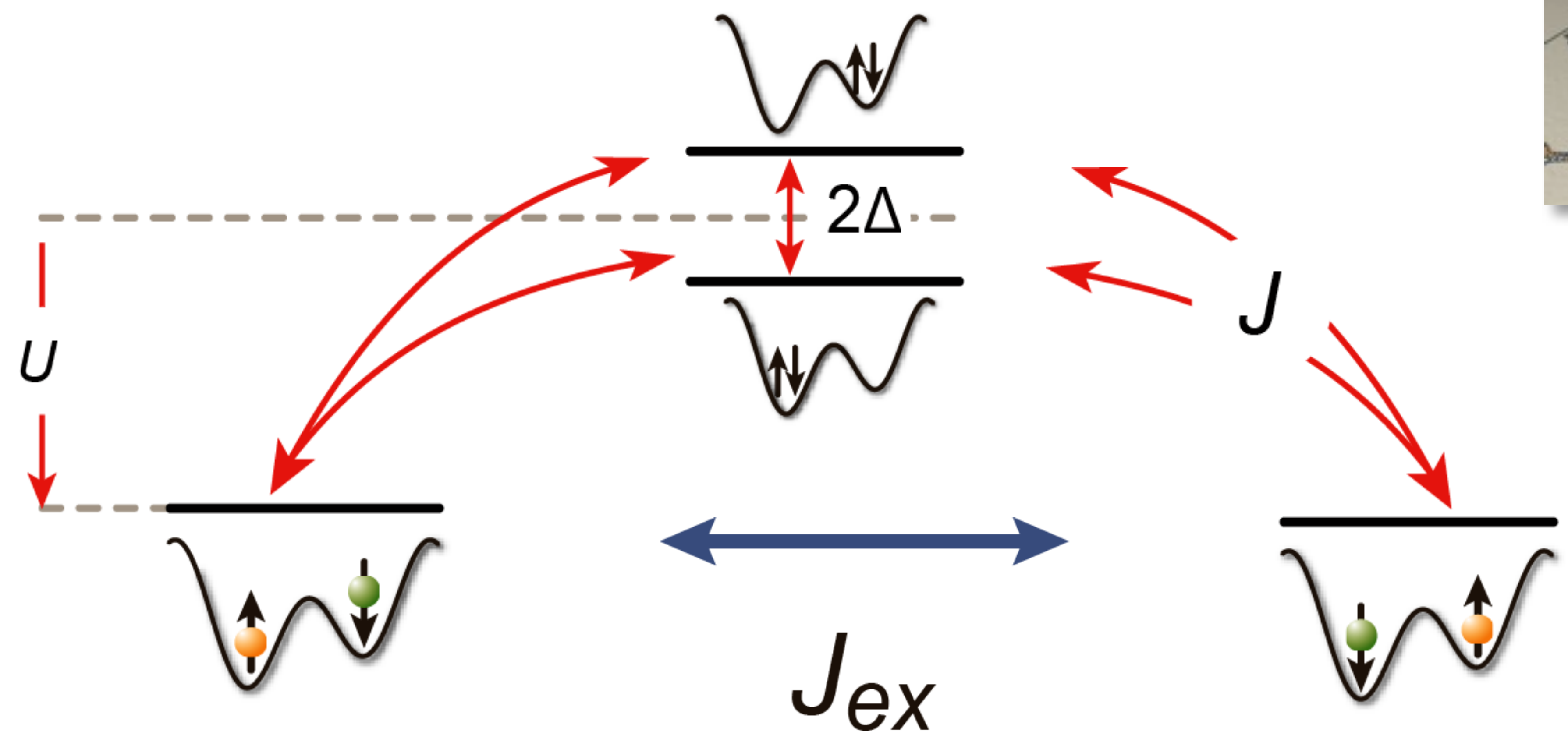




Experiments in the Superlattice

- **Isolated double-wells:**
  - Correlated tunneling, Superexchange interactions





Experiments in the Superlattice

- **Isolated double-wells:**
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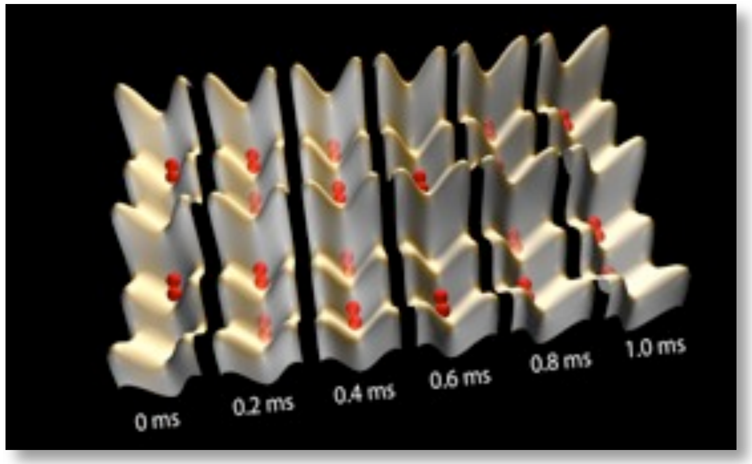
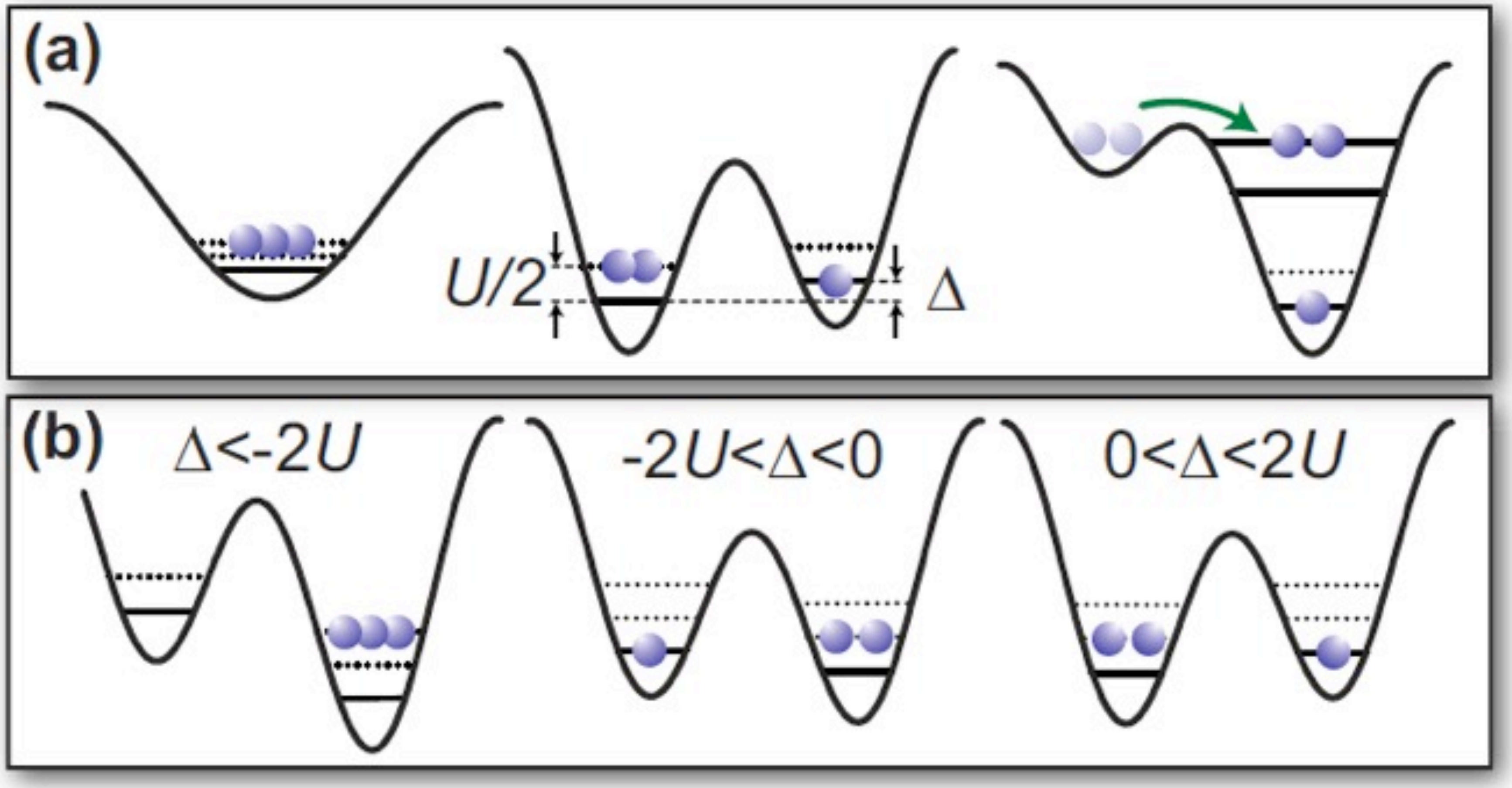
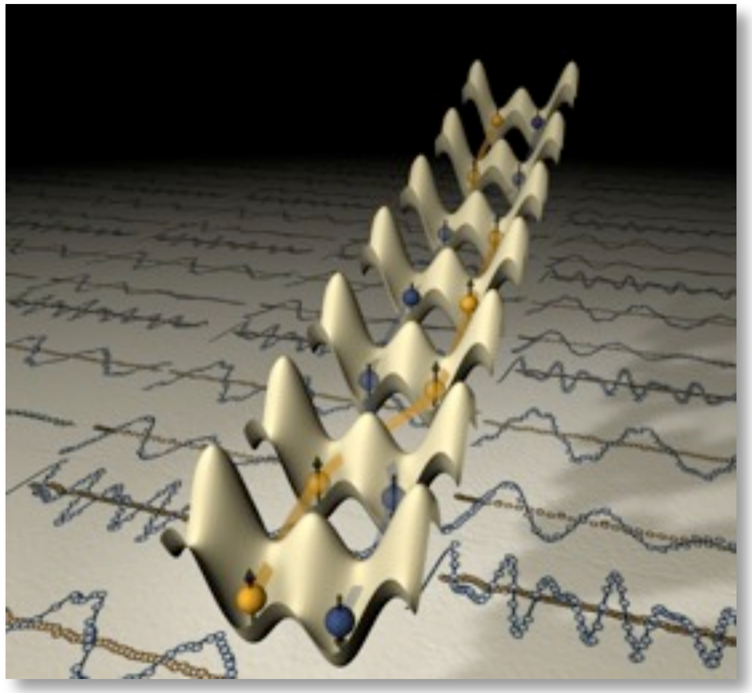
  - Counting atoms via interaction blockade







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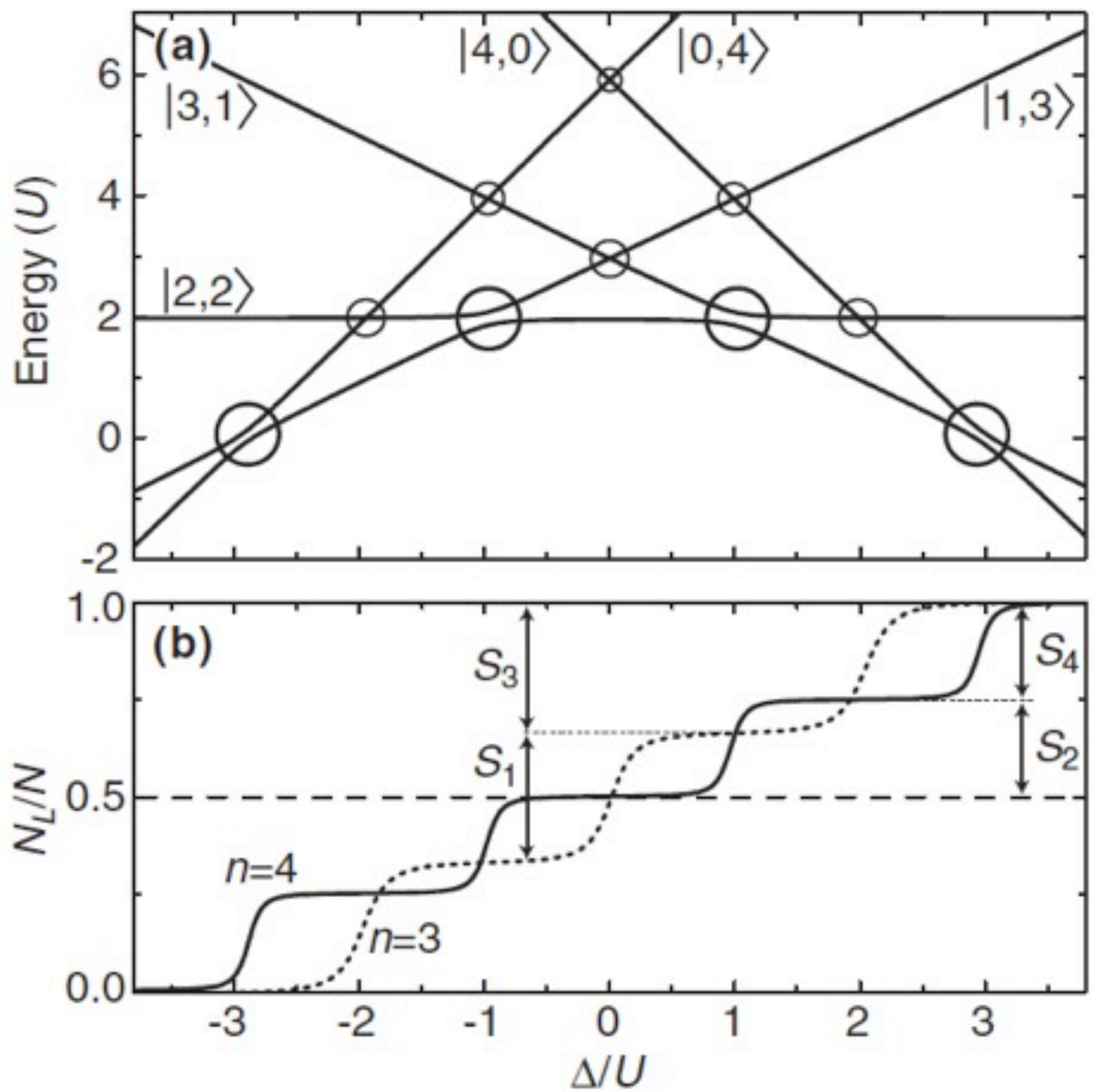

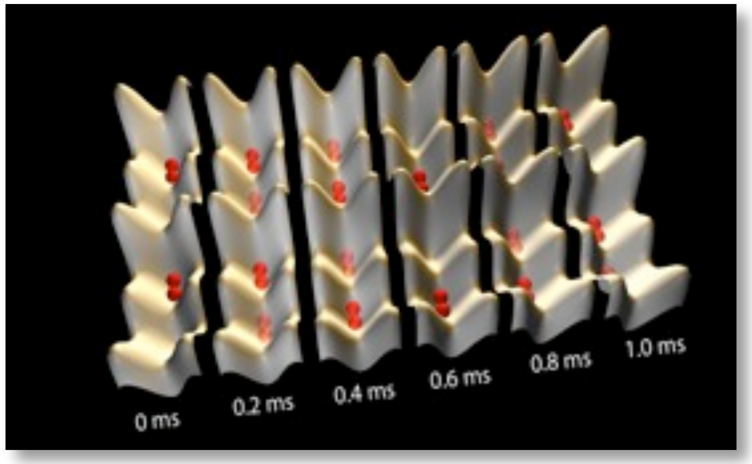

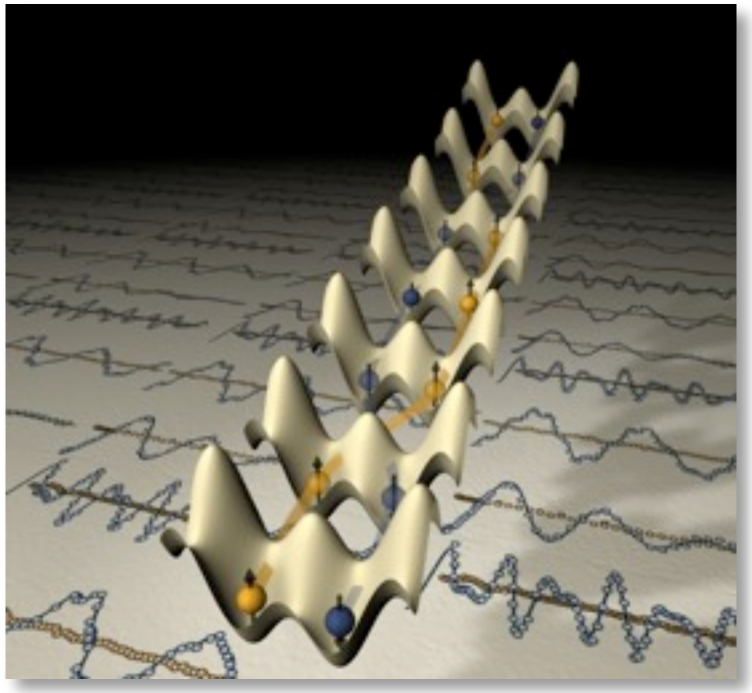

Experiments in the Superlattice

- **Isolated double-wells:**
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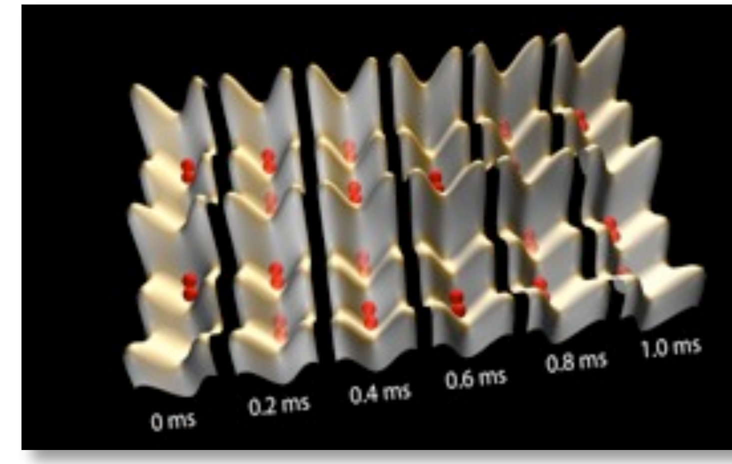
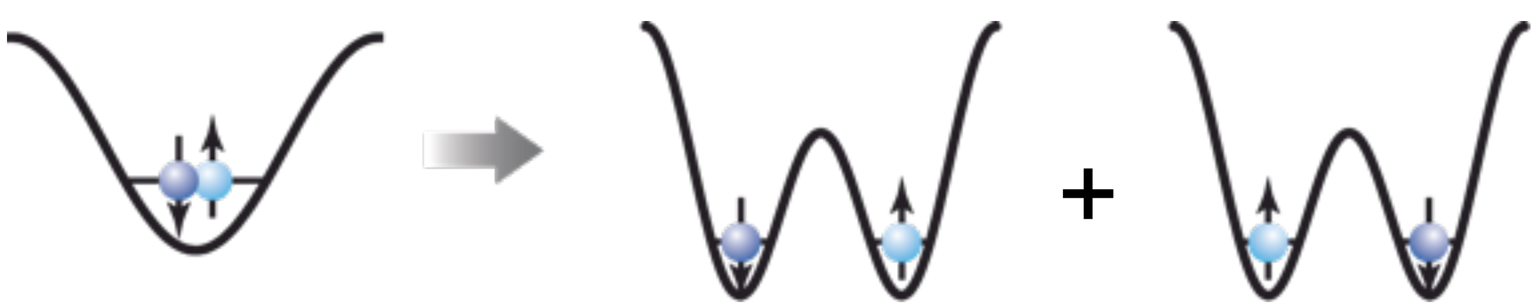
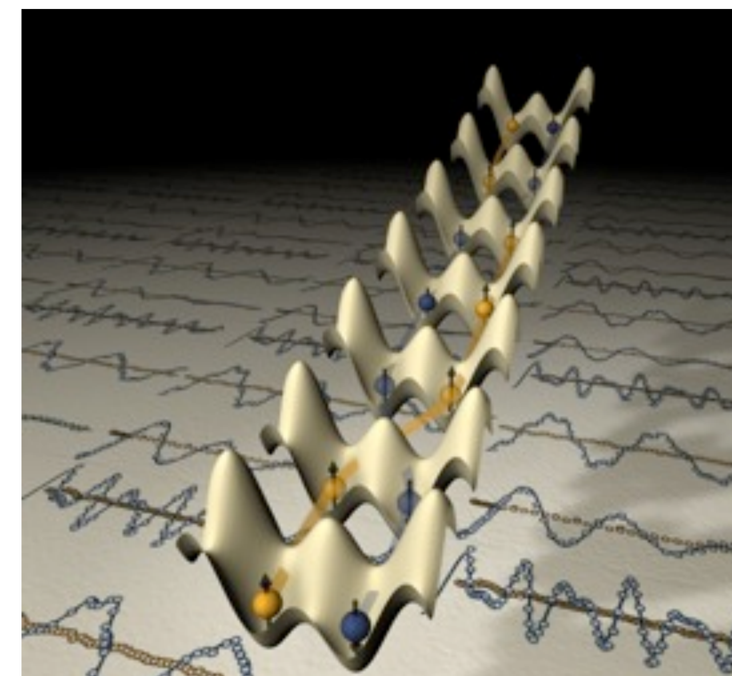
  - Control of n.n. spin correlations







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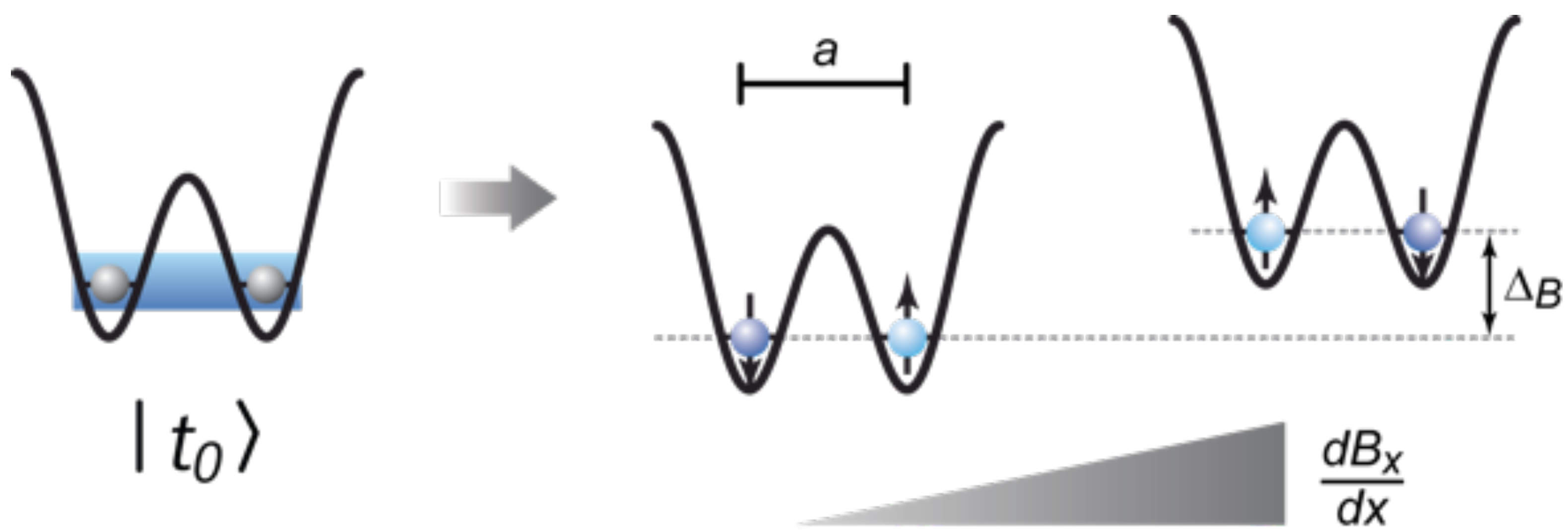

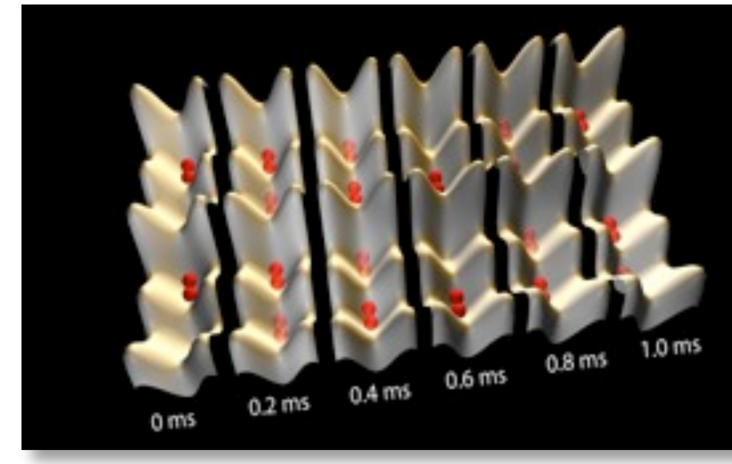

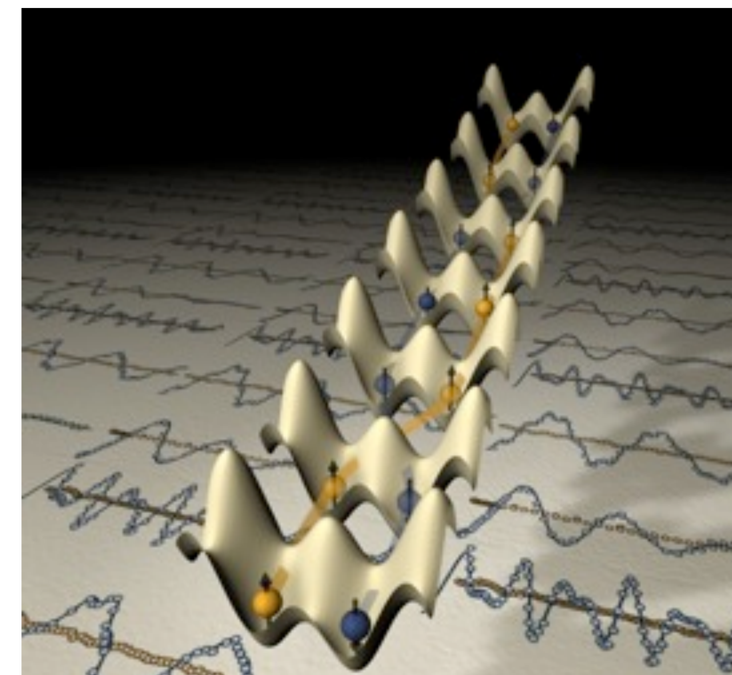

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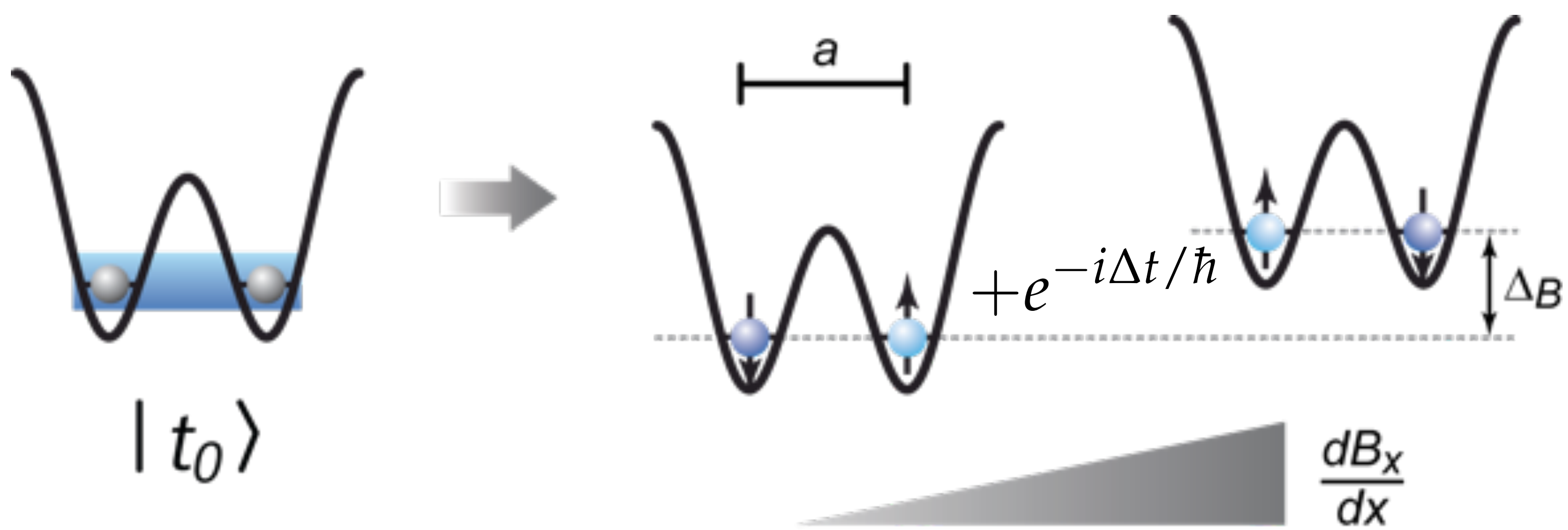

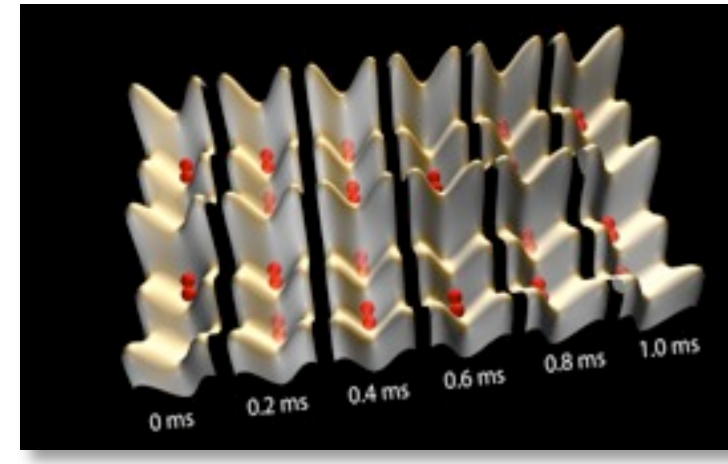

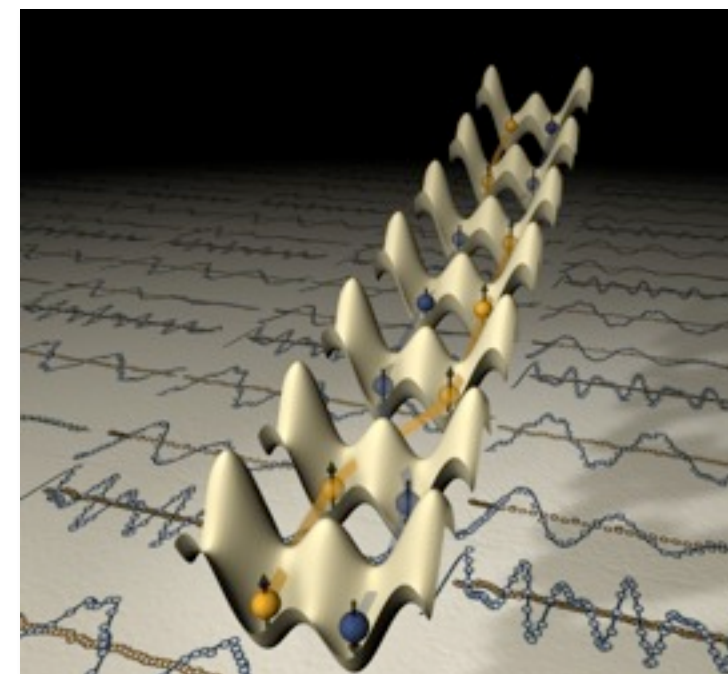

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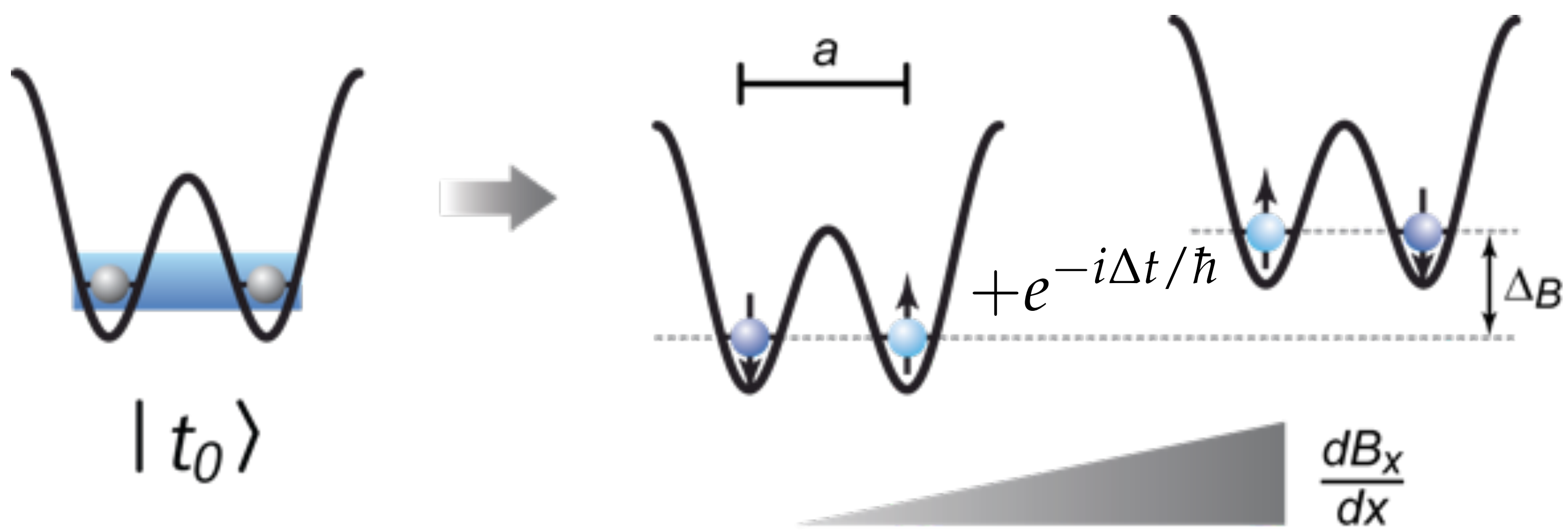

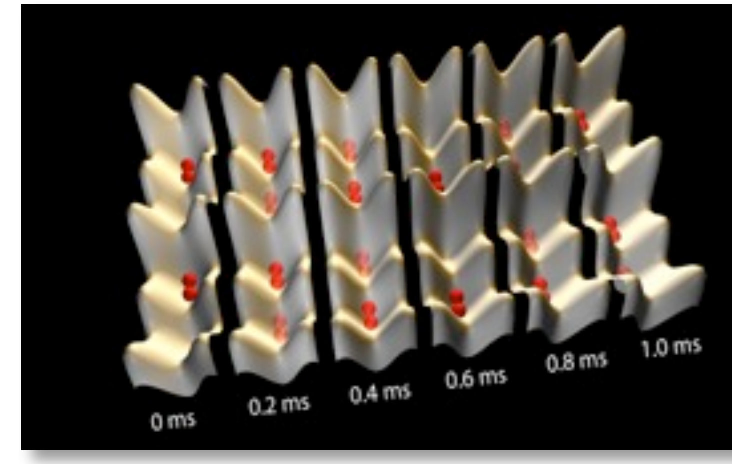

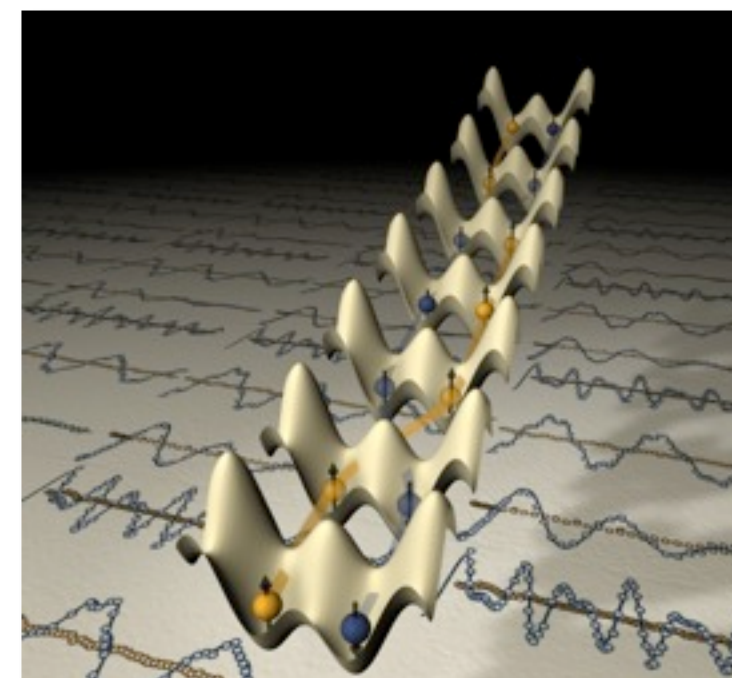

→ **Triplet**:

→ **Singlet**:

Experiments in the Superlattice

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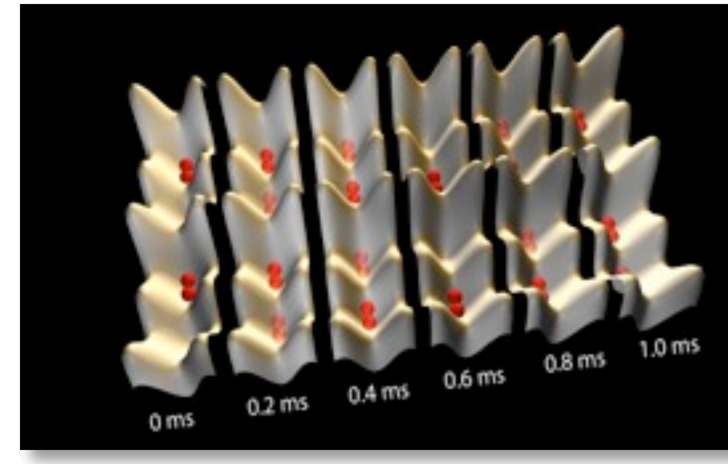
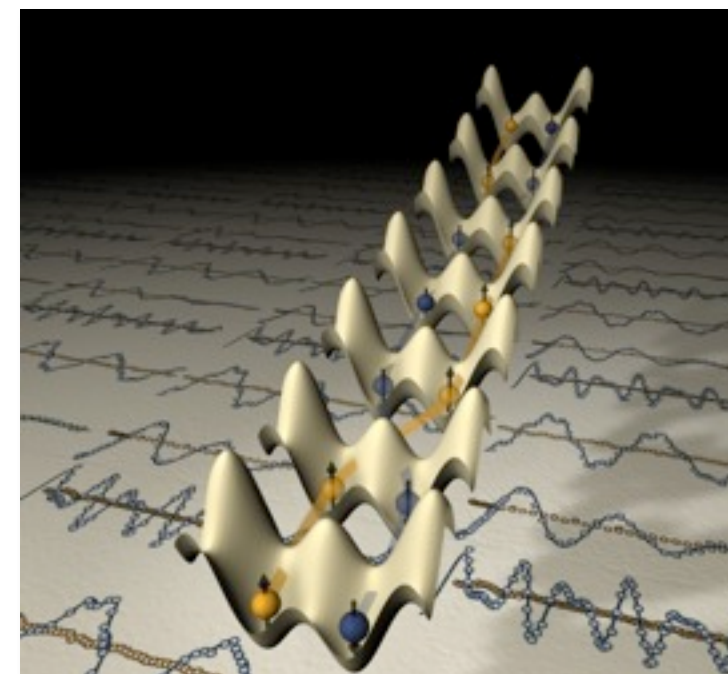
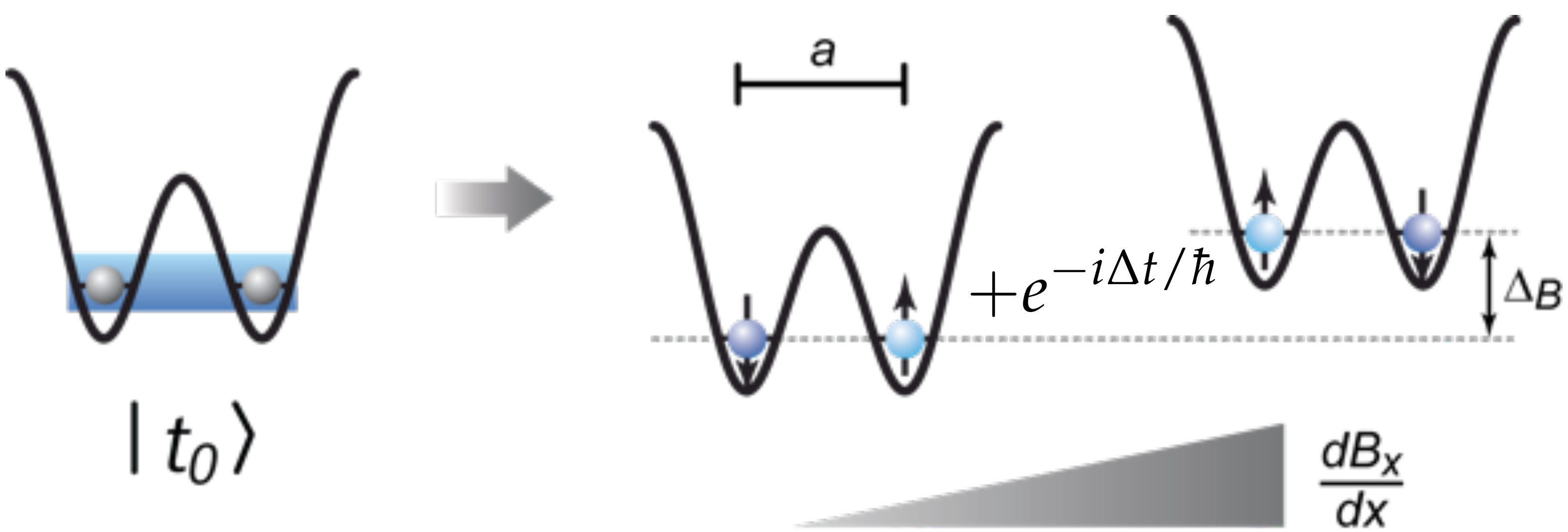
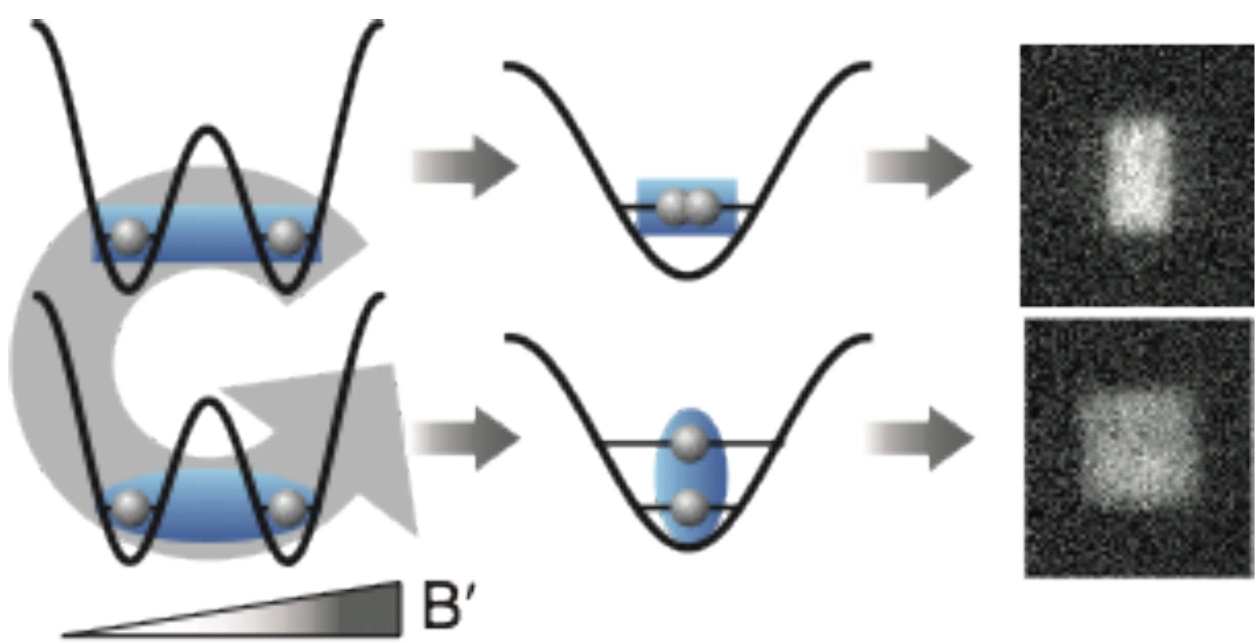






→ **Triplet**:

→ **Singlet**:

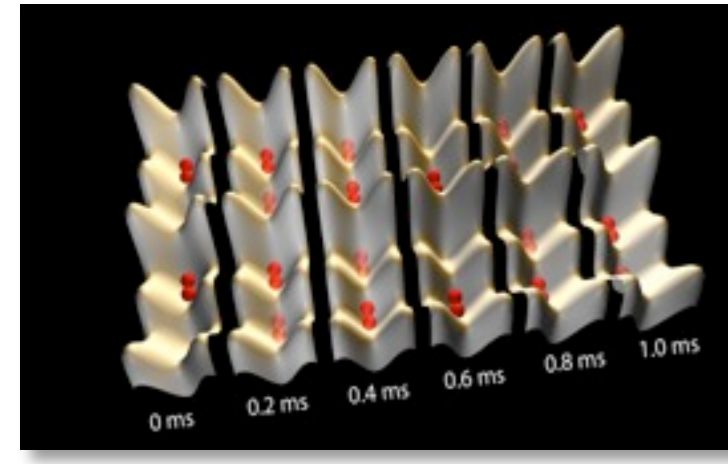


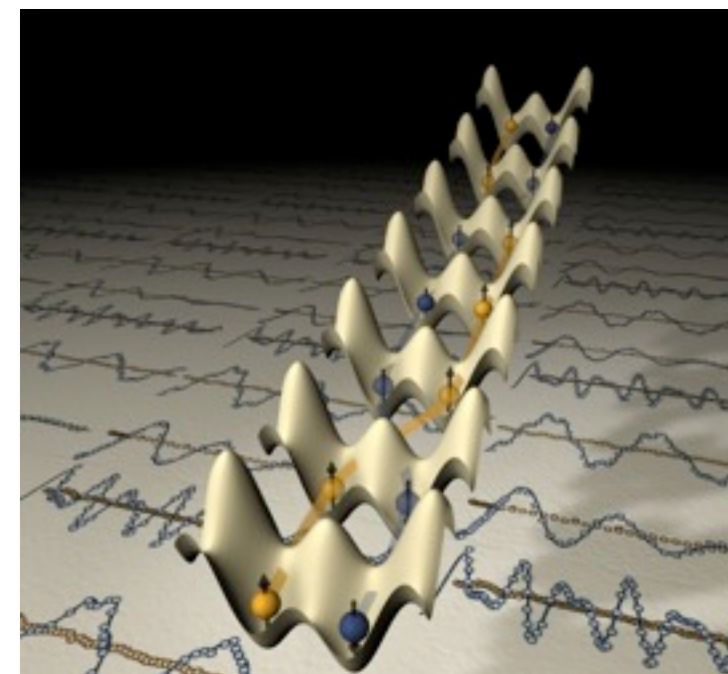
Experiments in the Superlattice

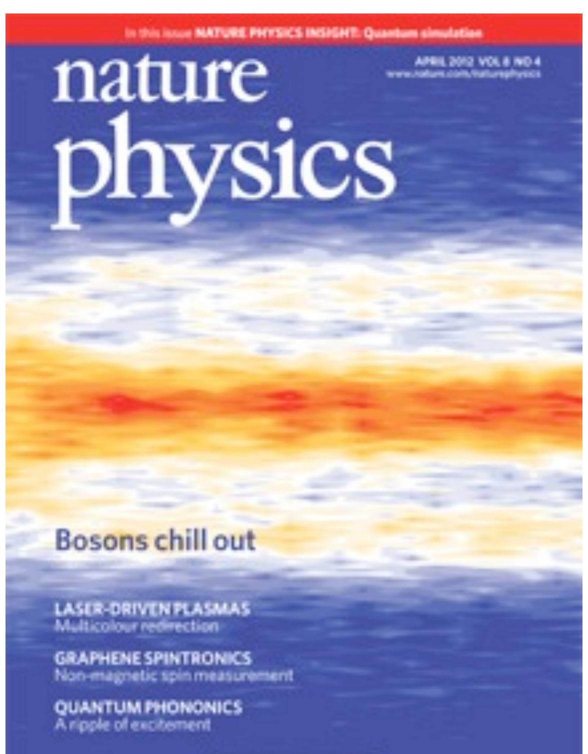
- **Isolated double-wells:**
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations

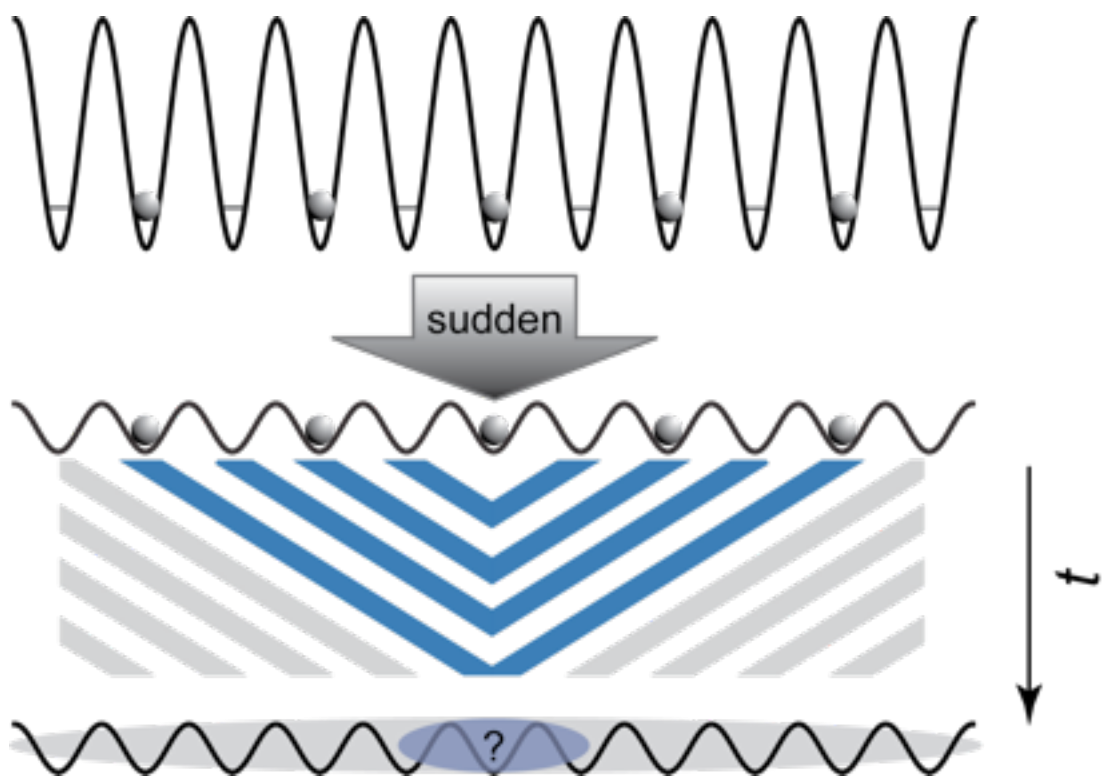
  ...

- **Non-equilibrium & adiabatic dynamics:**
  - Decay of patterned states (spin, density) after quantum quenches









Experiments in the Superlattice

- **Isolated double-wells:**
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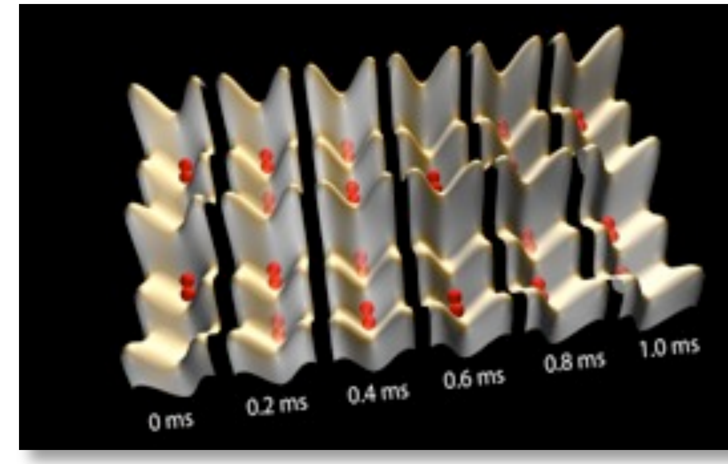
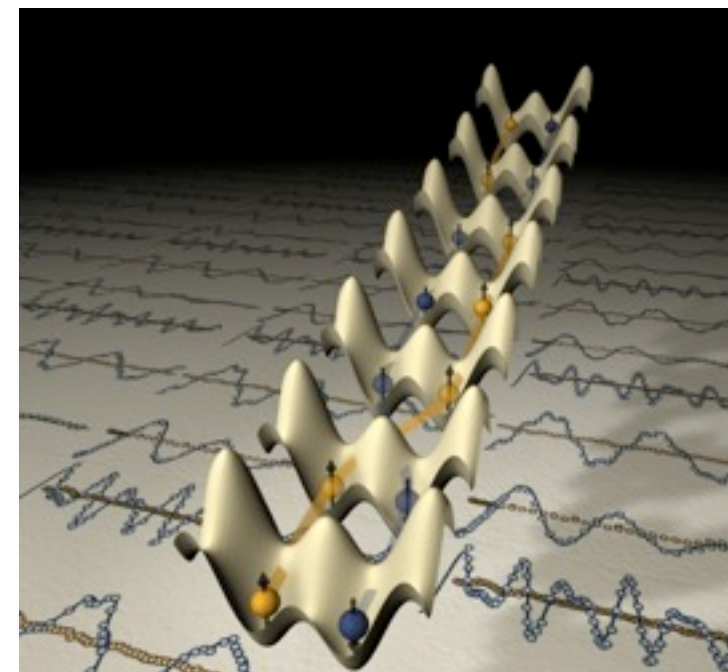
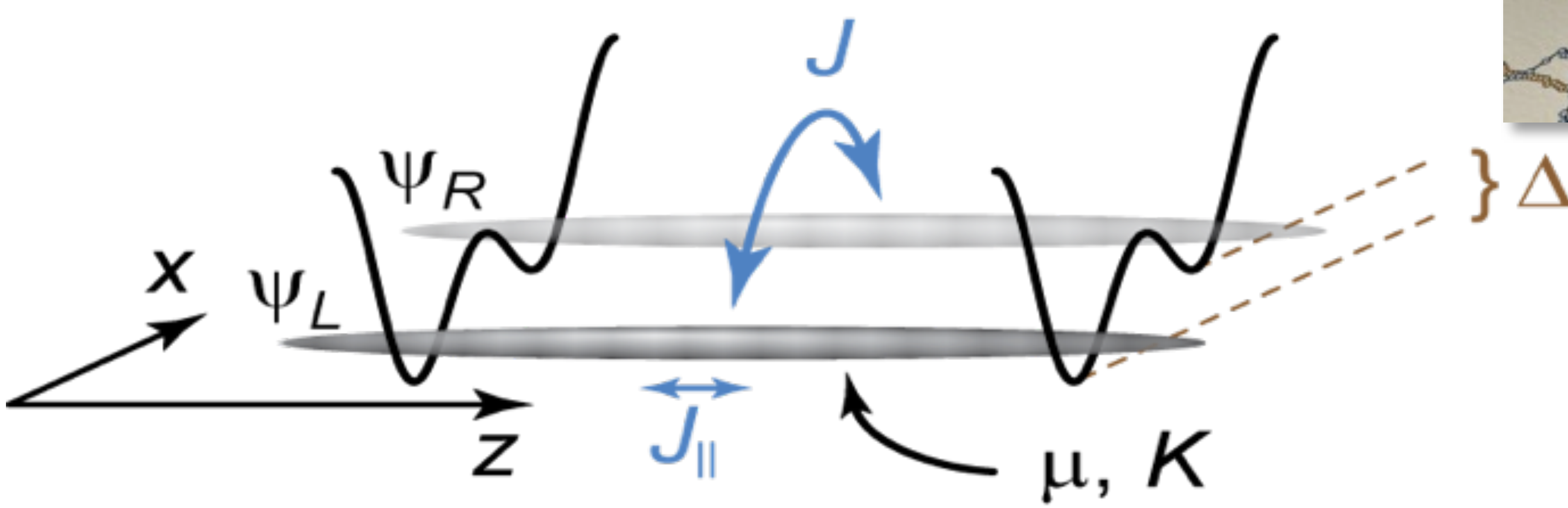


- **Non-equilibrium & adiabatic dynamics:**
  - Decay of patterned states (spin, density) after quantum quenches
  - Landau-Zener sweeps w. 1D gases





Experiments in the Superlattice

- **Isolated double-wells:**
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  ...
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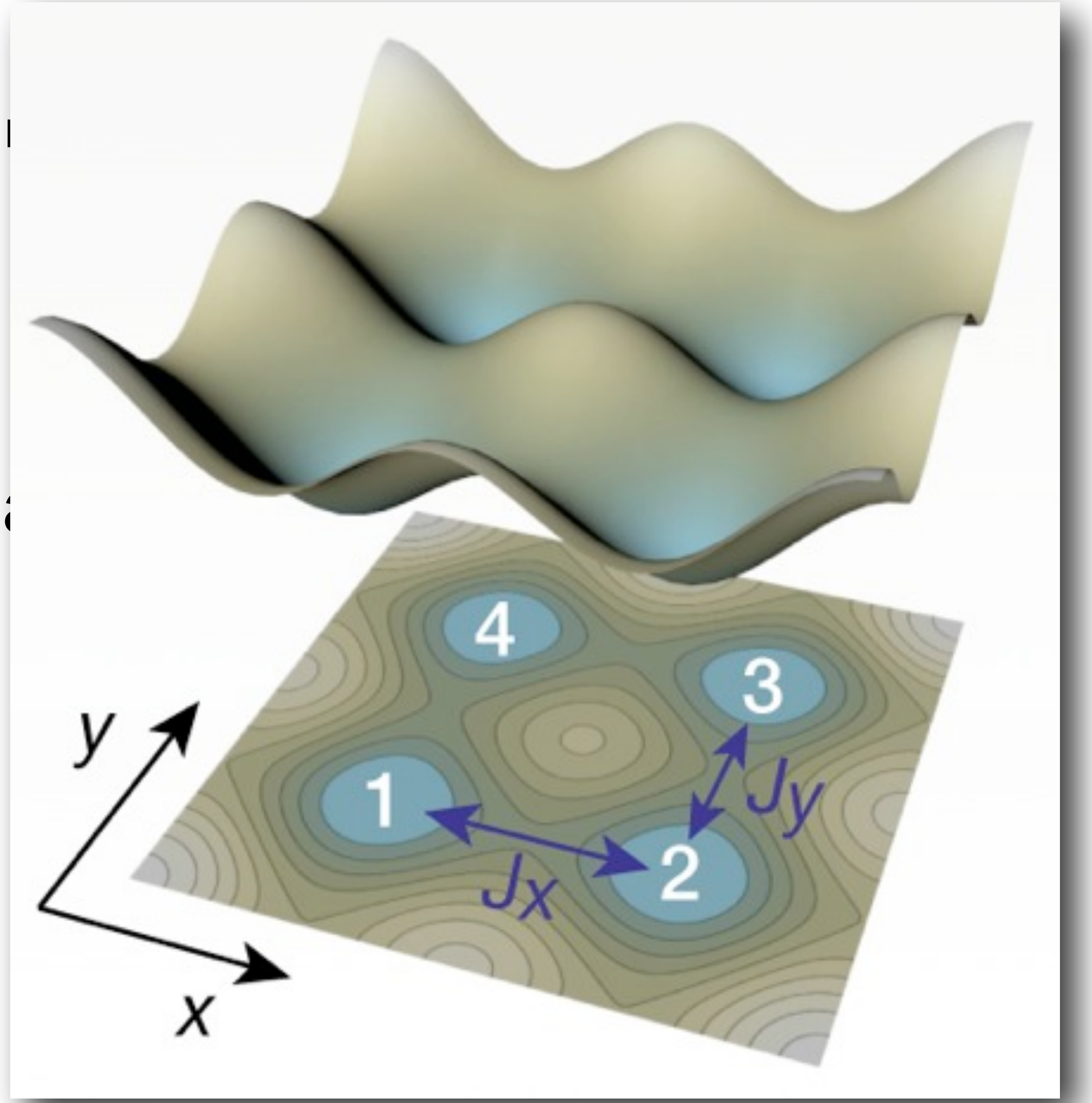
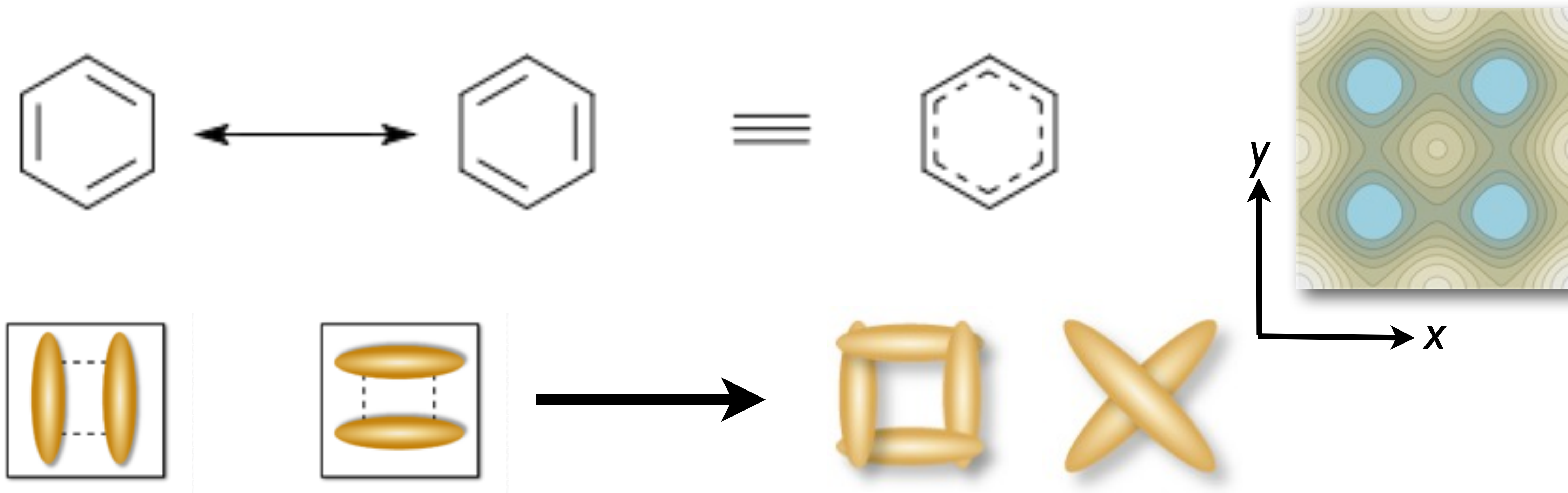
  ...
- **Isolated plaquettes:**
  - Resonating Valence Bond State



Experiments in the Superlattice



- **Isolated plaquettes:**
  - Resonating Valence Bond State

Experiments in the Superlattice

- **Isolated double-wells:**
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  …
- **Non-equilibrium & adiabatic dyn**
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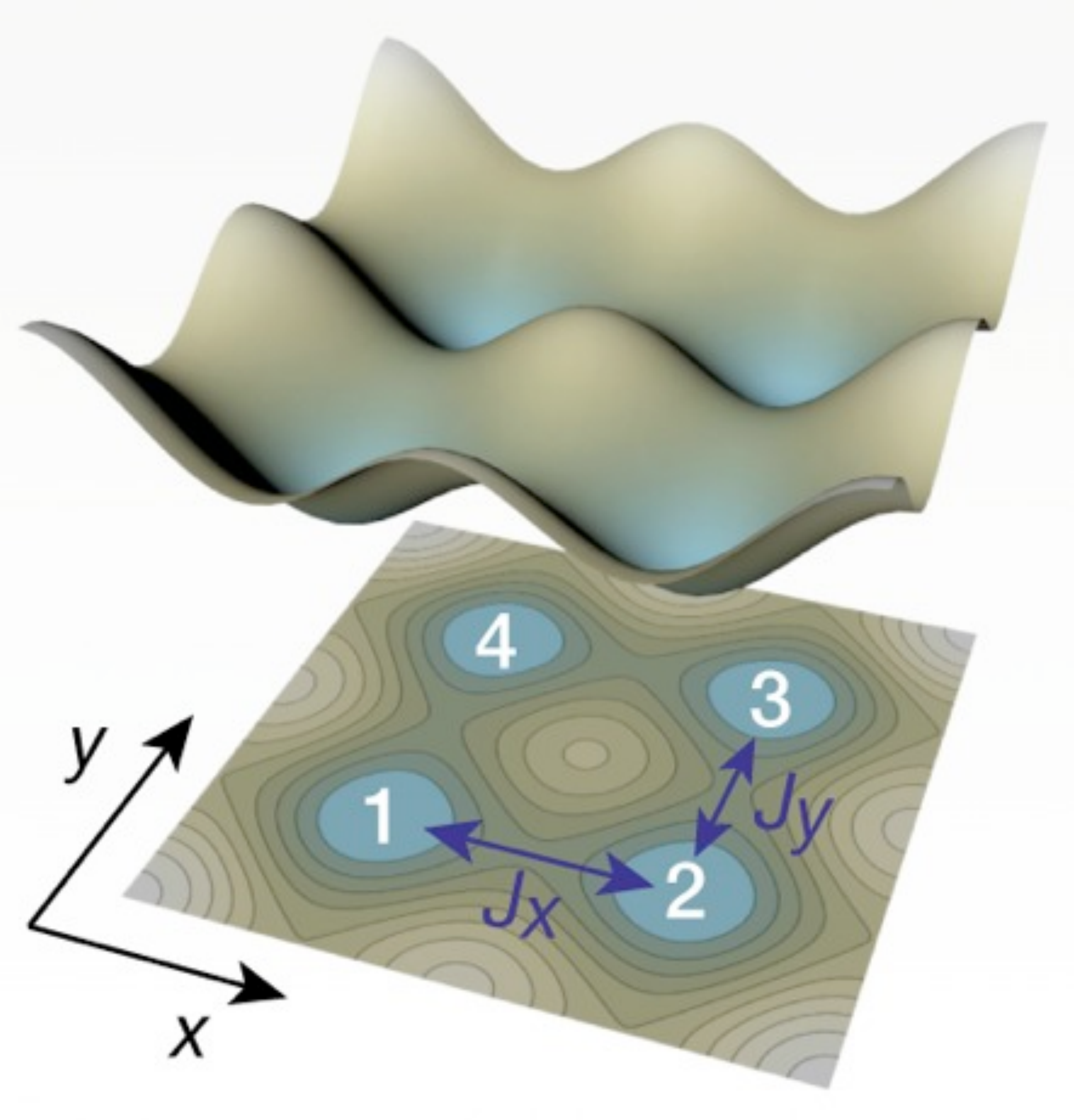
  …
- **Isolated plaquettes:**
  - Resonating Valence Bond State
  - **Artificial Gauge Field**
  - **Zak Phase in Topological Bloch Bands**

  …
- **Many-body phases in the superlattice**

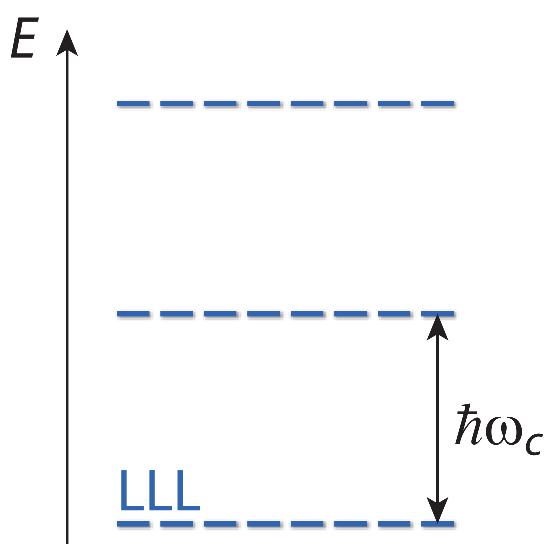


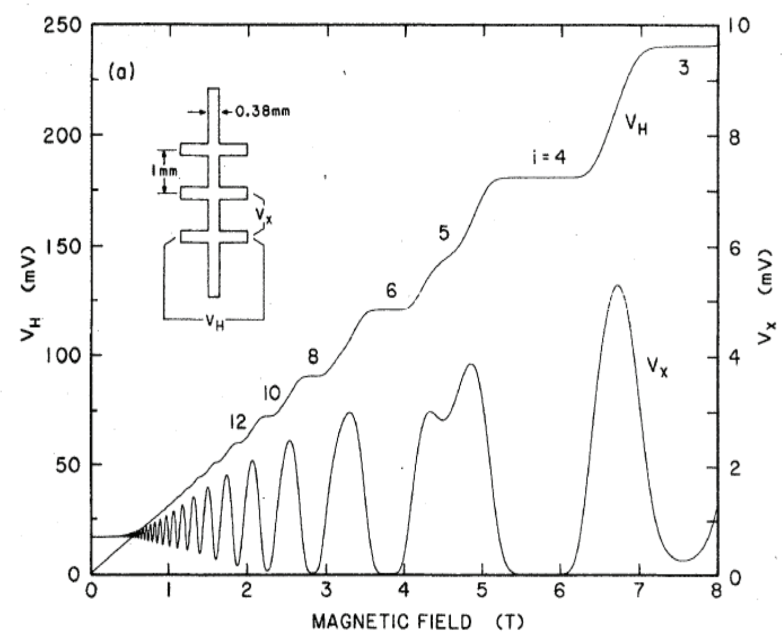
Creation of Strong Effective Magnetic Fields

M. Aidelsburger *et al.*,
PRL 107, 255301 (2011)

Quantum Hall effect in 2D electron gases

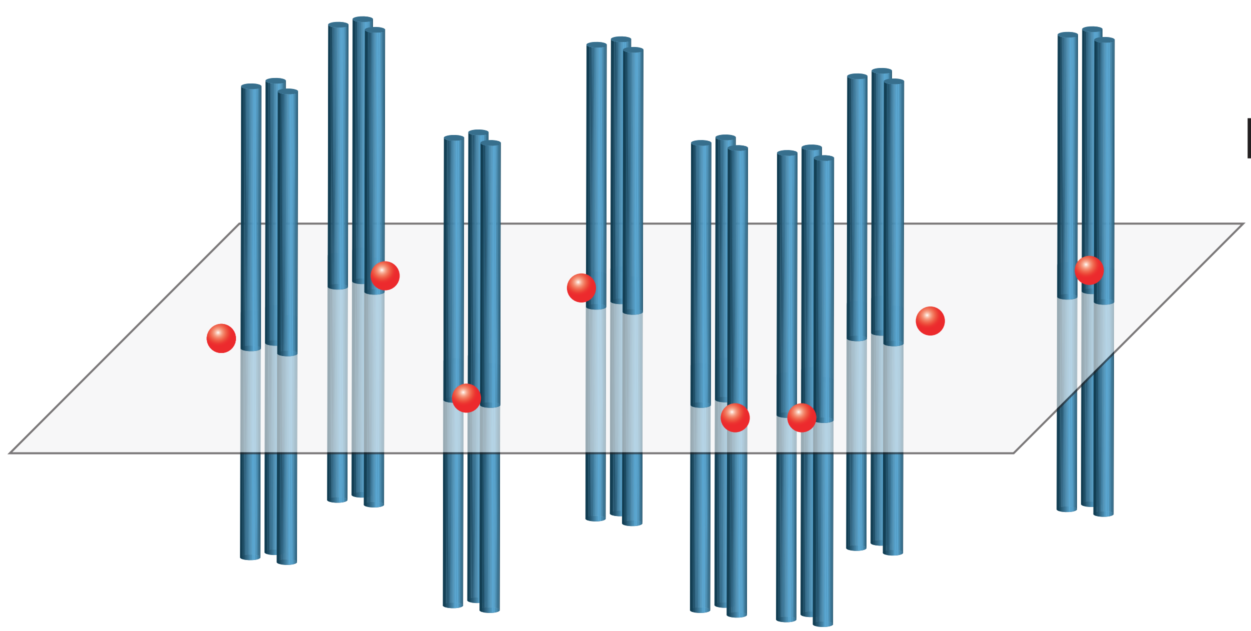
❖ Integer quantum Hall effect





$\sigma_{xy} = \nu\, e^2/h$,
ν integer

❖ Fractional quantum Hall effect



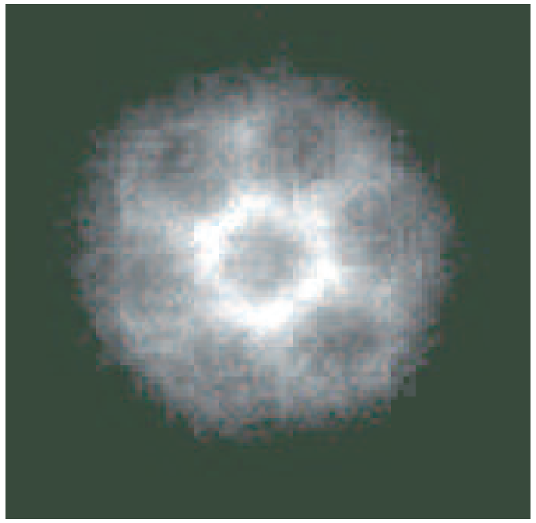
Laughlin state at $\nu = 1/3$

flux quantum ϕ_0=h/ec

electron

Artificial B fields with ultracold atoms

❖ Rotation

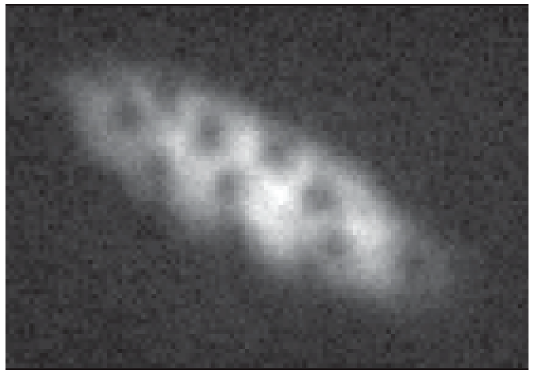


The Coriolis force $\mathbf{F}_{\mathrm{C}} = 2m\,\mathbf{v} \times \mathbf{\Omega}_{\mathrm{rot}}$ is analogous to the Lorentz force $\mathbf{F}_{\mathrm{L}} = q\,\mathbf{v} \times \mathbf{B}$

Issue: typically γ > 1000

K. Madison *et al*, Phys. Rev. Lett. **84**, 806 (2000)
J. R. Abo-Shaeer *et al*, Science **292**, 476 (2001)

❖ Raman-induced gauge field



Spatially dependent optical couplings lead to a Berry phase analogous to the Aharonov-Bohm phase.

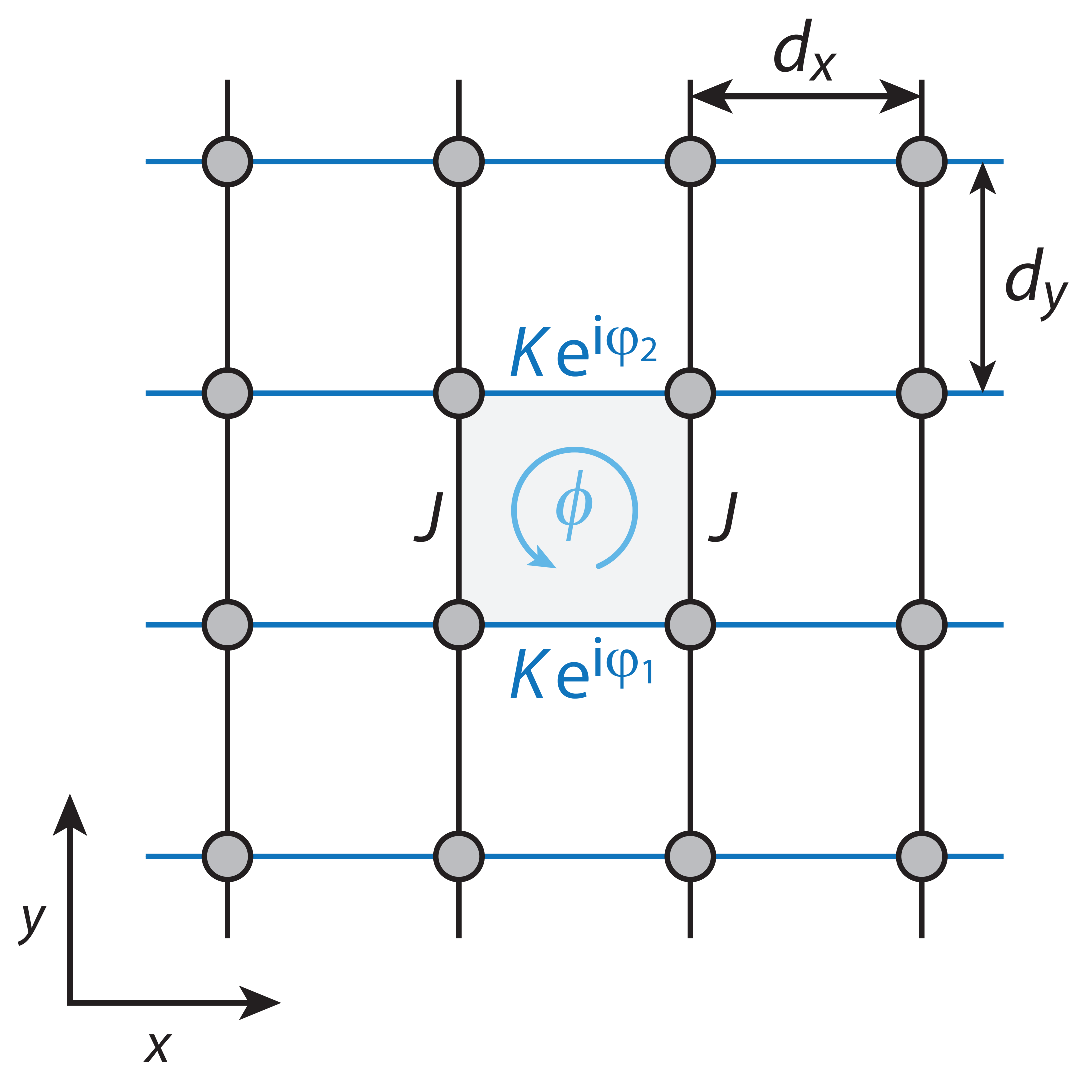
Issues: small *B* fields, heating from Raman lasers.

Y. Lin *et al*, Nature **462**, 628 (2009)

Artificial B fields with ultracold atoms in OLs

Controlling atom tunneling along *x* with Raman lasers leads to effective tunnel couplings with spatially-dependent Peierls phases $\phi(\mathbf{R})$

$$\hat{H} = -\sum_{\mathbf{R}} \left(K e^{i\varphi(\mathbf{R})}\, \hat{a}^{\dagger}_{\mathbf{R}} \hat{a}_{\mathbf{R}+\mathbf{d}_x} + J\, \hat{a}^{\dagger}_{\mathbf{R}} \hat{a}_{\mathbf{R}+\mathbf{d}_y} \right) + \mathrm{h.c.}$$



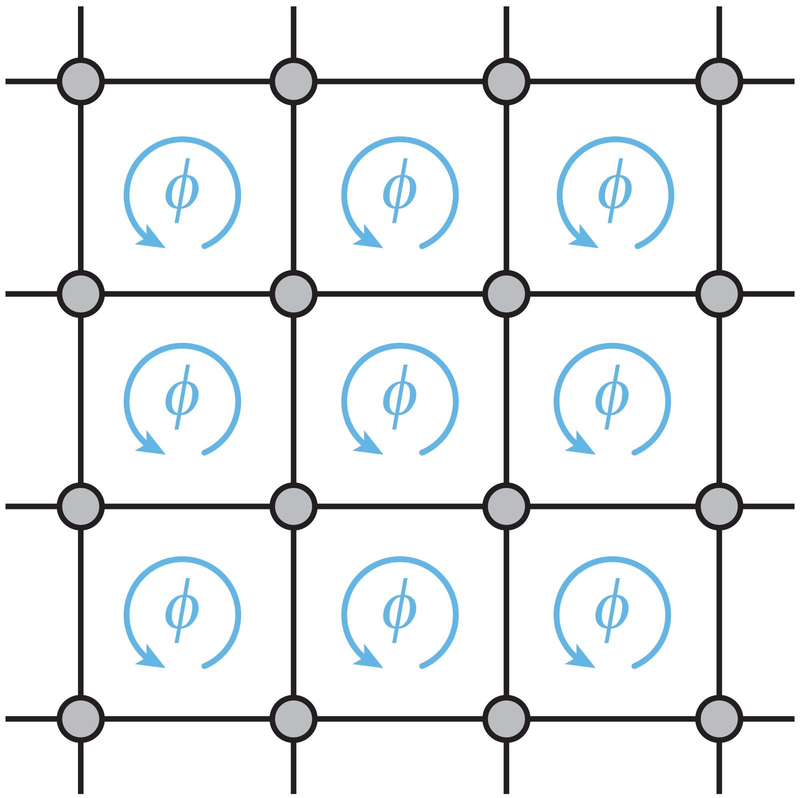
Magnetic flux through a plaquette

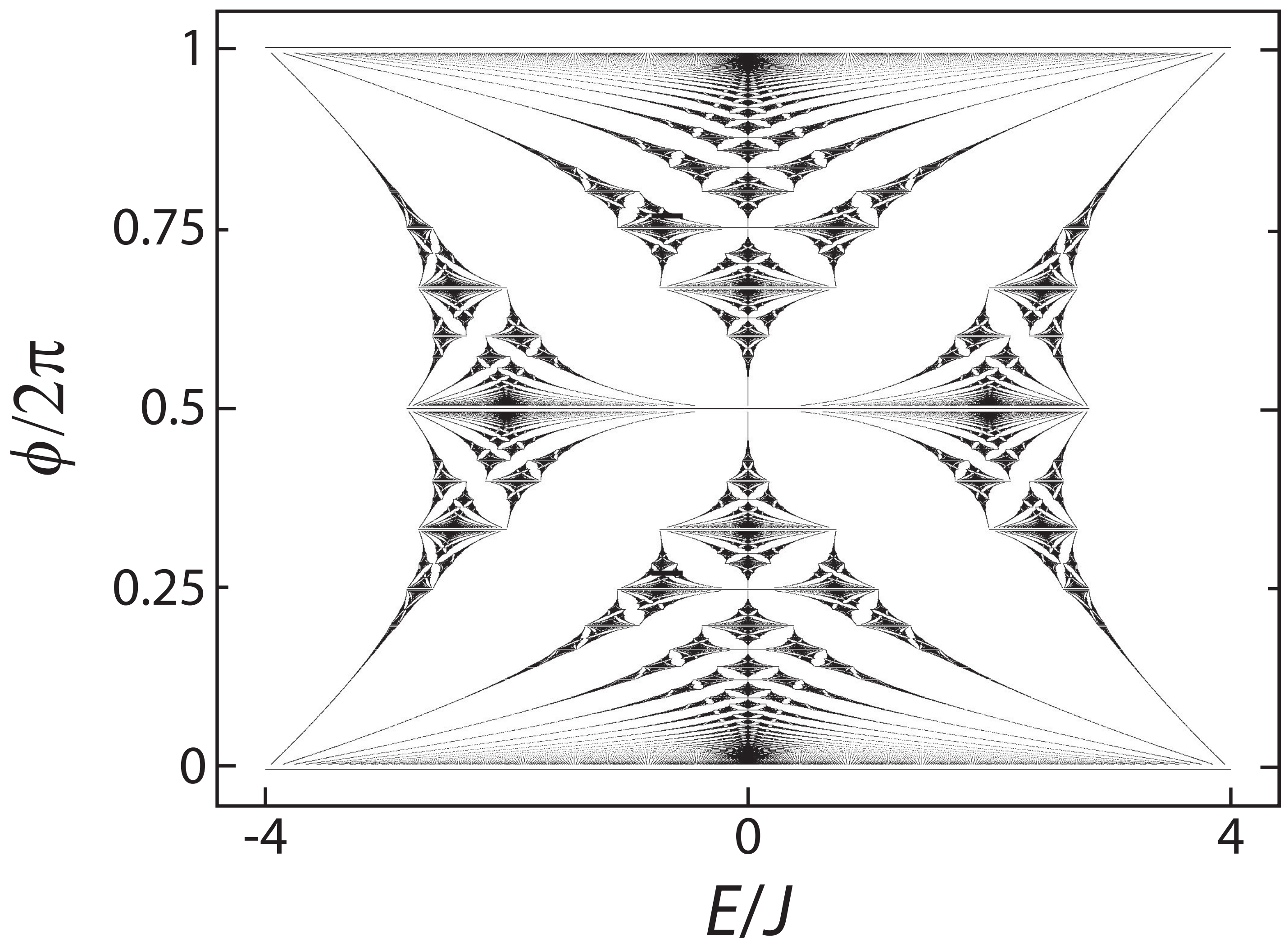
$$\phi = \int_{\square} B\, \mathrm{d}S = \varphi_1 - \varphi_2$$

D. Jaksch & P. Zoller, NJP **5**, 56 (2003)
F. Gerbier & J. Dalibard, NJP **12**, 033007 (2010)
E. Mueller, PPA **70**, 041603 (2004)}
A. Kolovsky, Europhys. Lett. **93**, 20003 (2011)

Harper Hamiltonian and Hofstadter butterfly

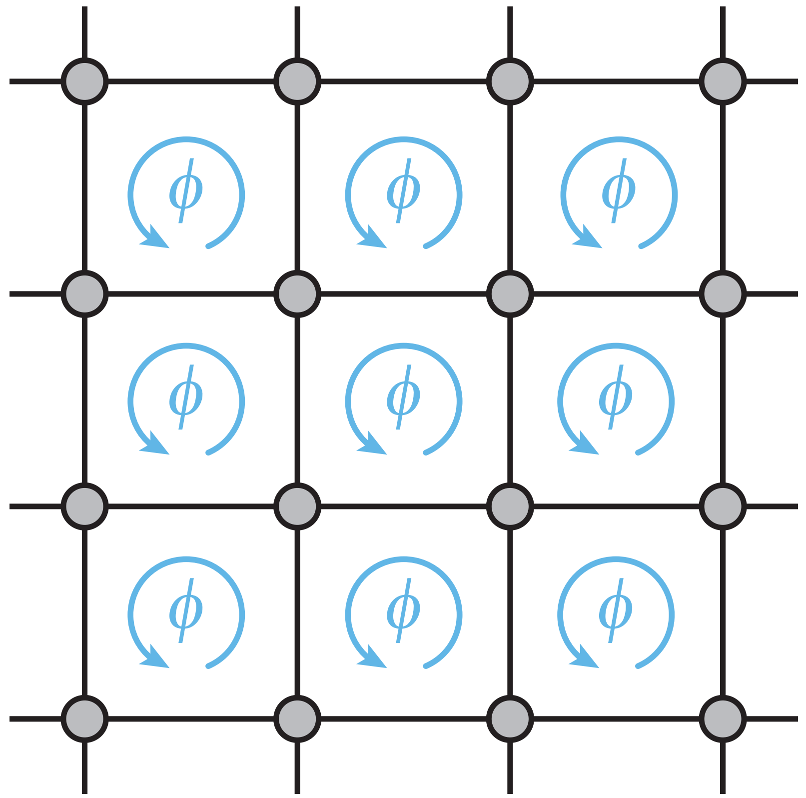
Harper Hamiltonian: *J*=*K* and ϕ uniform.

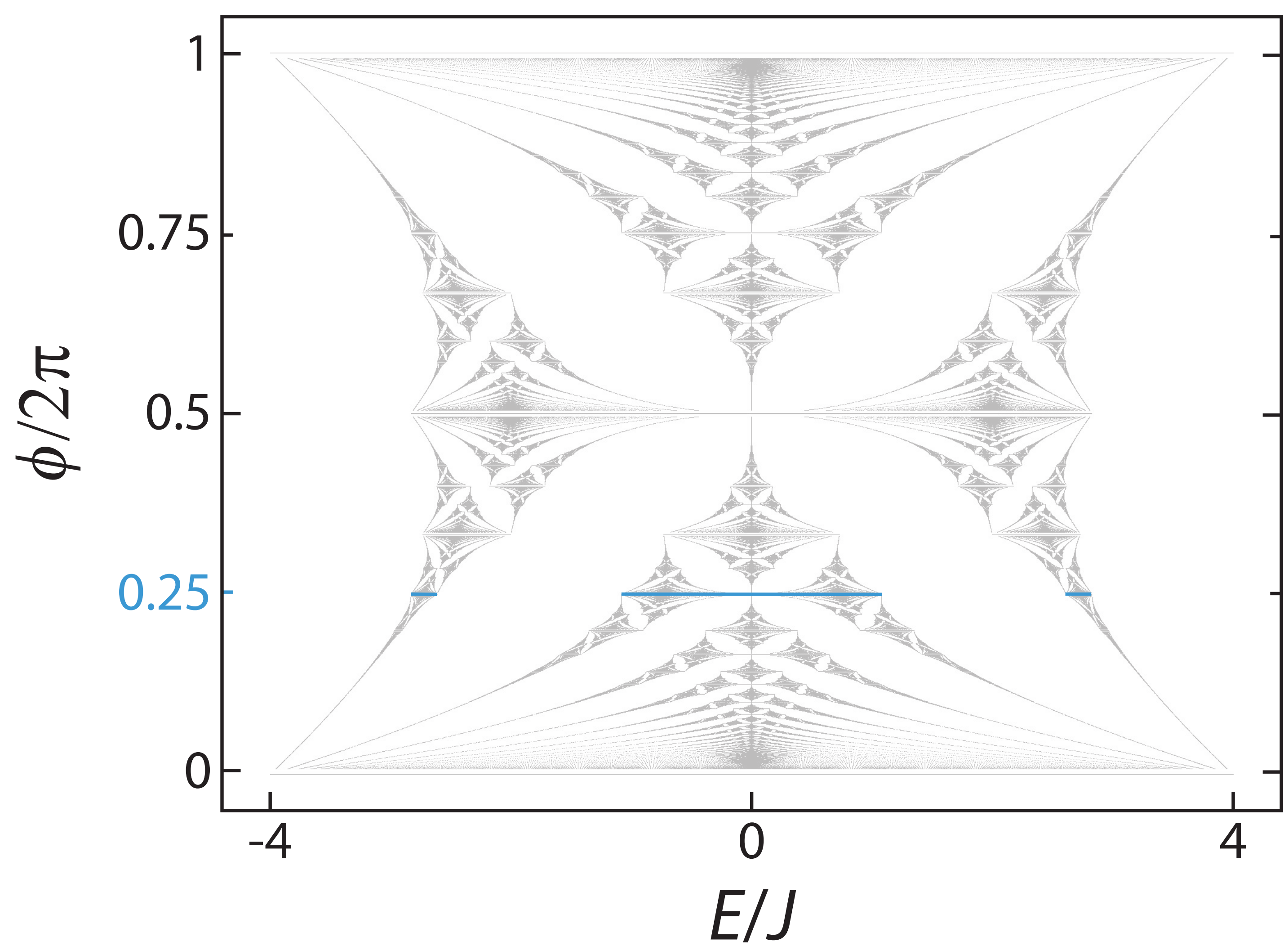




Harper Hamiltonian and Hofstadter butterfly

Harper Hamiltonian: J=K and ϕ uniform.

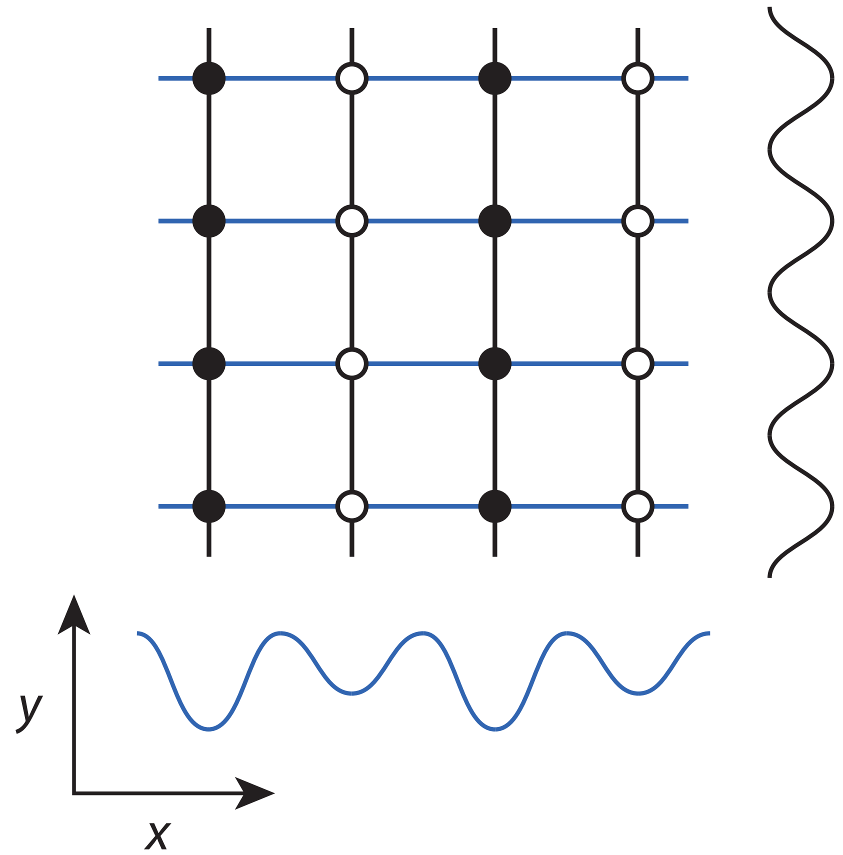




- Lowest band is topologically equivalent to lowest Landau level
- ν=1/2 + repulsive interactions ⟶ Laughlin state for Bosons.

Staggered flux lattice with Rb atoms

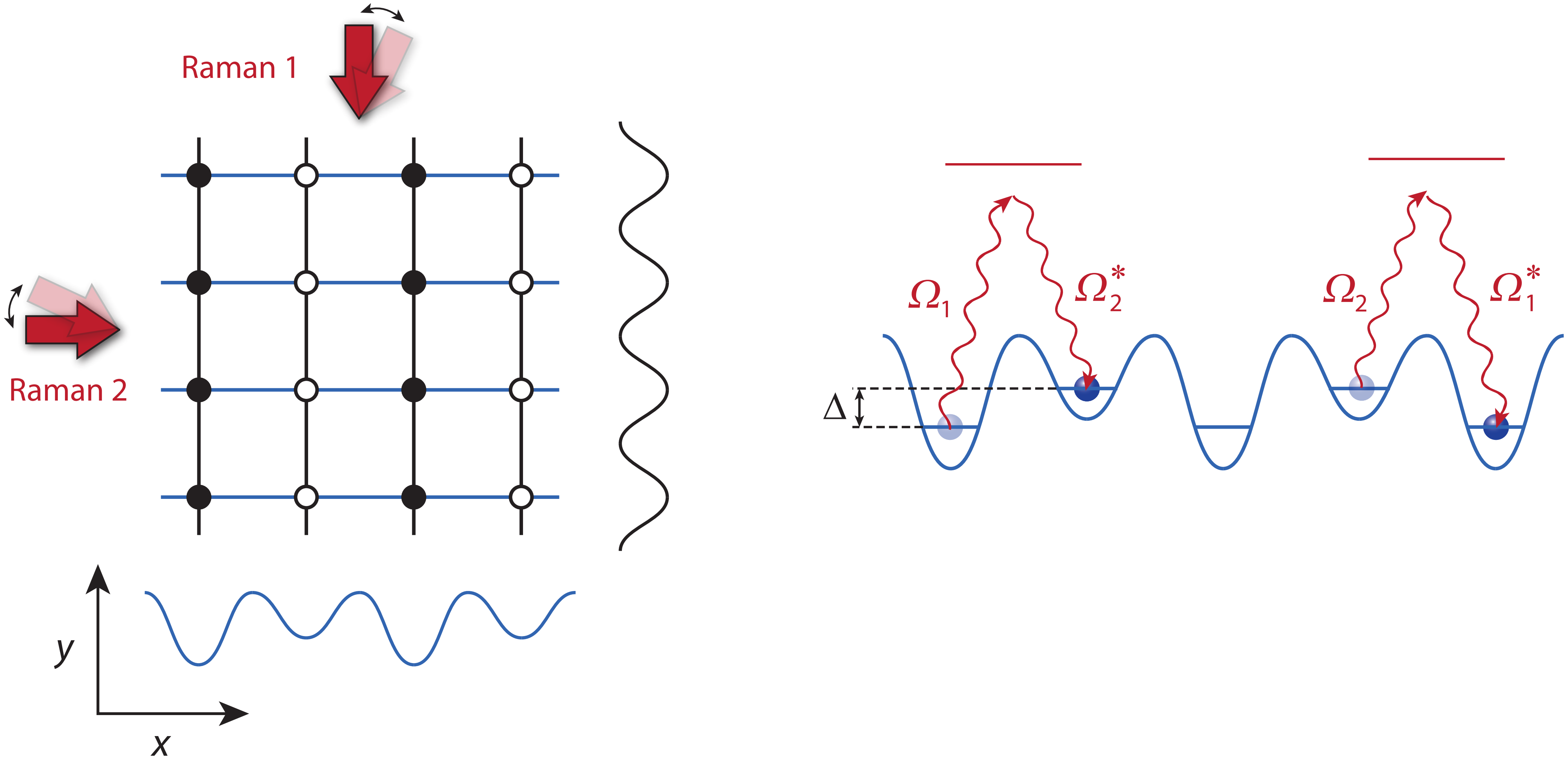
Consider a 2D optical lattice, where tunneling is inhibited along the *x* direction by a superlattice potential



D. Jaksch & P. Zoller, NJP **5**, 56 (2003)
F. Gerbier & J. Dalibard, NJP **12**, 033007 (2010)
A. Kolovsky, Europhys. Lett. **93**, 20003 (2011)

Staggered flux lattice with Rb atoms

Tunneling along this direction can be restored using Raman beams.



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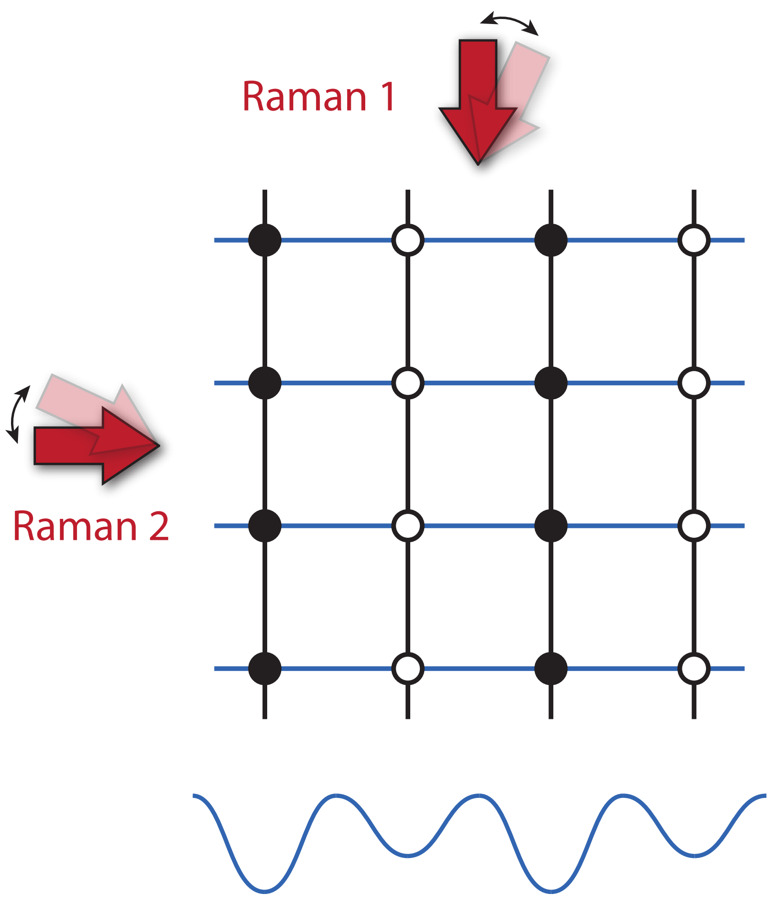

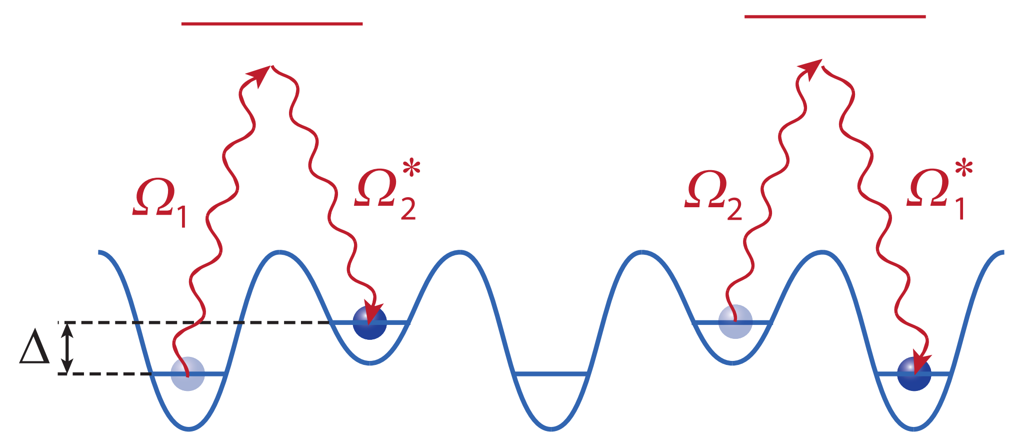

$$\delta\mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$$

$$K_{|\bullet\rangle\to|\circ\rangle}(\mathbf{R}) = \int \mathrm{d}\mathbf{r}\, w^*_{\bullet}(\mathbf{r}-\mathbf{R})\, w_{\circ}(\mathbf{r}-\mathbf{R}-\mathbf{d}_x)\,\Omega(\mathbf{r})$$

$$= K\, e^{i\delta\mathbf{k}\cdot\mathbf{R}} \quad \text{for} \quad \Omega(\mathbf{r}) = V_K\, e^{i\delta\mathbf{k}\cdot\mathbf{r}}$$

D. Jaksch & P. Zoller, NJP **5**, 56 (2003)
F. Gerbier & J. Dalibard, NJP **12**, 033007 (2010)
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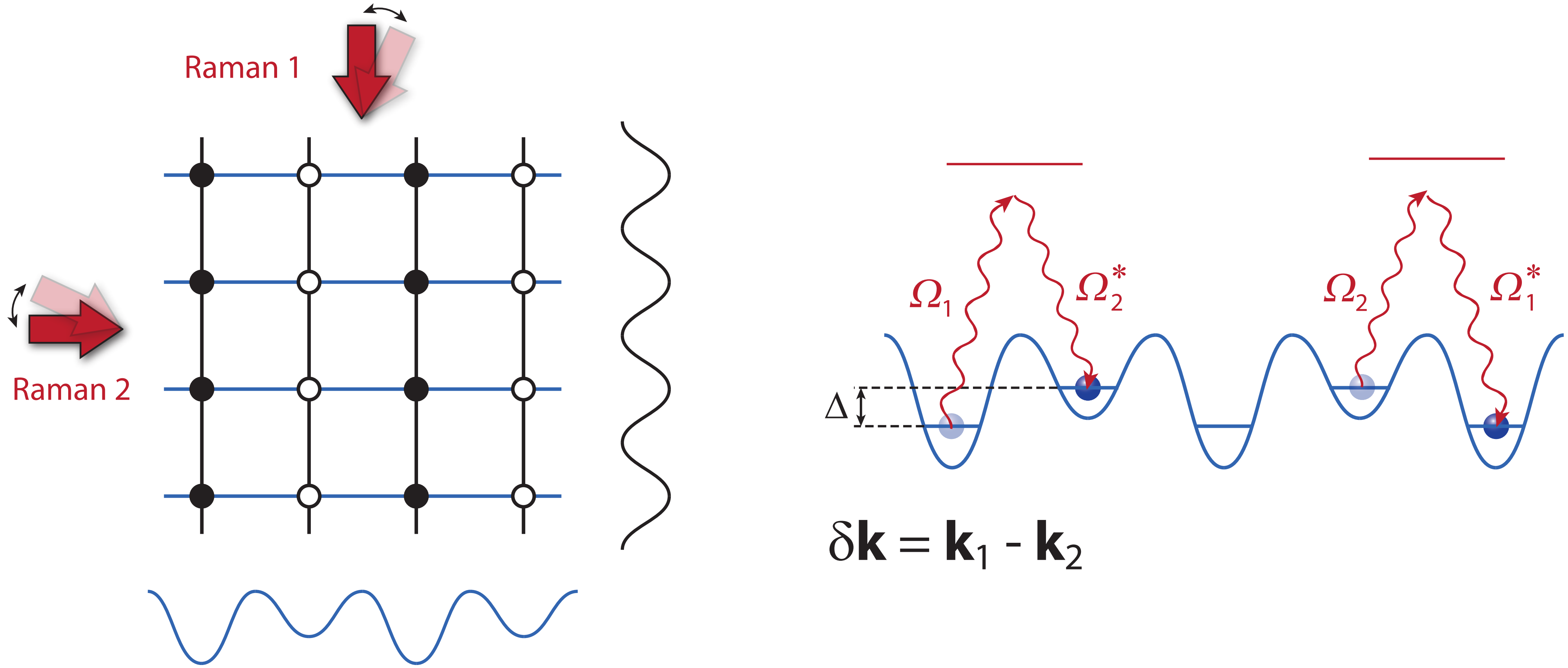

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$$K_{|\circ\rangle\to|\bullet\rangle}(\mathbf{R}') = K\, e^{-i\delta\mathbf{k}\cdot\mathbf{R}'}$$

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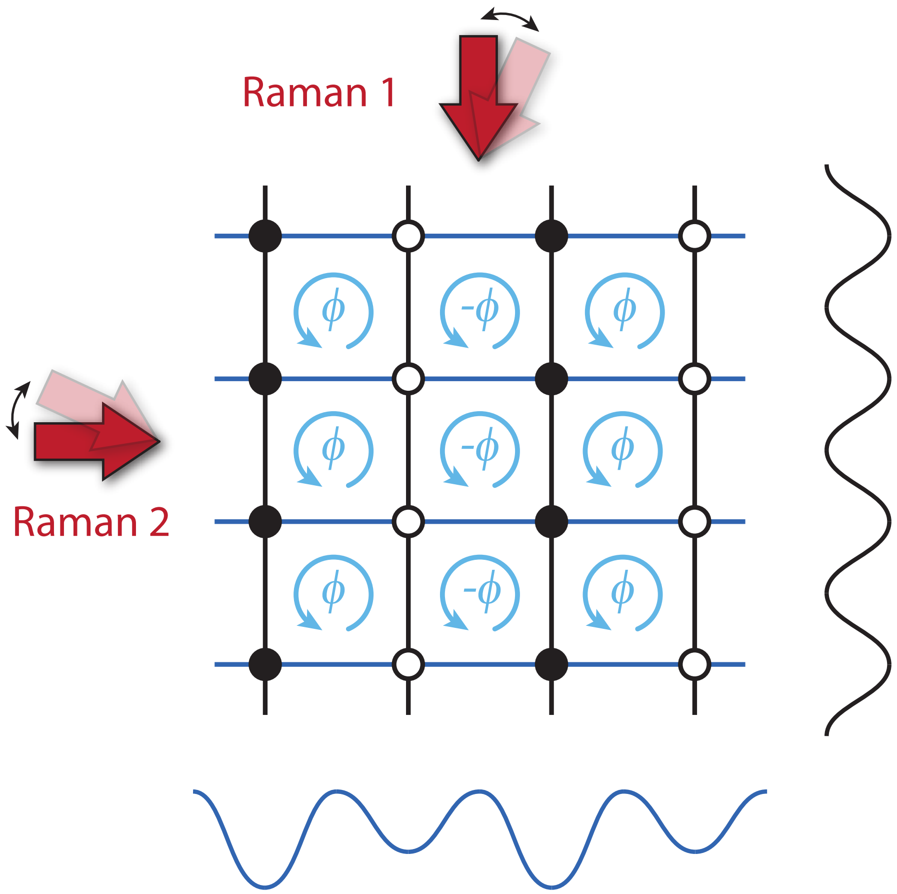

- → Staggered flux ϕ with zero mean
- → Tunable flux value, $\delta\mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$ (our setup: $\phi = \pi/2$)

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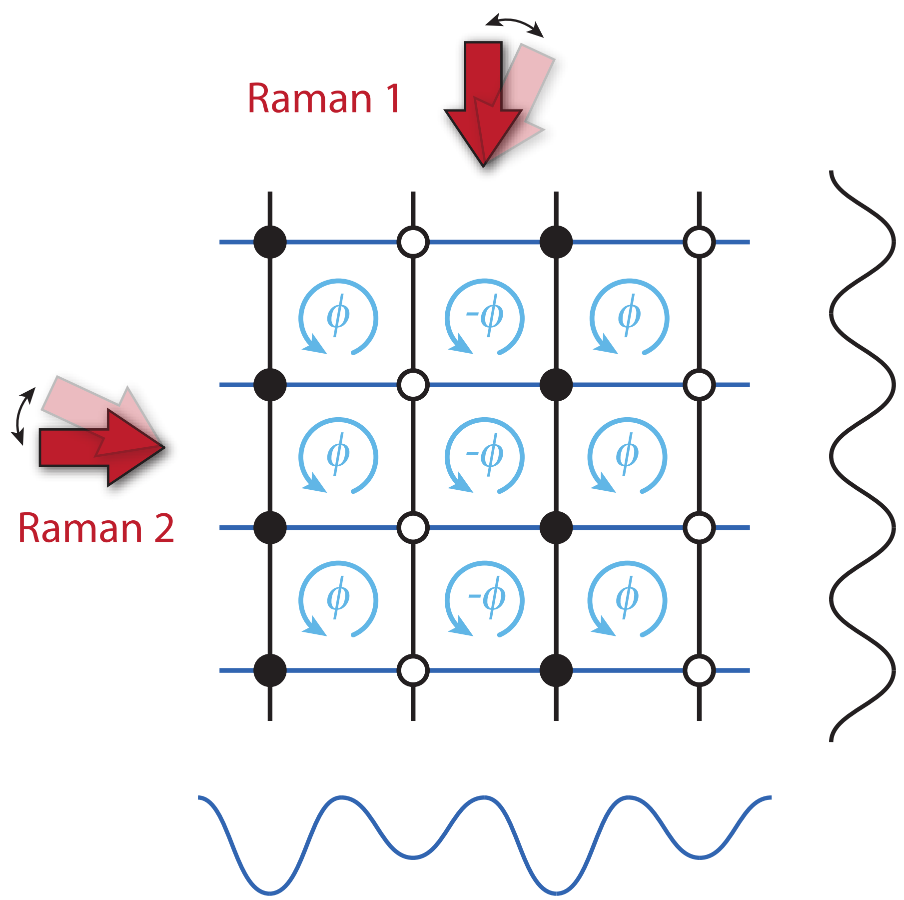

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$$K_{|\bullet\rangle\to|\circ\rangle}(\mathbf{R}) = K\, e^{i\delta\mathbf{k}\cdot\mathbf{R}}, \quad K_{|\circ\rangle\to|\bullet\rangle}(\mathbf{R}') = K\, e^{-i\delta\mathbf{k}\cdot\mathbf{R}'}$$

Methods to rectify the flux:

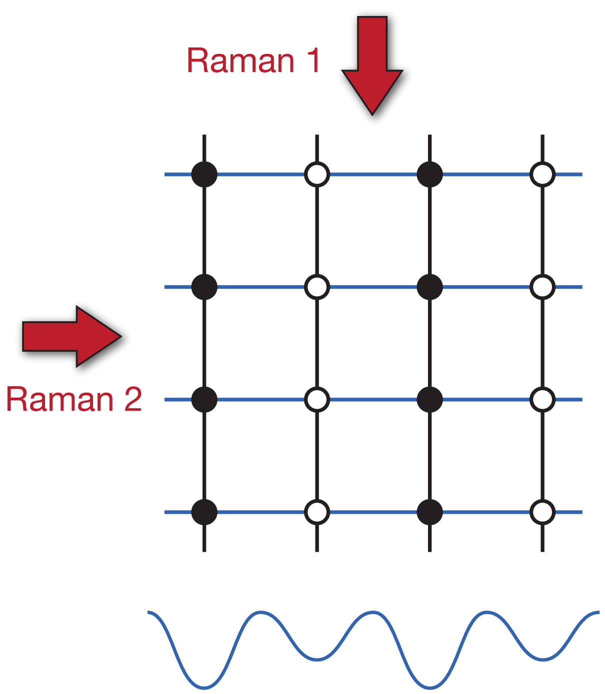
- Linear potential gradient
- State-dependent lattices

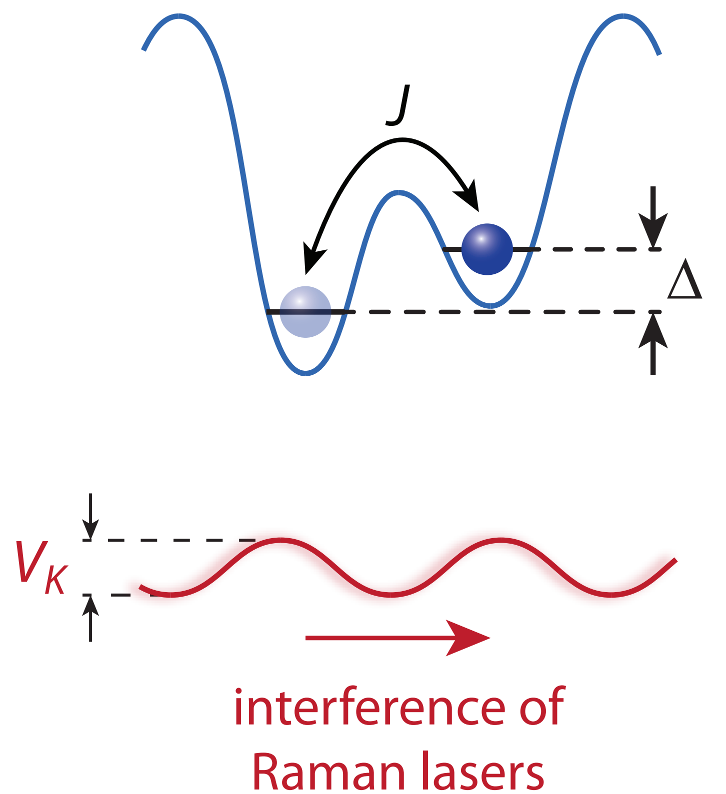
D. Jaksch & P. Zoller, NJP **5**, 56 (2003)
F. Gerbier & J. Dalibard, NJP **12**, 033007 (2010)
A. Kolovsky, Europhys. Lett. **93**, 20003 (2011)

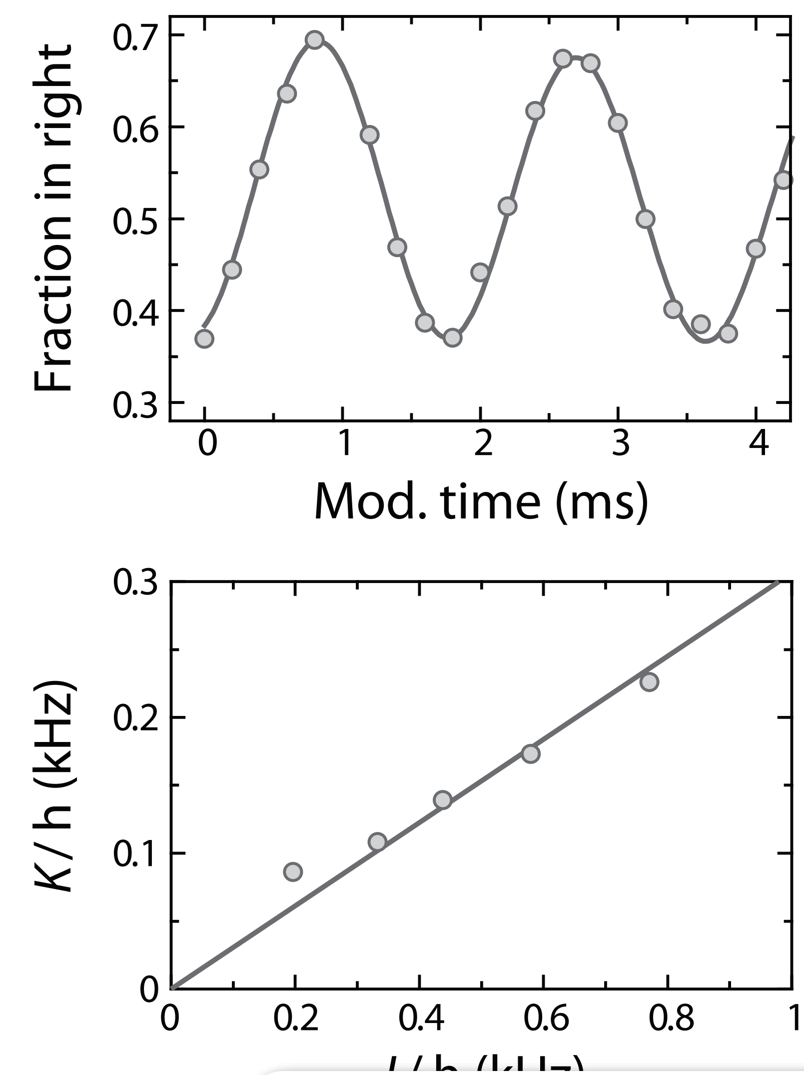
Raman-assisted tunneling

In the limit of $\mathbf{V}_K \ll \Delta$ the amplitude of the Raman-assisted tunneling is given by:

$$K \simeq \frac{1}{2\sqrt{2}} \frac{V_K J}{\Delta}$$

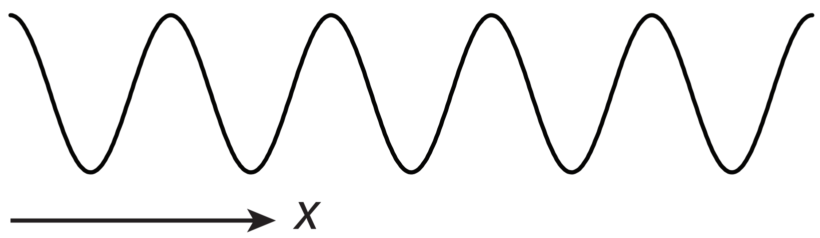






Experimental sequence

❖ We load a ^{87}Rb condensate into a 2D-optical lattice.



$J = 2\pi \times 60(3)$ Hz

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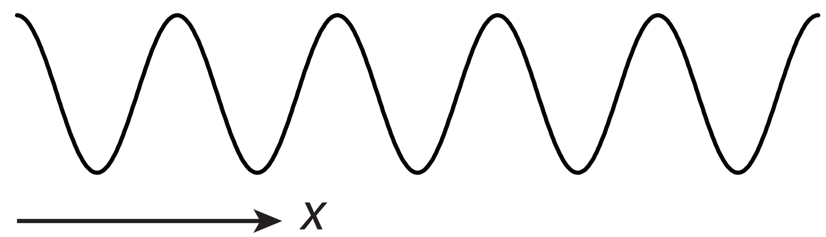

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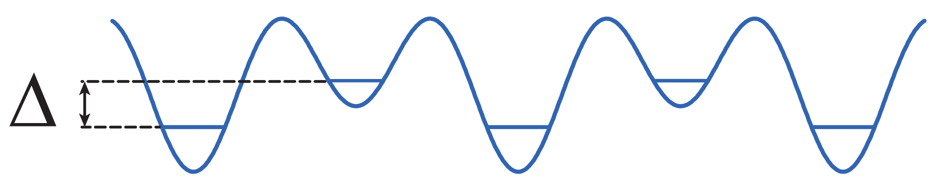
❖ We inhibit tunneling along *x* with a superlattice.



$\Delta = 2\pi \times 4.4(1)$ kHz

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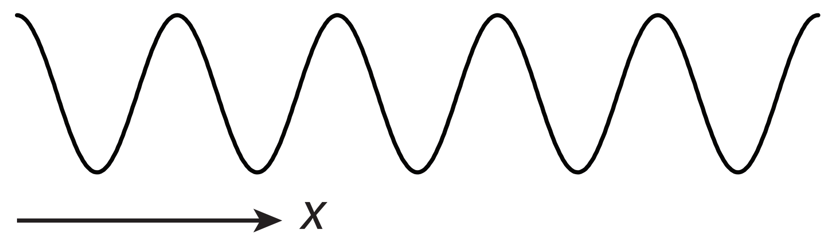

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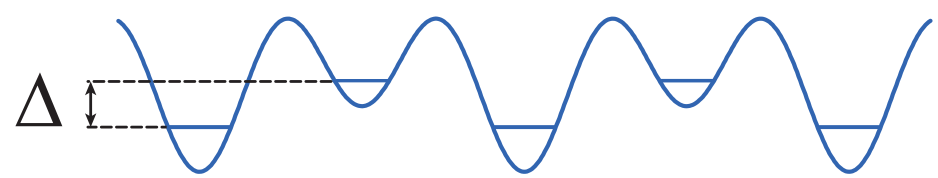
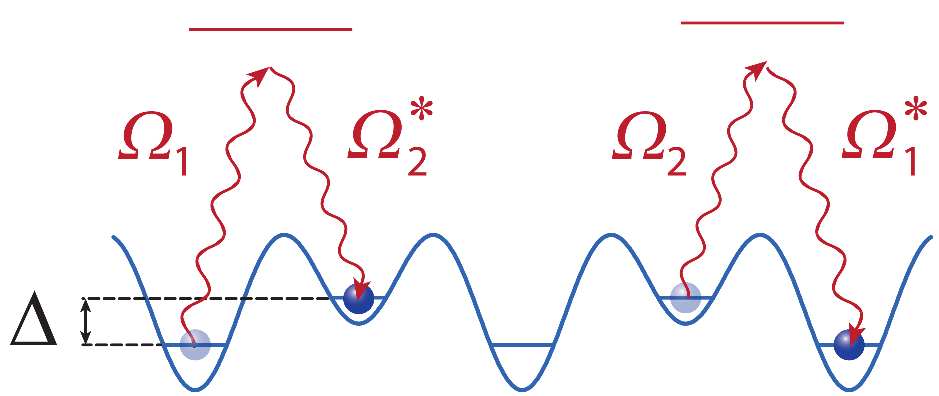


$\Delta = 2\pi \times 4.4(1)$ kHz

❖ We switch on Raman lasers on resonance to induce tunneling.



$K = 2\pi \times 59(2)$ Hz

Experimental sequence

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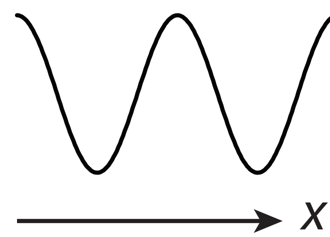

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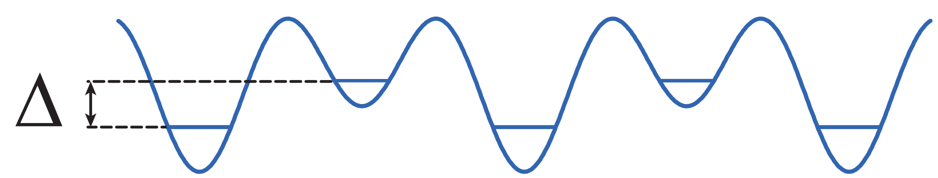

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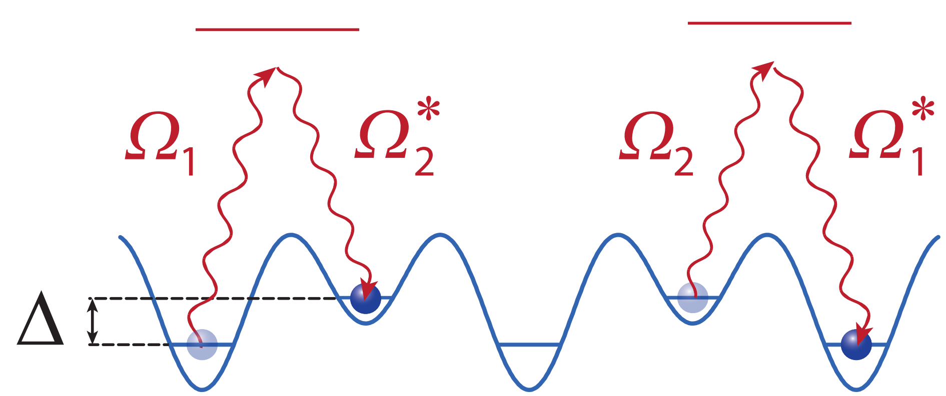
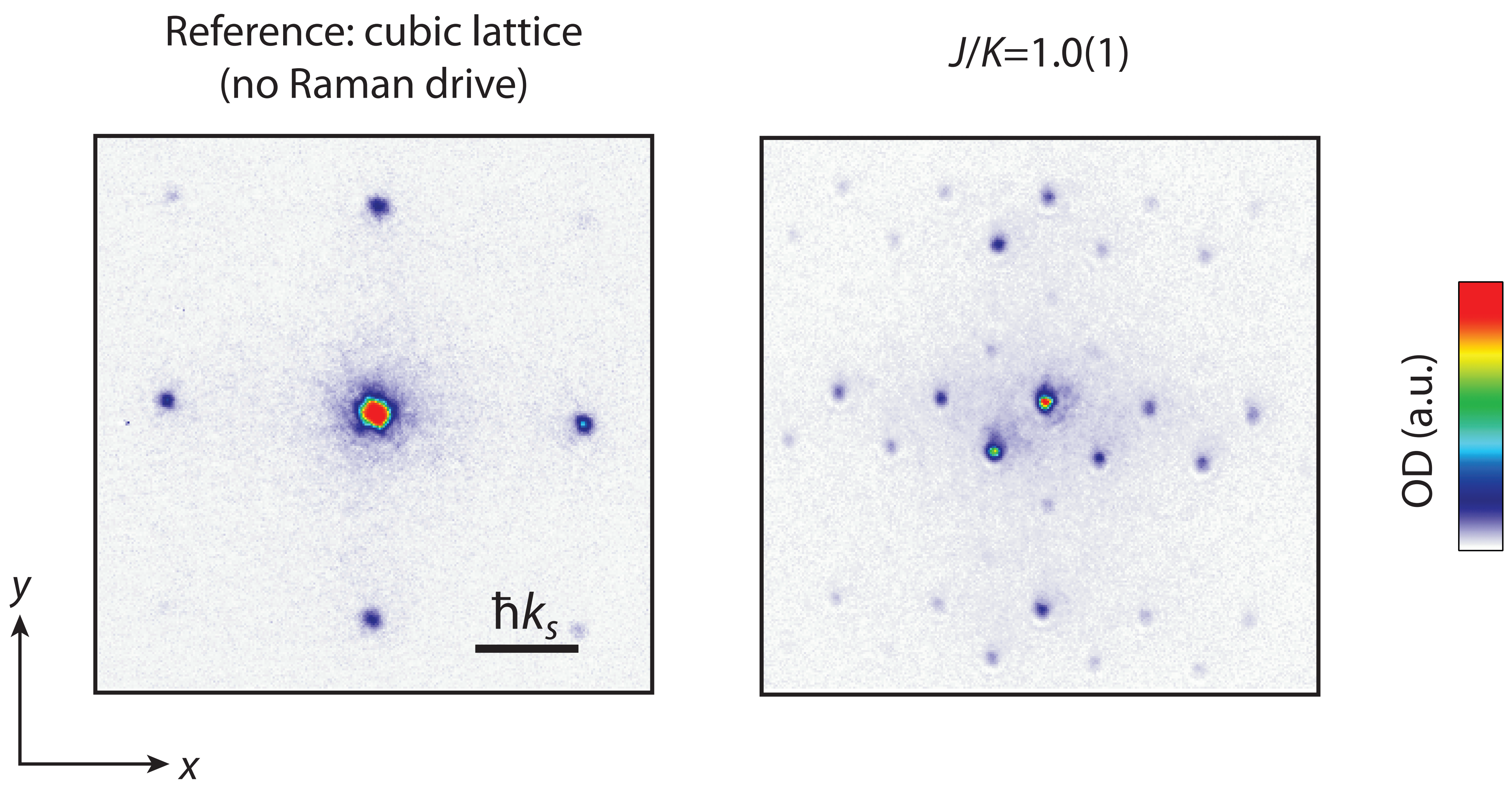


$K = 2\pi$ x 59(2) Hz

❖ After 10 ms hold time, TOF images.

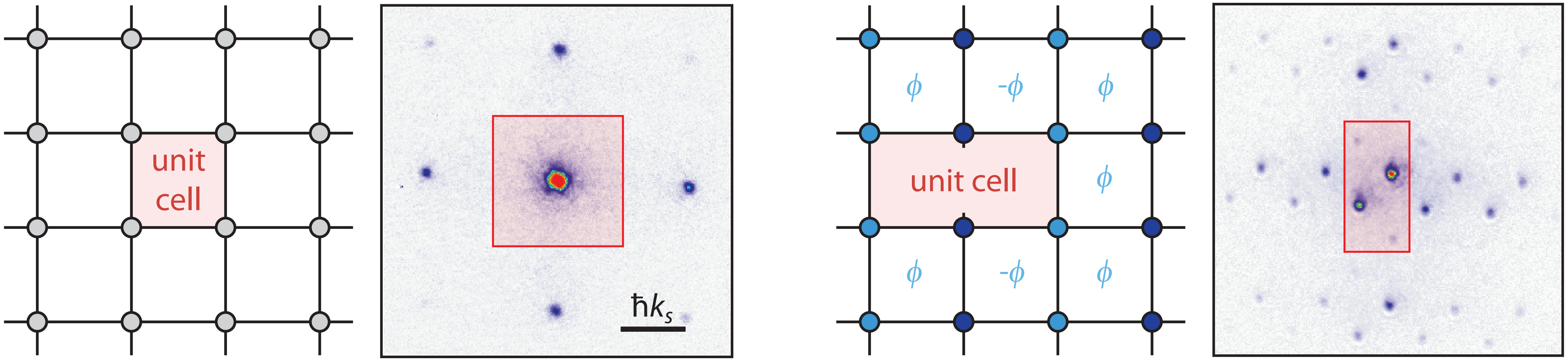
Momentum distribution (J/K=1): observations



Due to the frustration introduced by the phase factors in $K(\mathbf{R})$, the condensation occurs for non-zero momenta.

Band structure

- 'Magnetic' Brillouin zone



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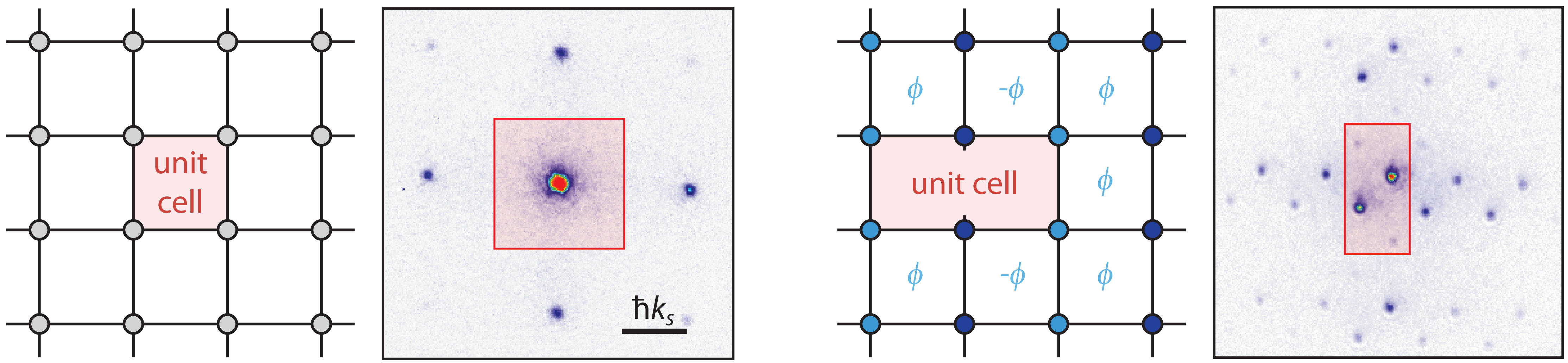

- Single-particle spectrum in the tight-binding approximation
  From the magnetic translation symmetries:

$$\psi_{|k_x,k_y\rangle}(\mathbf{R} = m\,\mathbf{d_x} + n\,\mathbf{d_y}) = \mathrm{e}^{i(m\cdot k_x d_x + n\cdot k_y d_y)} \times \begin{cases} \psi_e & m \text{ even} \\ \psi_o\ \mathrm{e}^{i\frac{\pi}{2}(m+n)} & m \text{ odd} \end{cases} ,$$

Band structure

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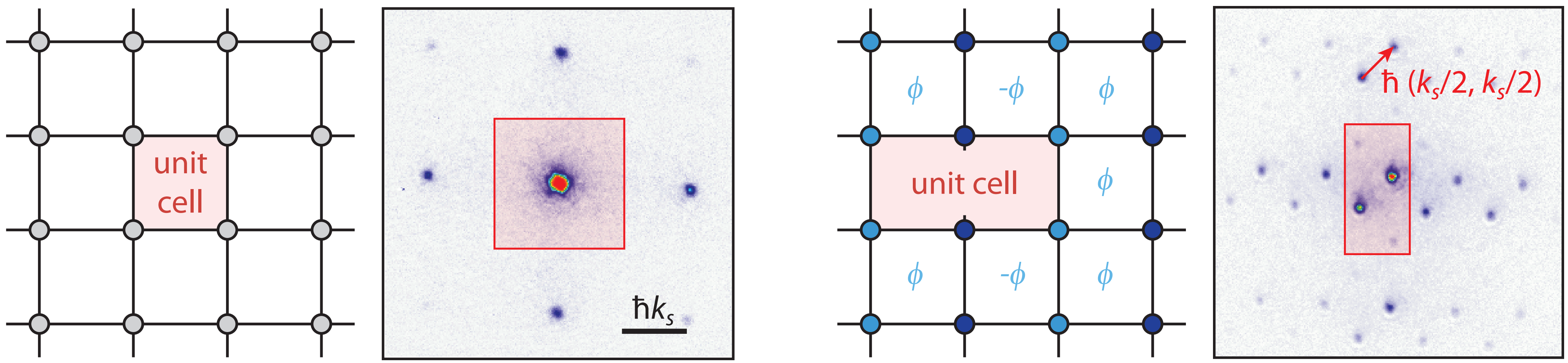

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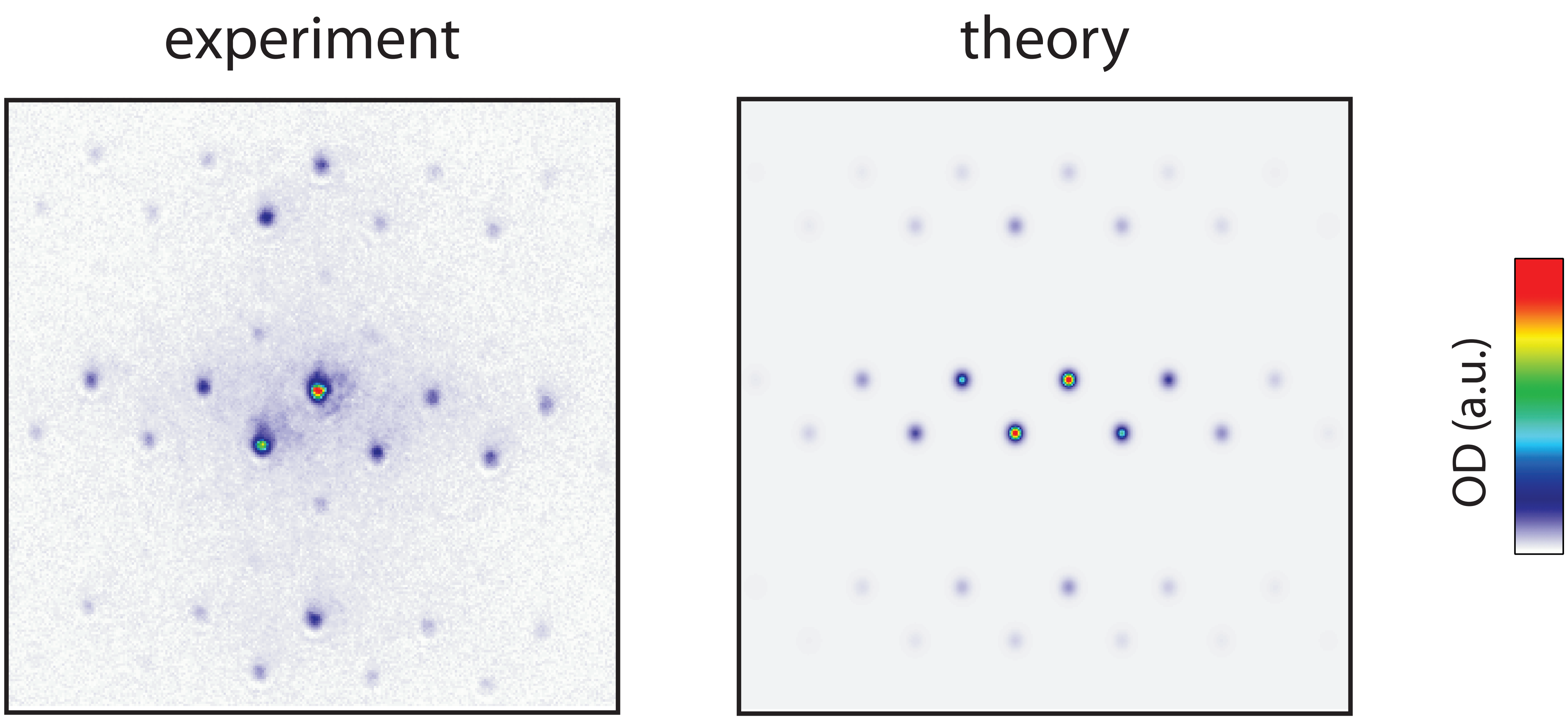
$$\psi_{|k_x,k_y\rangle}(\mathbf{R} = m\,\mathbf{d_x} + n\,\mathbf{d_y}) = \mathrm{e}^{i(m\cdot k_x d_x + n\cdot k_y d_y)} \times \begin{cases} \psi_e & m \text{ even} \\ \psi_o\ \mathrm{e}^{i\frac{\pi}{2}(m+n)} & m \text{ odd} \end{cases},$$

An eigenstate $|k_x, k_y\rangle$ has two momentum components at

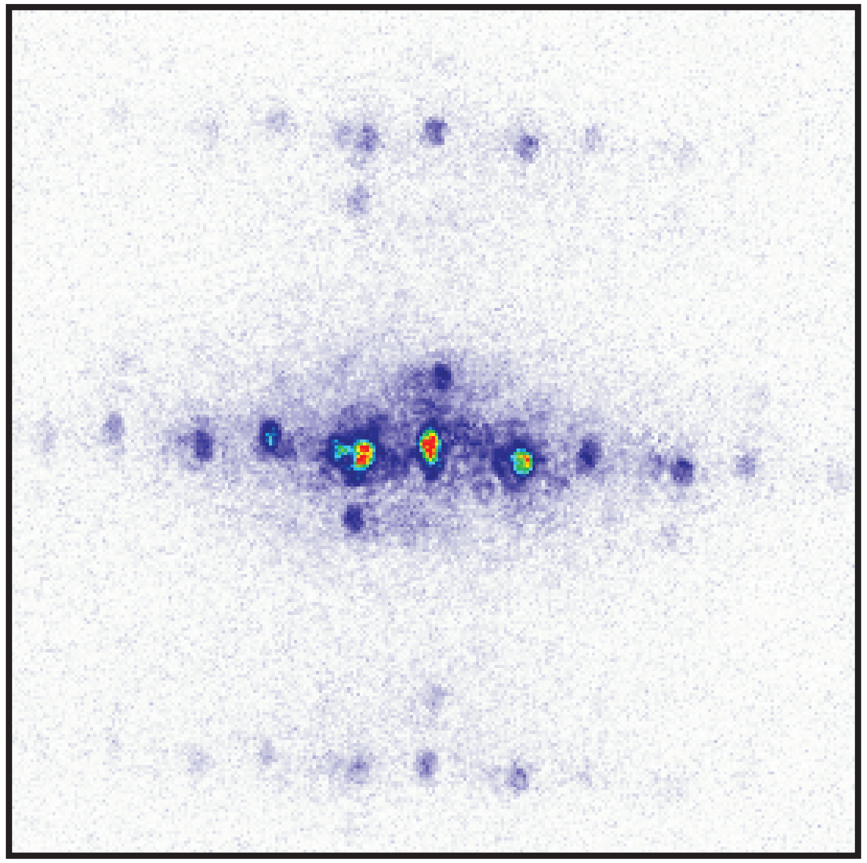
(k_x, k_y) and $(k_x, k_y) + (k_s/2, k_s/2)$

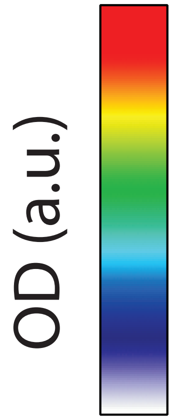
Momentum distribution (J/K=1): comparison with theory



Momentum distribution (J/K=2.5)

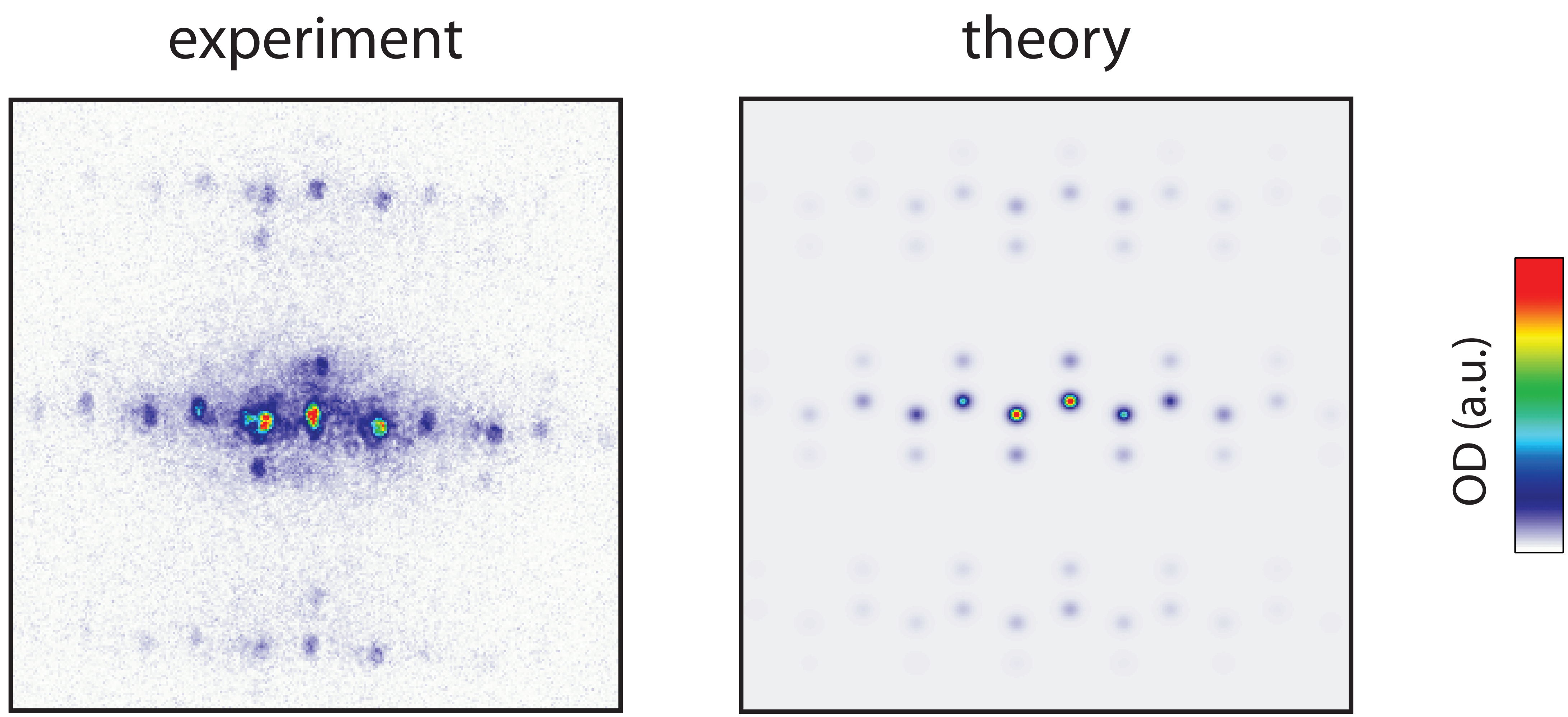
experiment





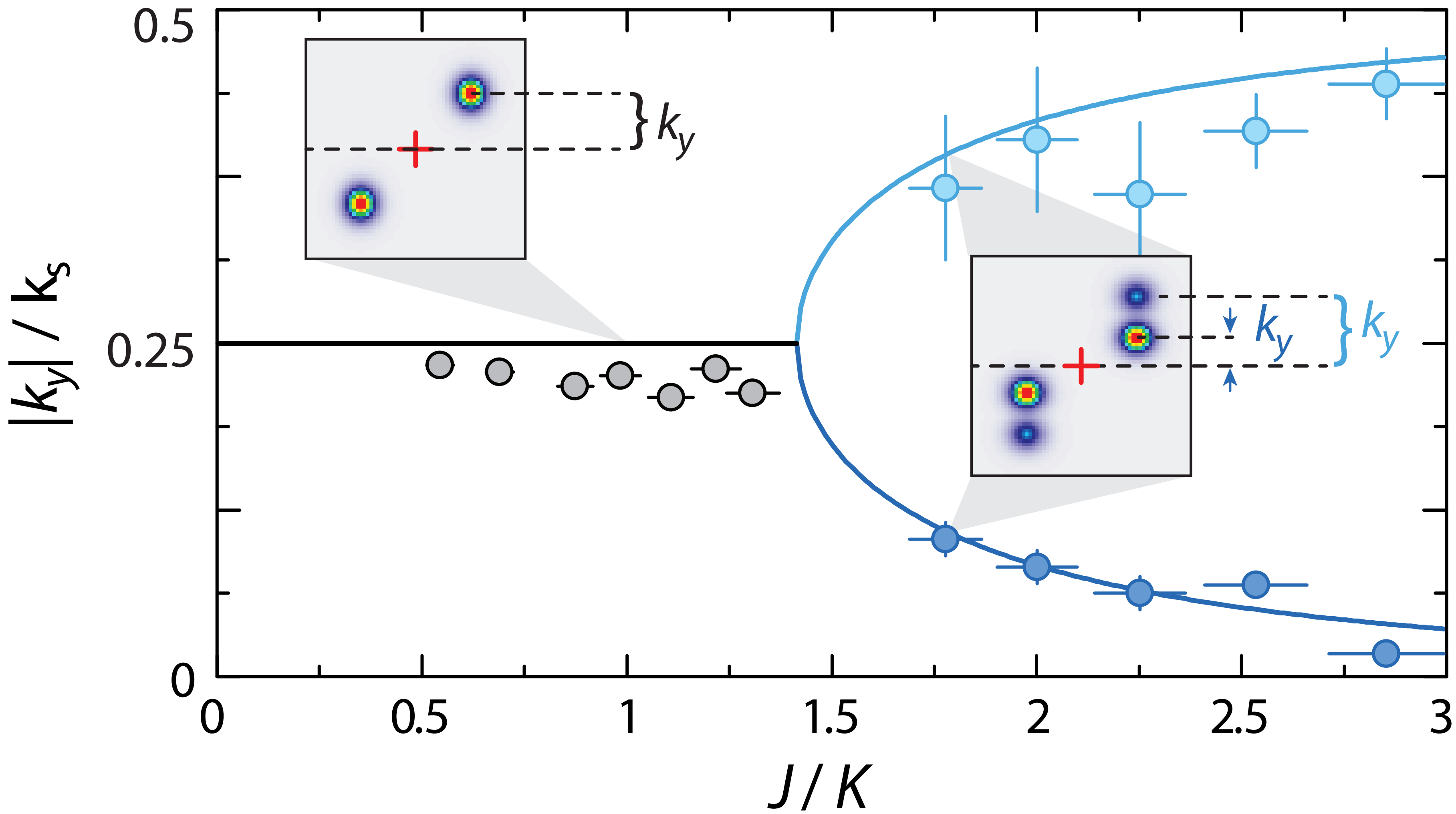
The diffraction peaks are splitted ⟶ two-fold ground state degeneracy

Momentum distribution (J/K=2.5)



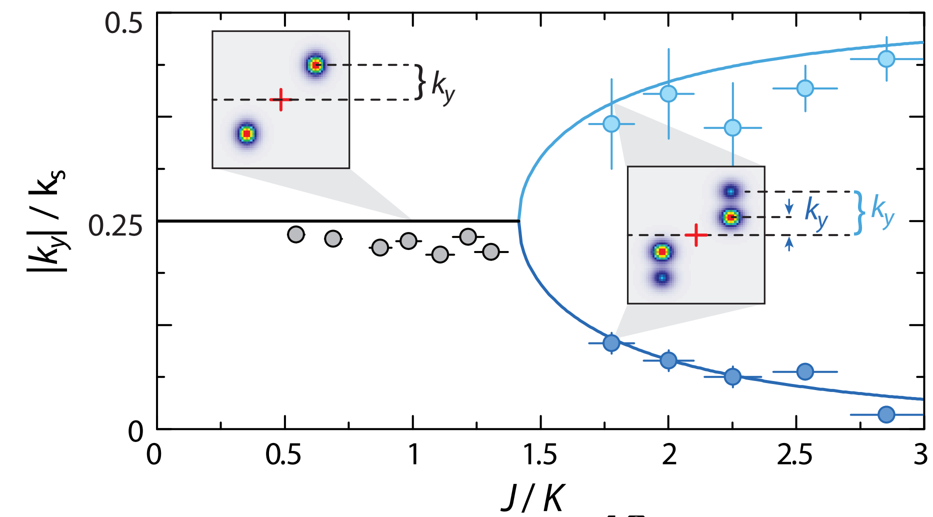
The diffraction peaks are splitted ⟶ two-fold ground state degeneracy

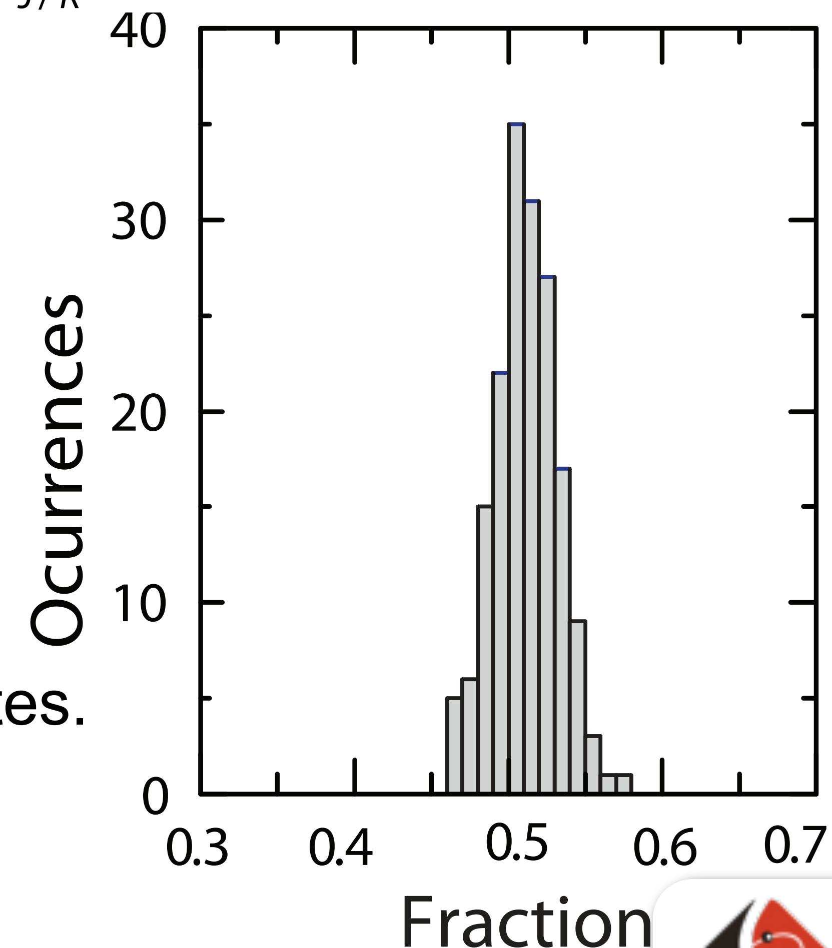
Momenta of the two degenerate ground states



G. Moeller, N. Cooper, PRA **82**, 1 (2010)
J. Struck *et al.*, Science **333**, 996 (2011)

Momenta of the two degenerate ground states



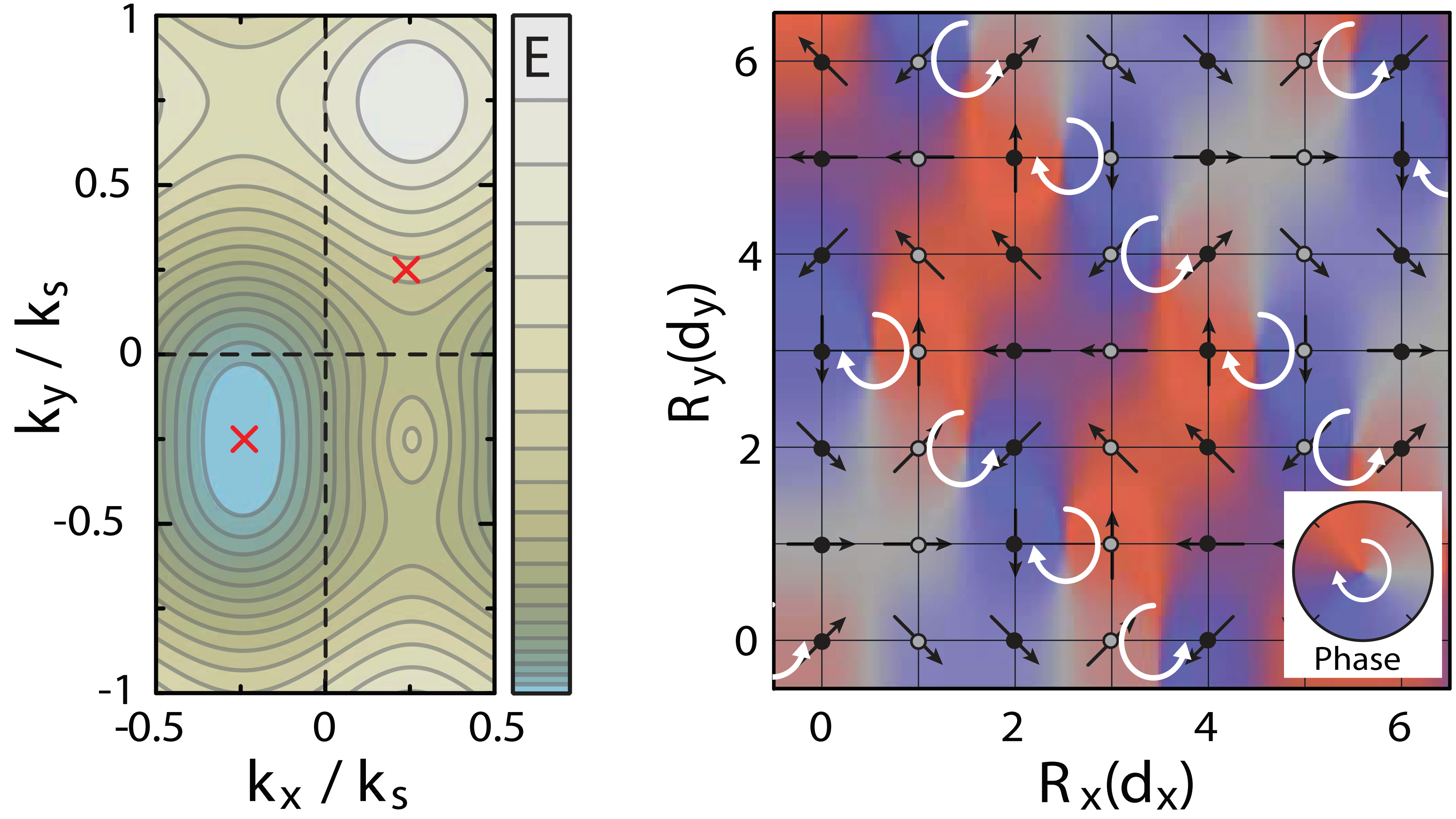


In the case of ground state degeneracy,
we observe an equal population of both states.

G. Moeller, N. Cooper, PRA **82**, 1 (2010)
J. Struck *et al.*, Science **333**, 996 (2011)

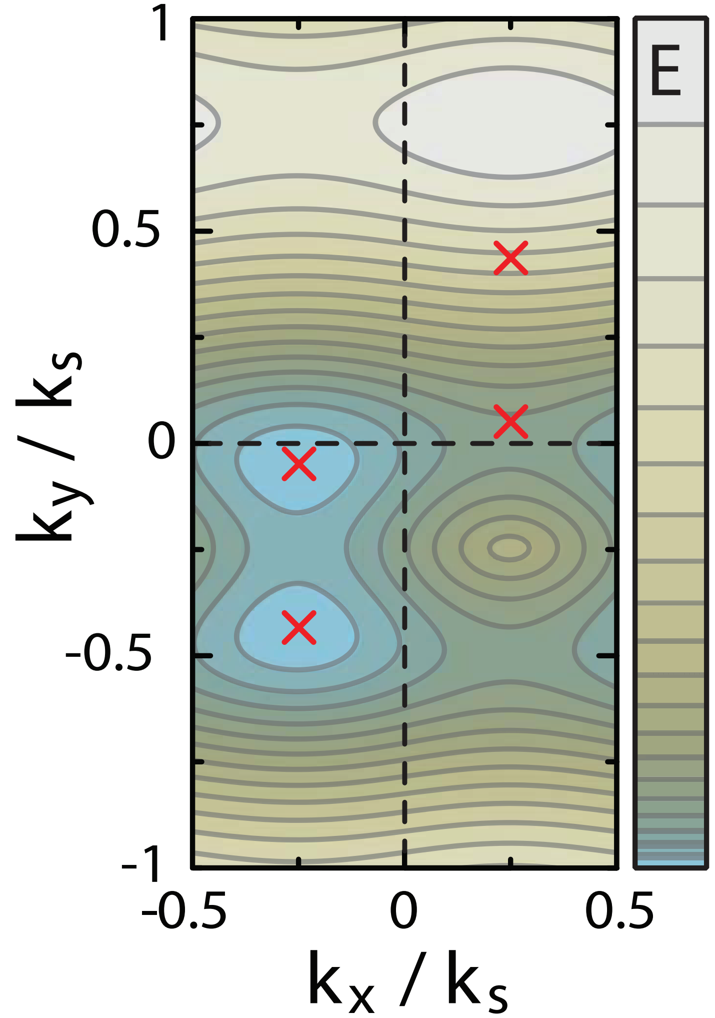
Dispersion relation and spatial phase distribution

J = K

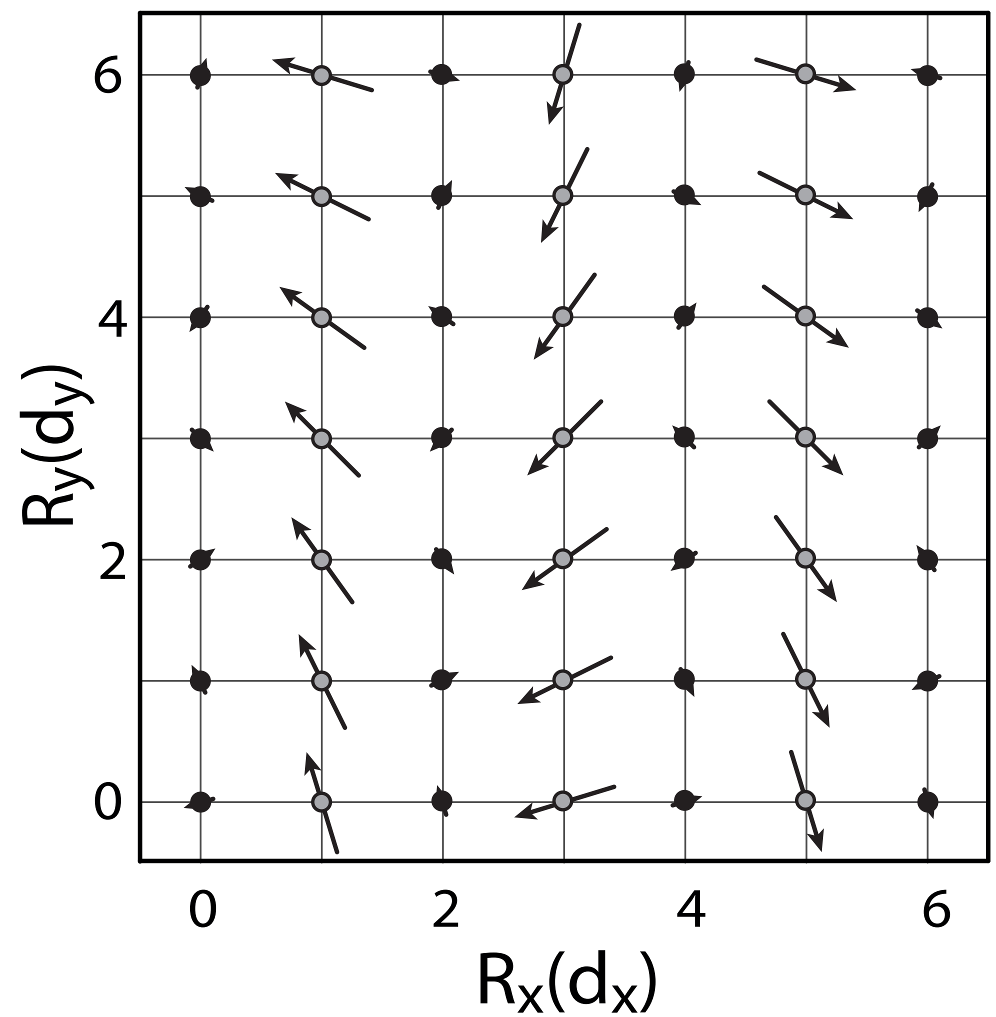


Dispersion relation and spatial phase distribution

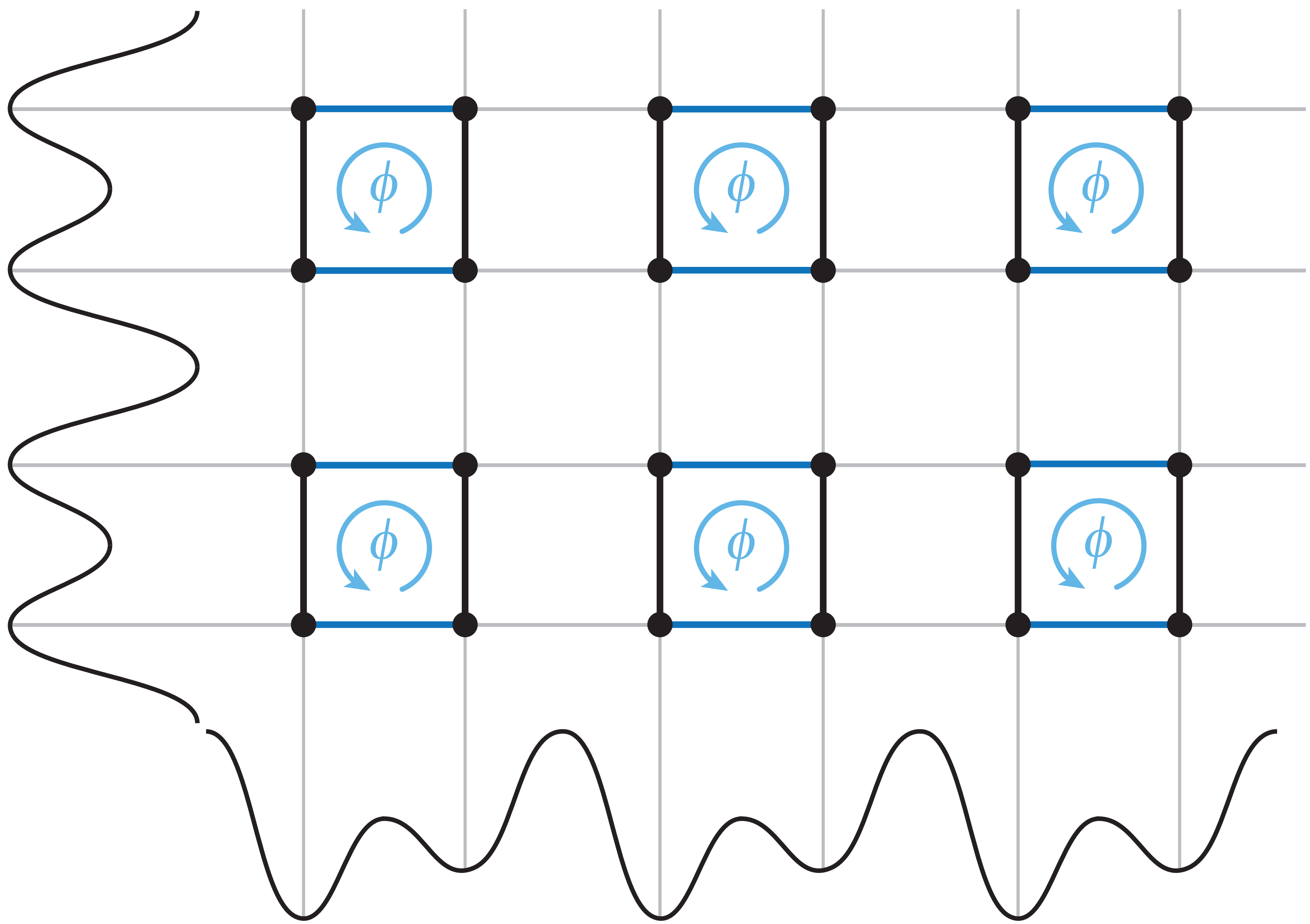
J=2.5 K



Striped density pattern



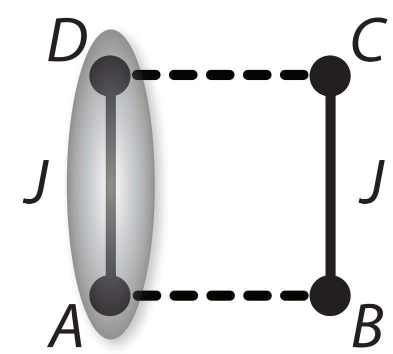
A lattice of plaquettes

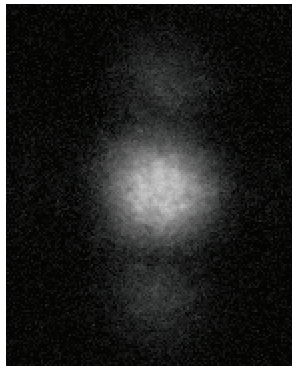


State preparation for phase imprinting

- Load single atoms into ground state of tilted plaquettes:

$$|\psi_0\rangle = \frac{|A\rangle + |D\rangle}{\sqrt{2}}$$





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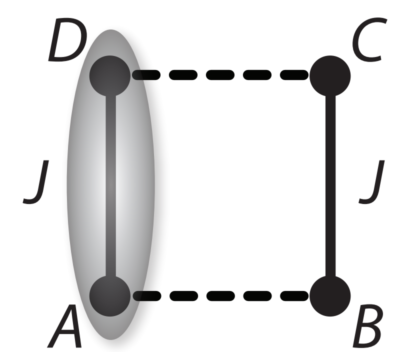

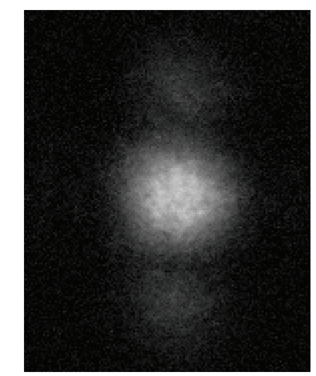

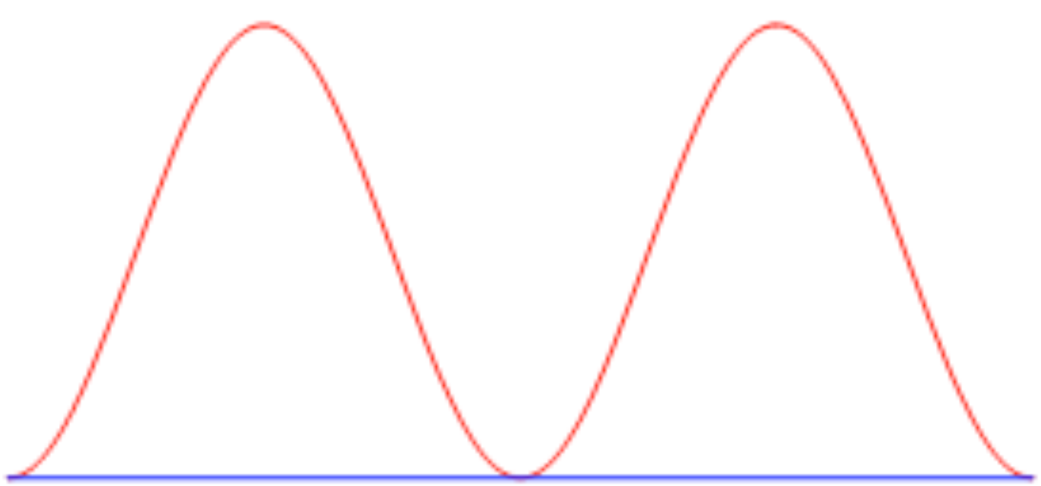

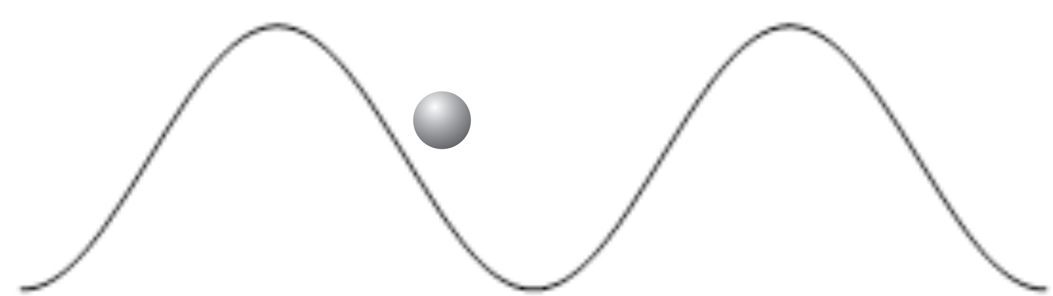

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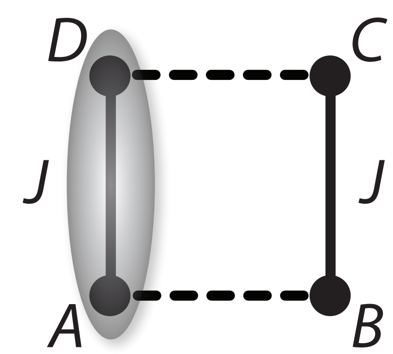
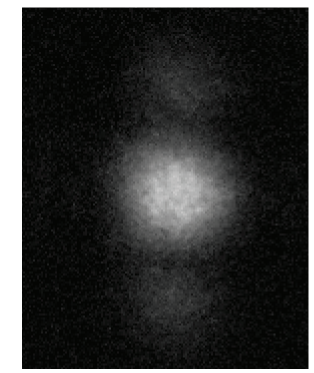
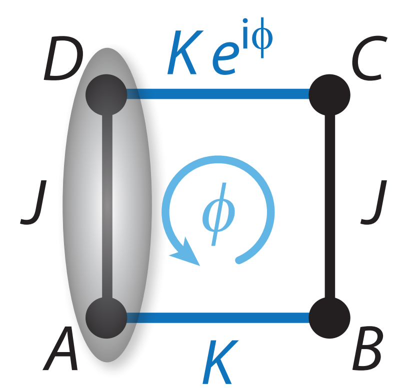




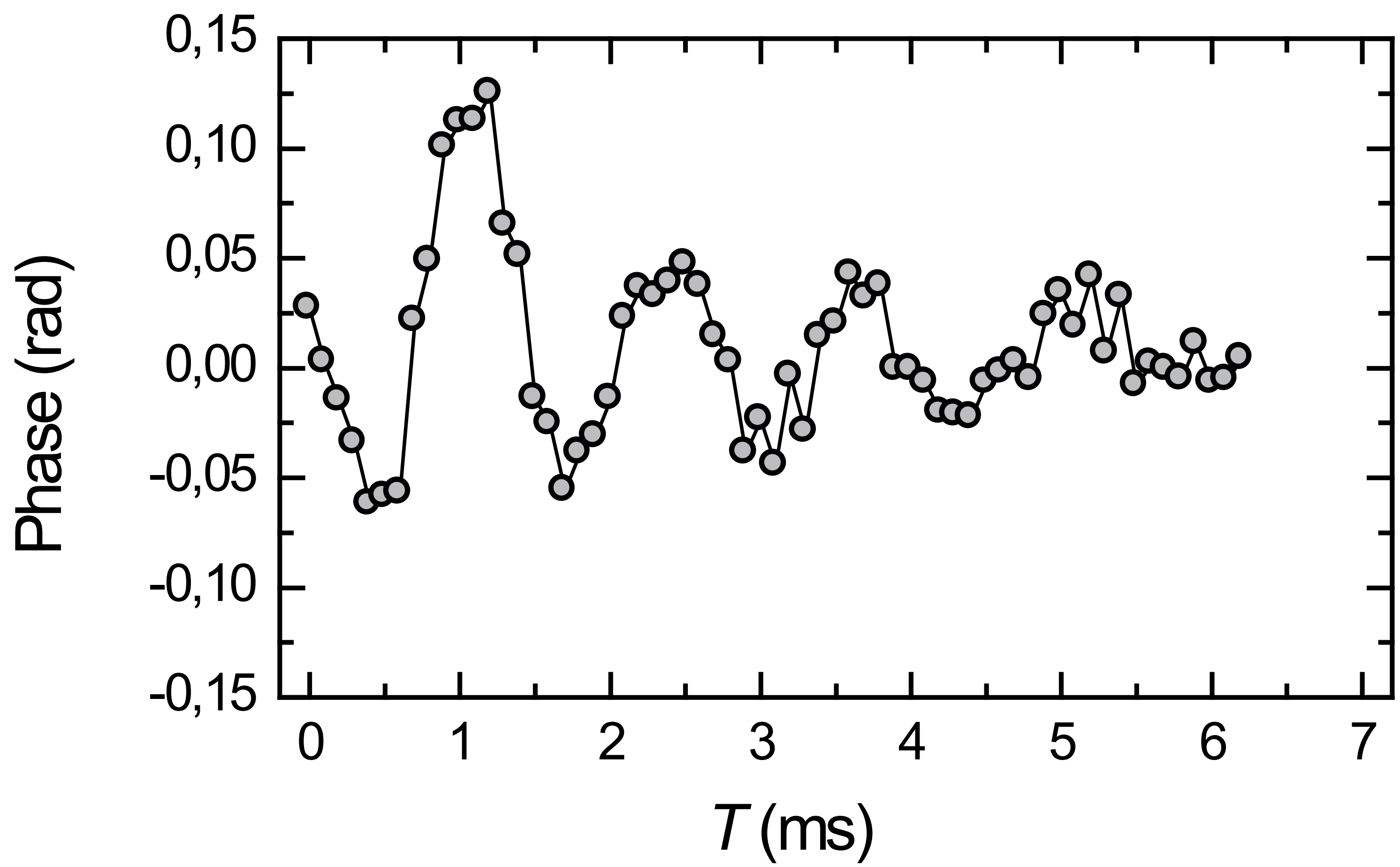
- Switch on Raman coupling to induce atom transfer to the *B*, *C* sites
  In the limit *J*<<*K* the state is coupled to

$$|\psi_1\rangle = \frac{|B\rangle + i|C\rangle}{\sqrt{2}}$$

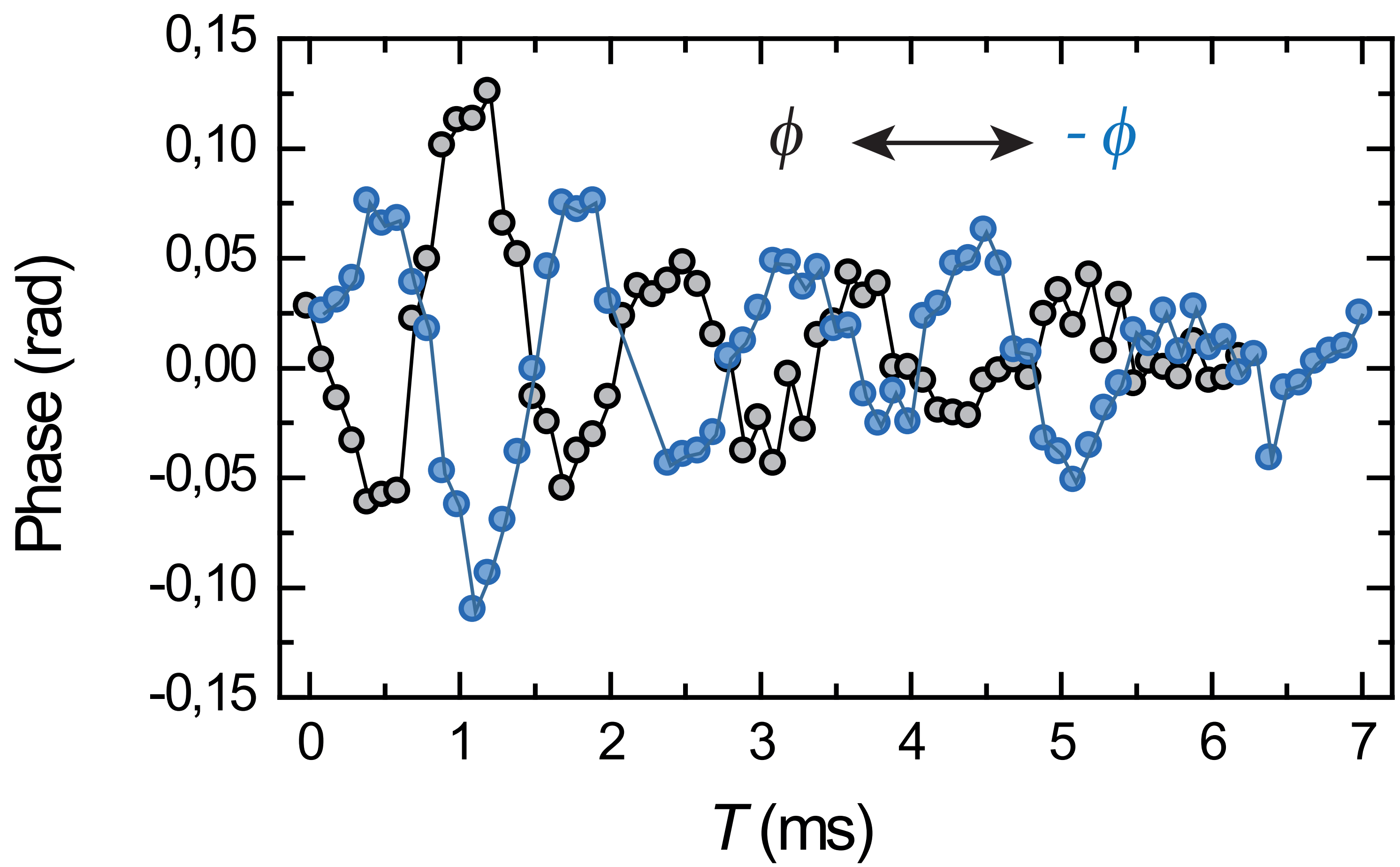


Non-trivial phase evolution

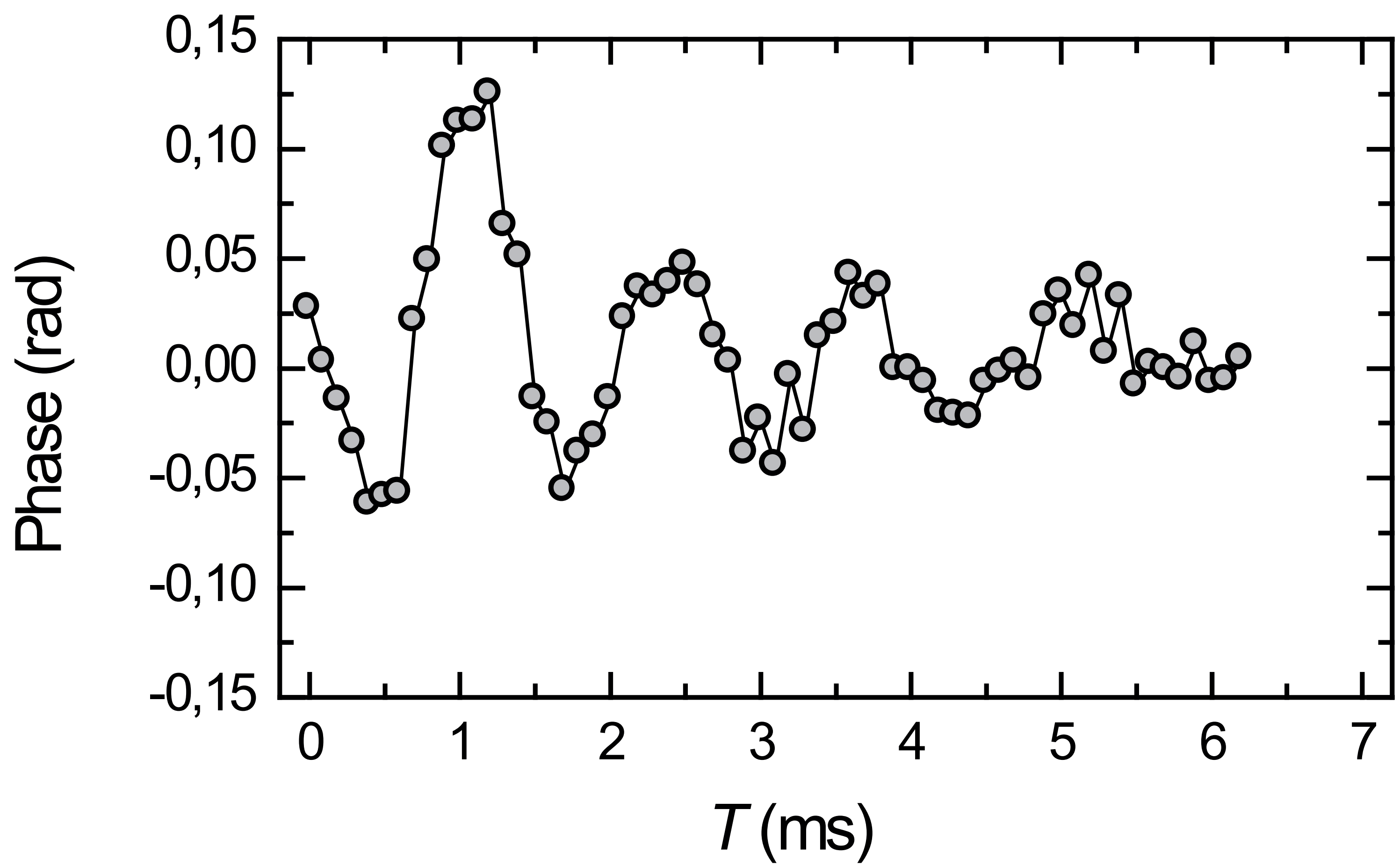
Observation of phase-imprinting

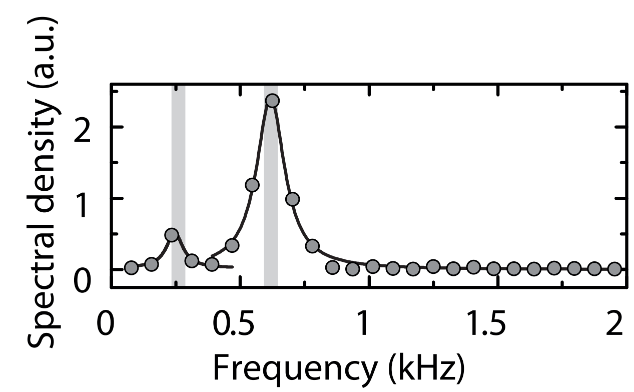


Observation of phase-imprinting



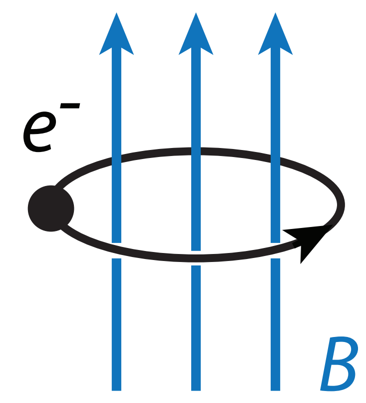
Observation of phase-imprinting





Quantum `Cyclotron' Orbit

- Classical:
  Charged particle in
  a uniform magnetic field



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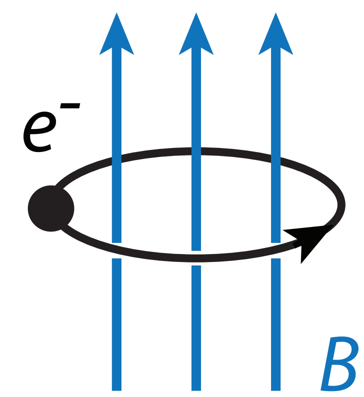
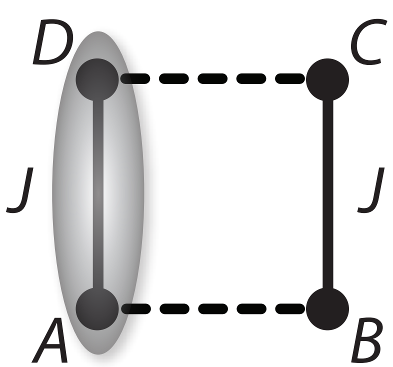


- Measure quantum analogue:
  Initial state:
  Single atom in ground
  state of tilted plaquette



$$|\psi_0\rangle = \frac{|A\rangle + |D\rangle}{\sqrt{2}}$$

Quantum `Cyclotron' Orbit

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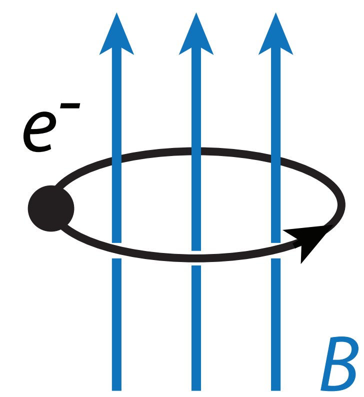

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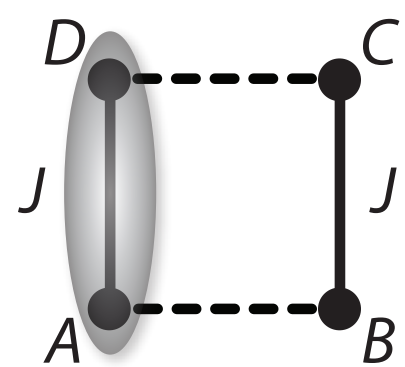

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Switch on Raman coupling to
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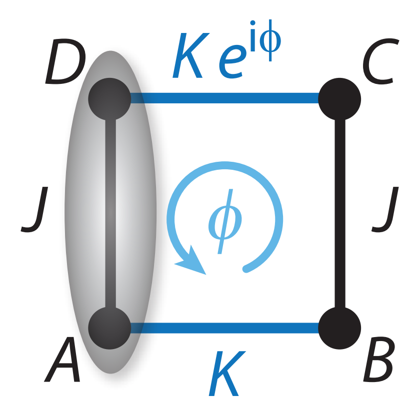
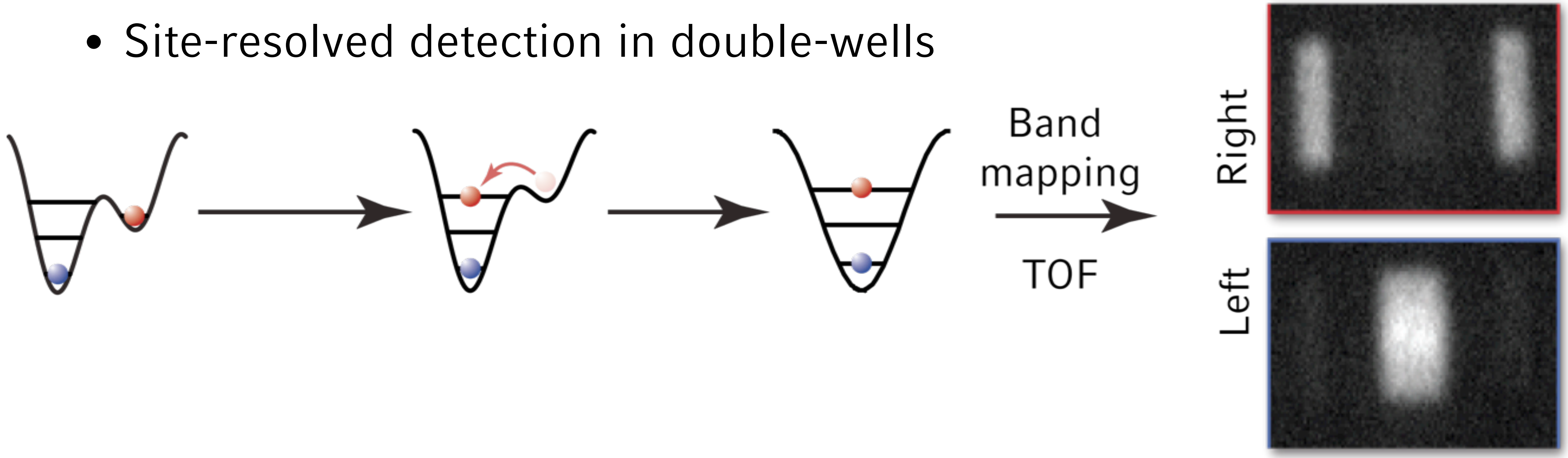


Site-resolved detection

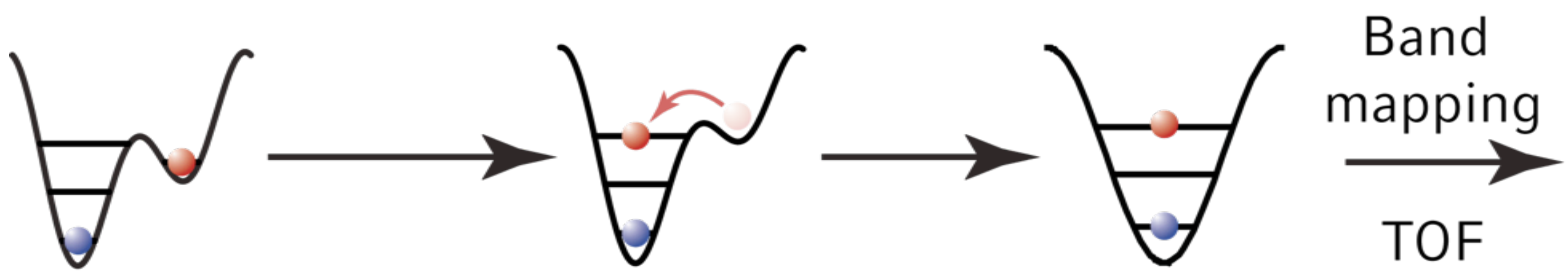
Site-resolved detection

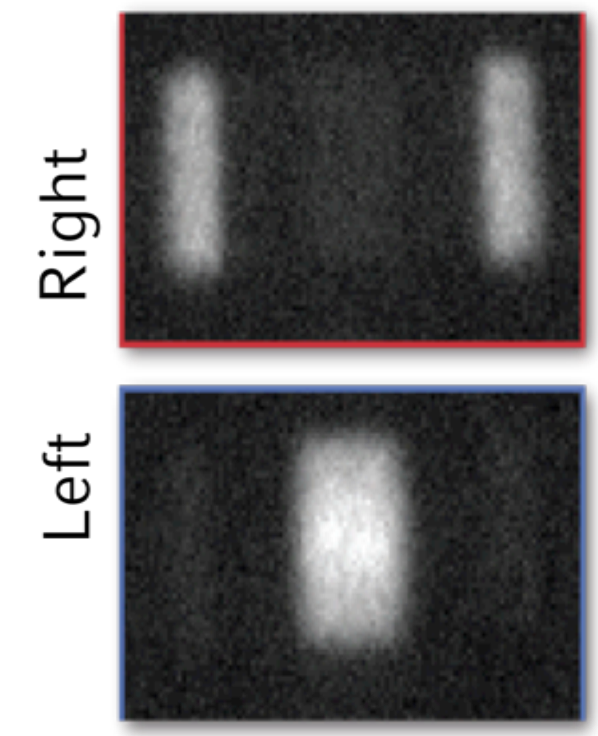
- Site-resolved detection in double-wells



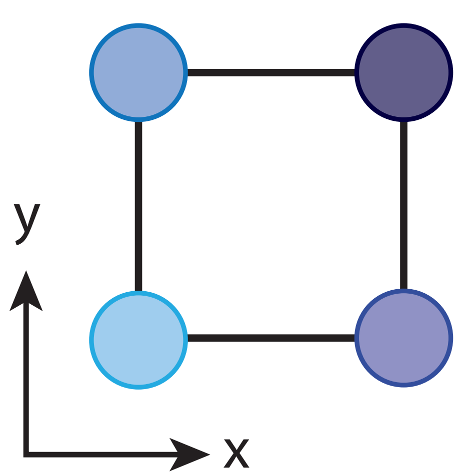
Site-resolved detection

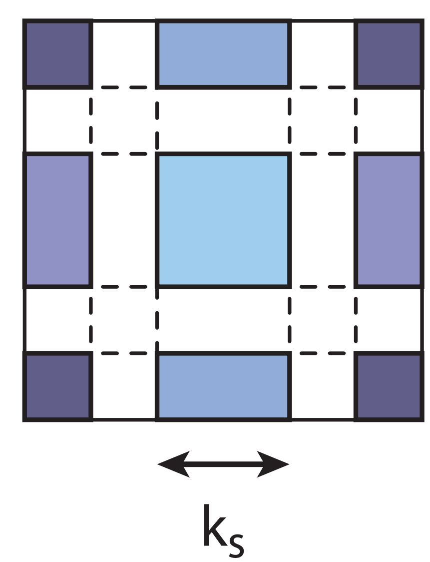
- Site-resolved detection in double-wells

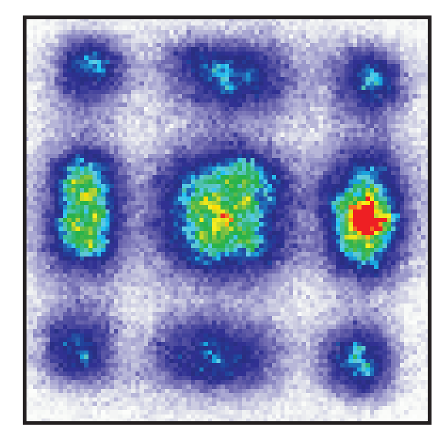




- Generalization to a lattice of plaquettes







Site-resolved detection

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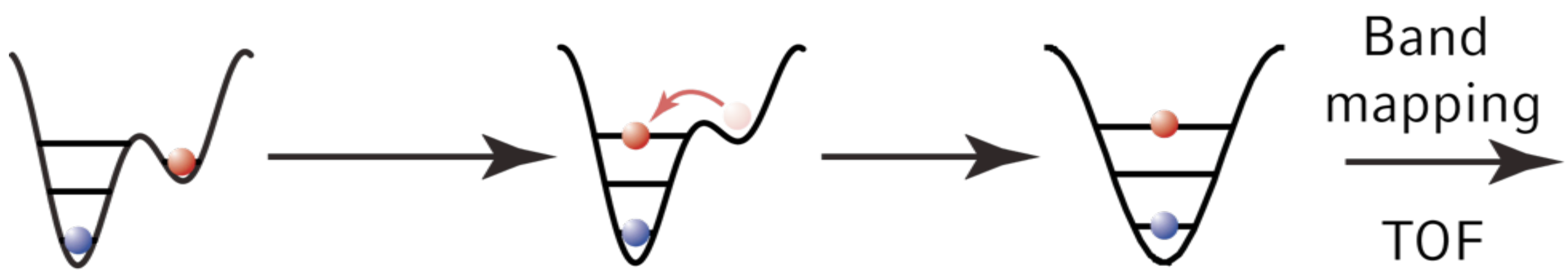

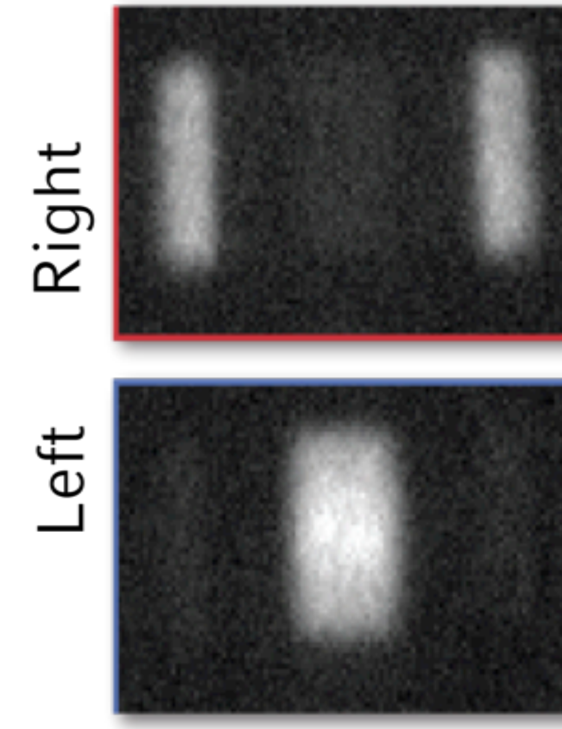

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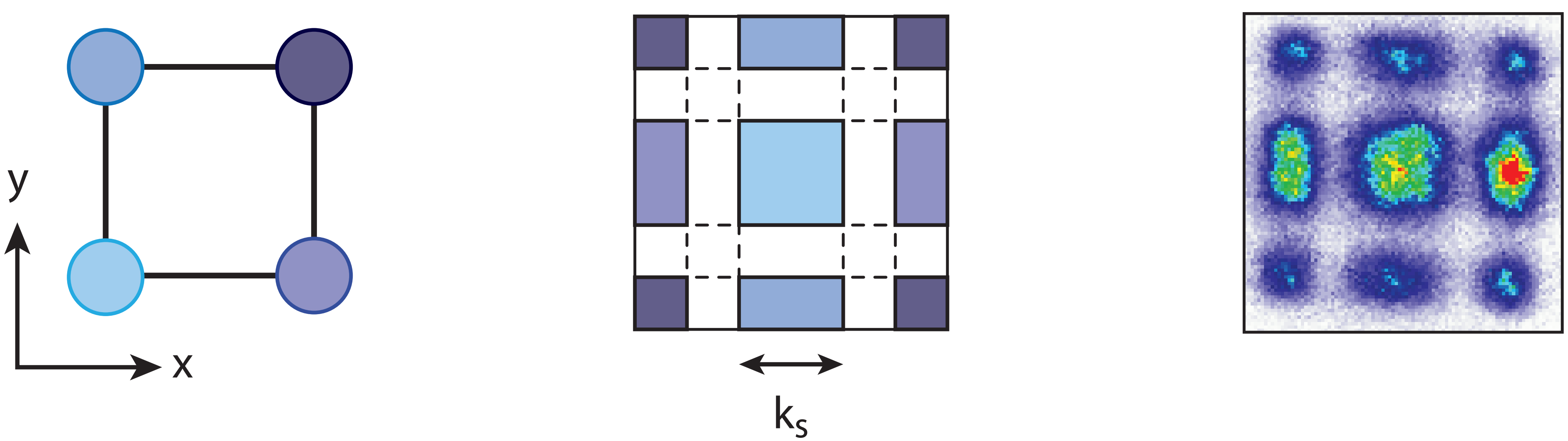
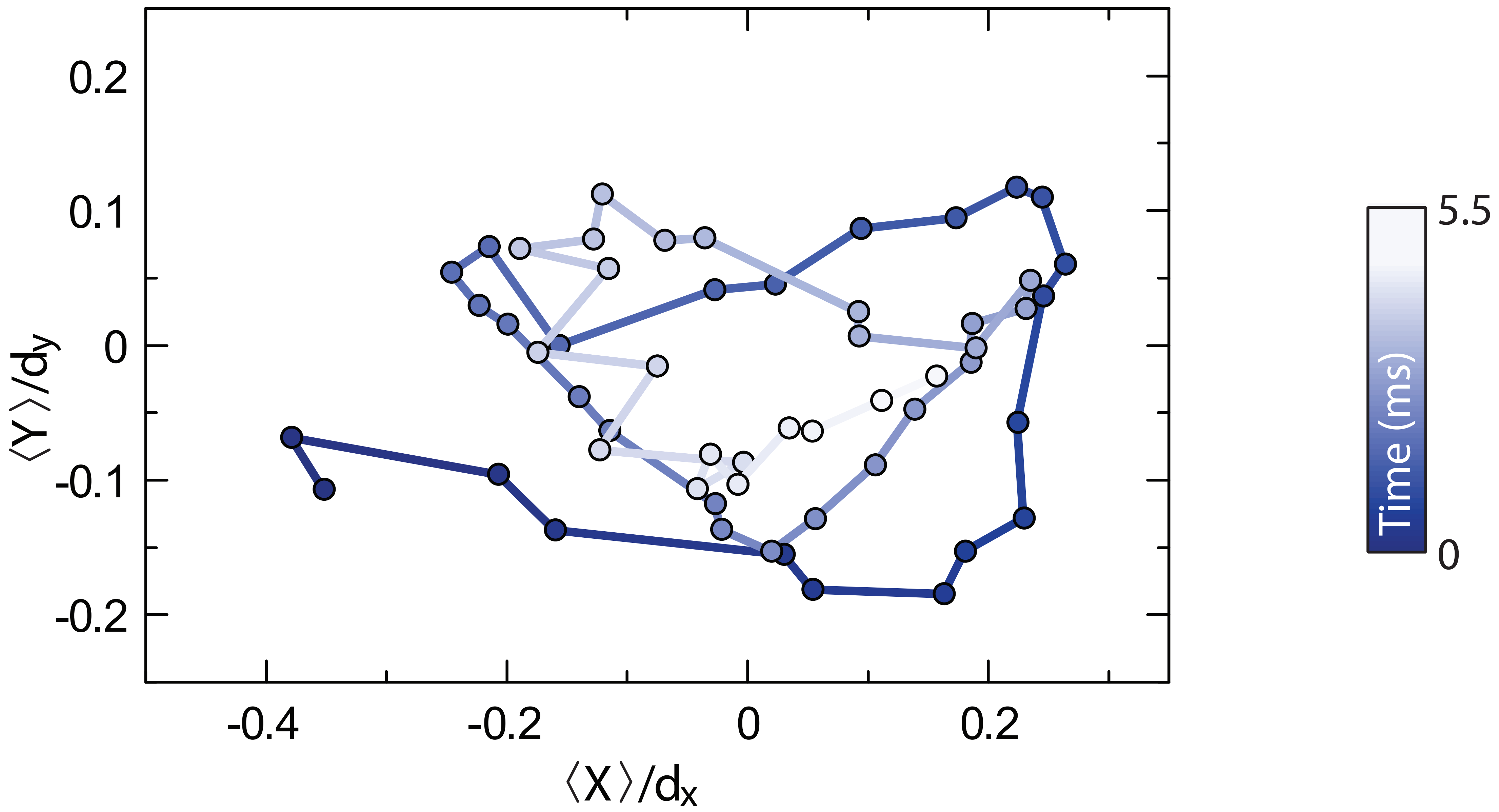


- Evaluate mean atom positions $\langle X \rangle$ and $\langle Y \rangle$

`Cyclotron' Orbit

The mean atom position during the evolution.



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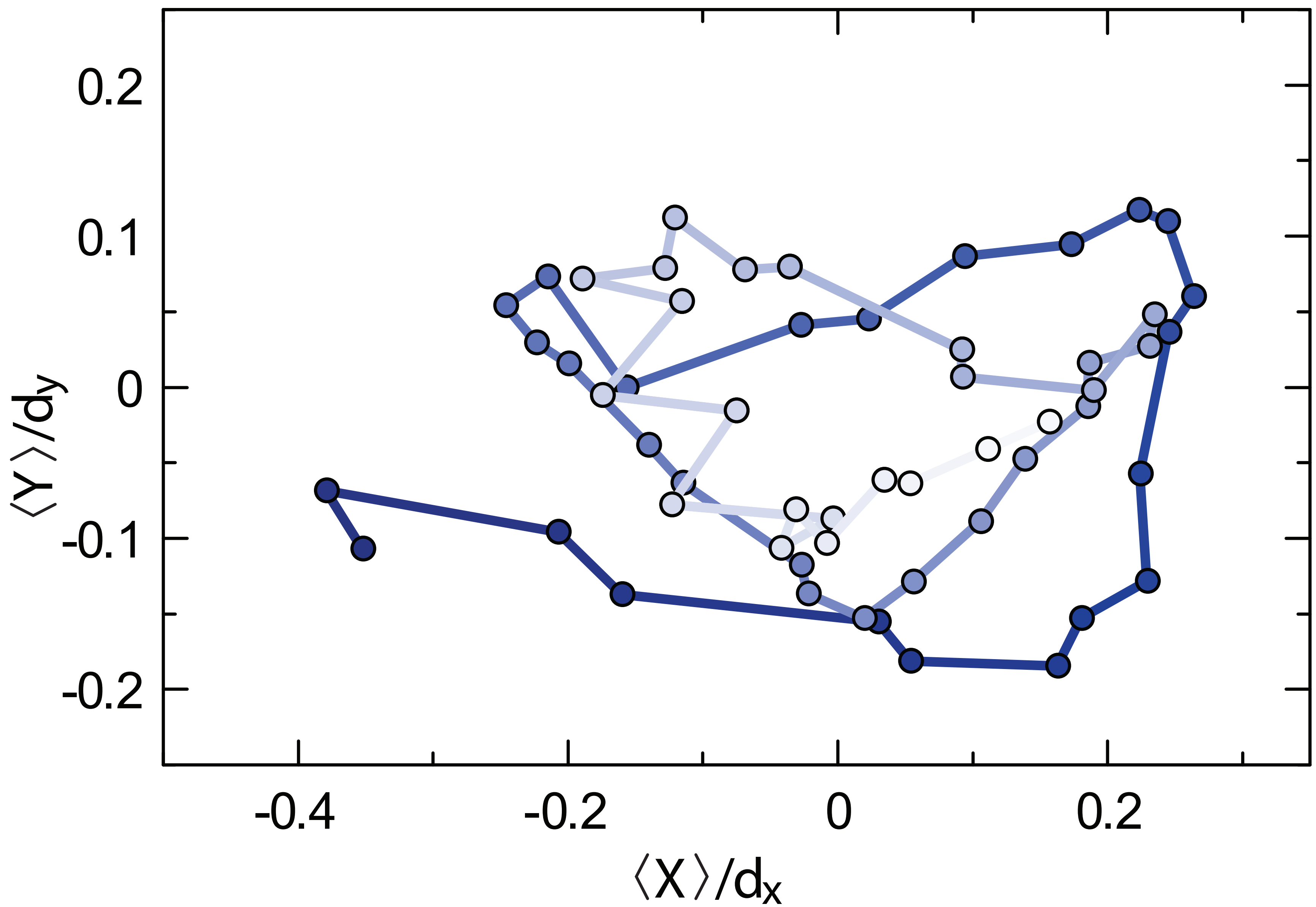
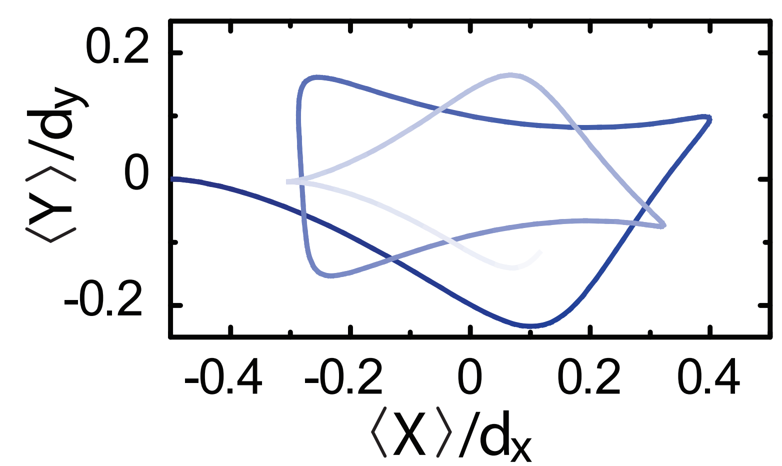


theory



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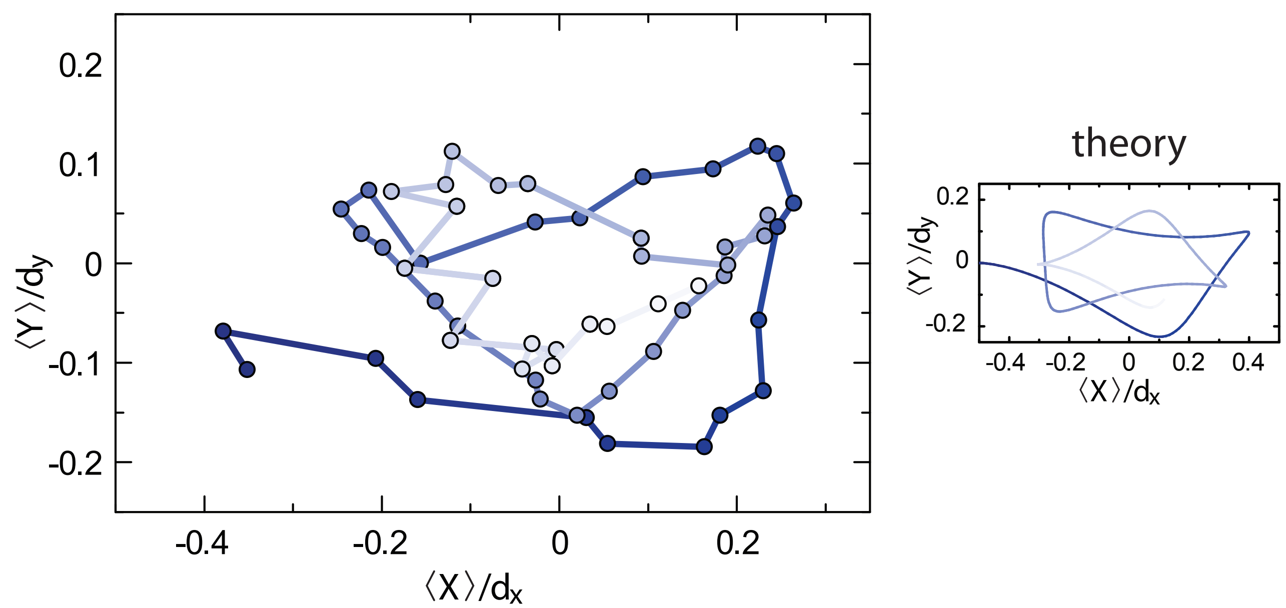

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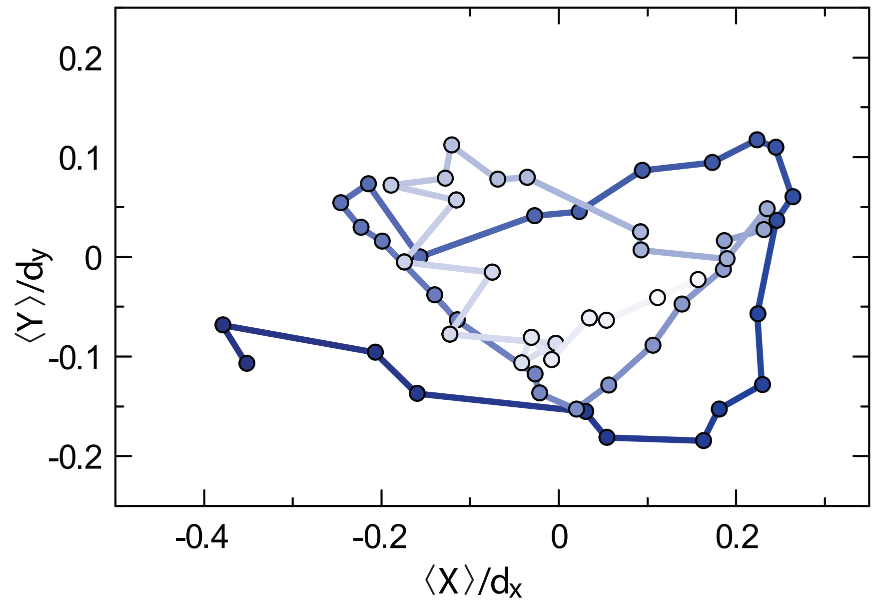
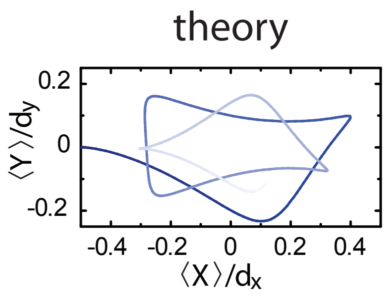




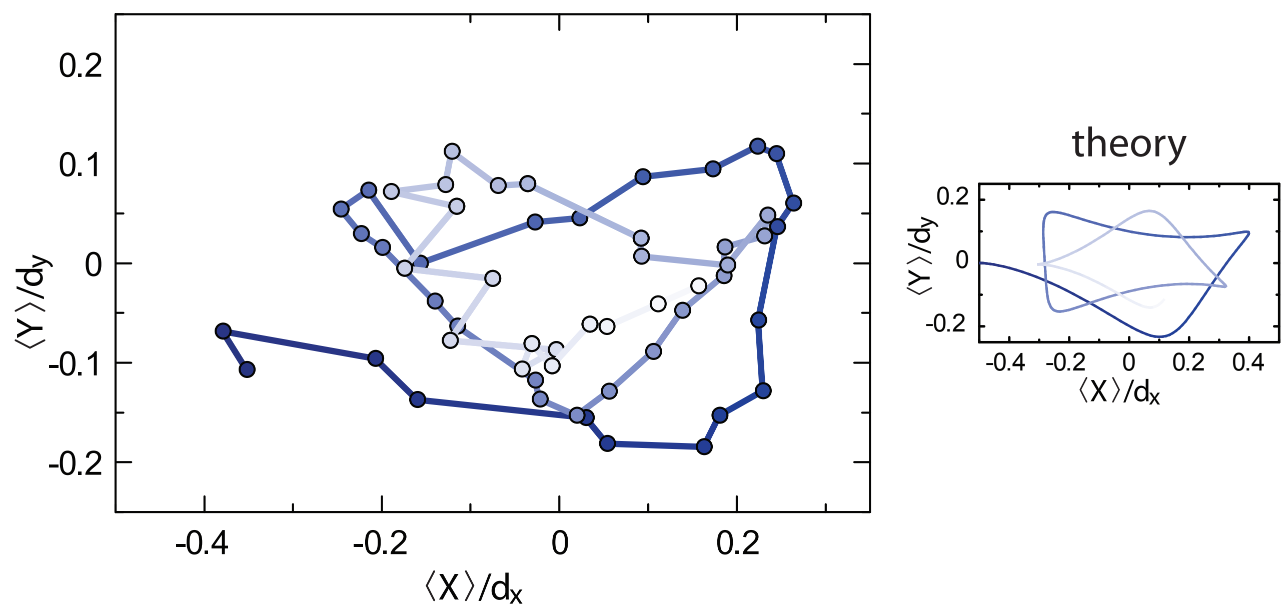
From this evolution we fit the value of the phase

$$\phi = 0.73(5)\ \pi/2$$

Deviation from $\phi=\pi/2$

`Cyclotron' Orbit

The mean atom position during the evolution.



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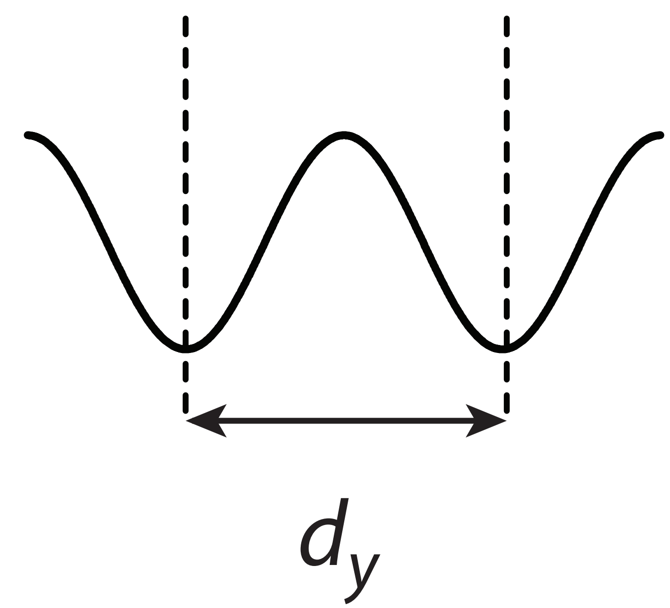

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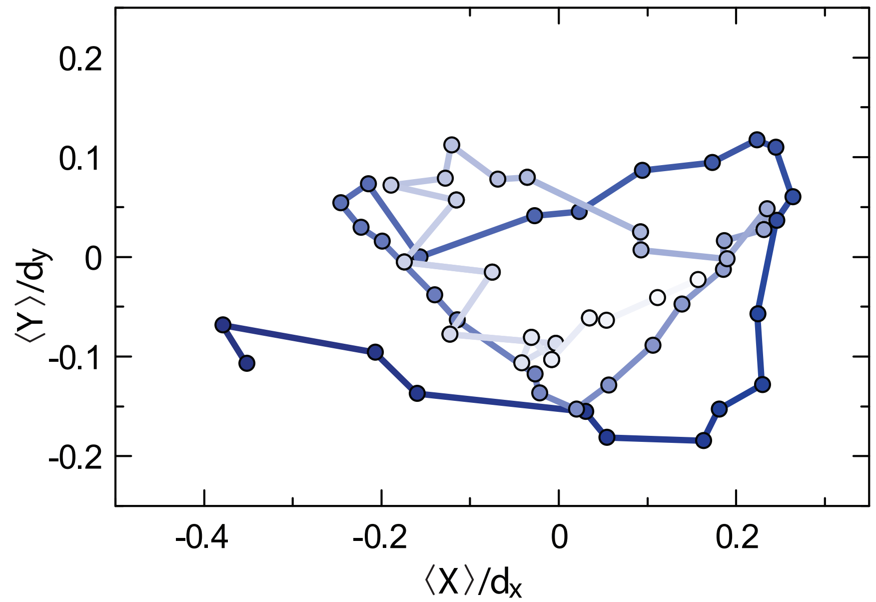

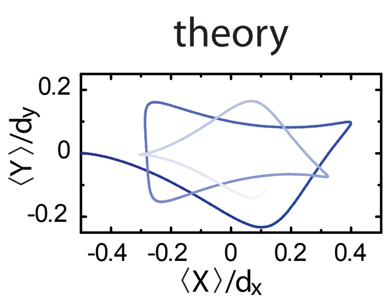

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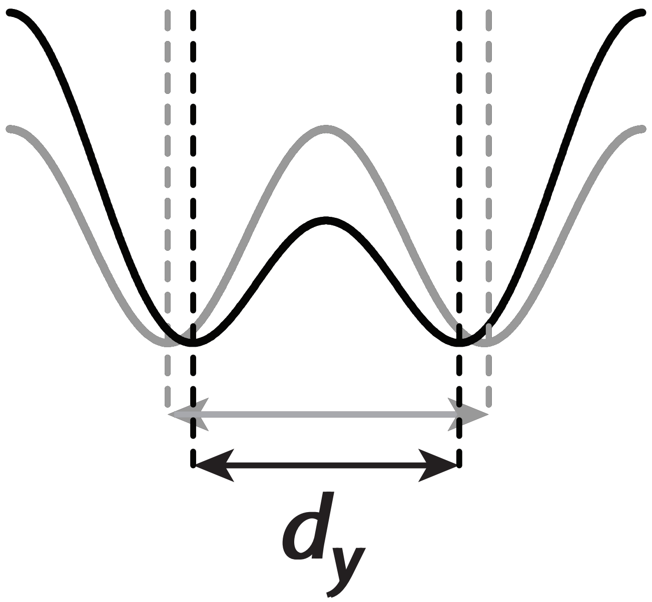
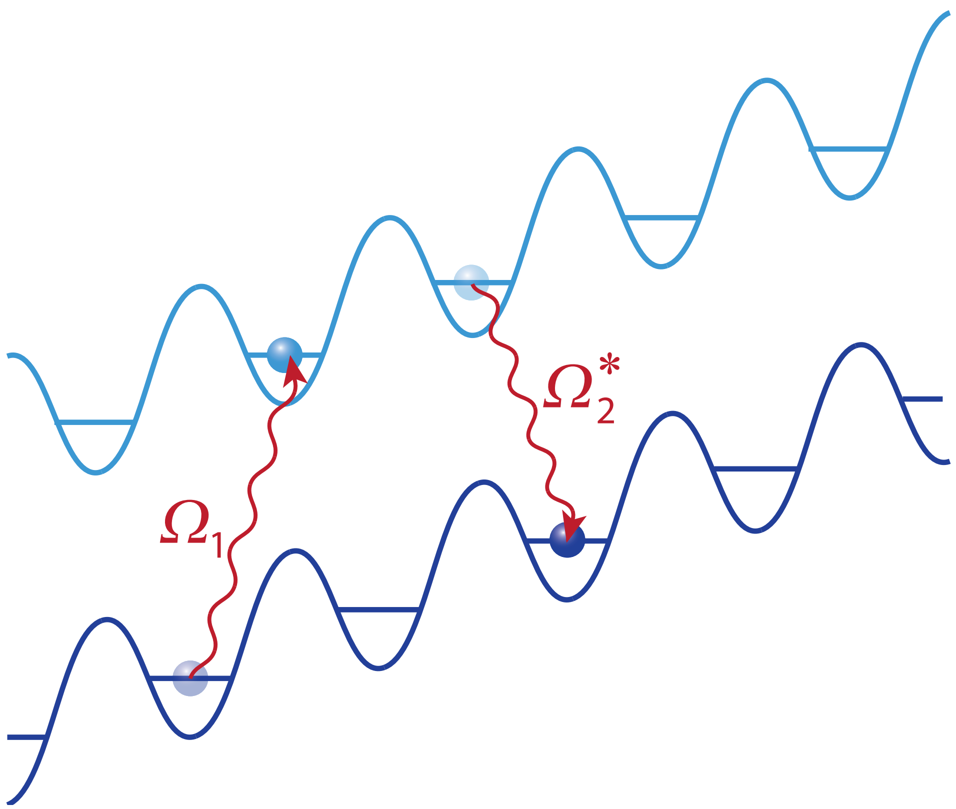


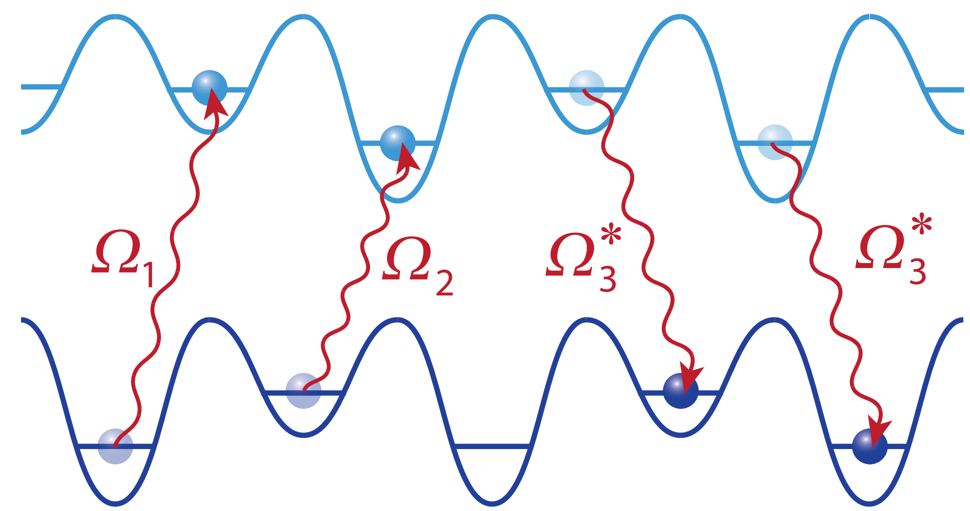
Deviation from $\phi=\pi/2$

Outlook: Rectify the flux



Using a linear potential

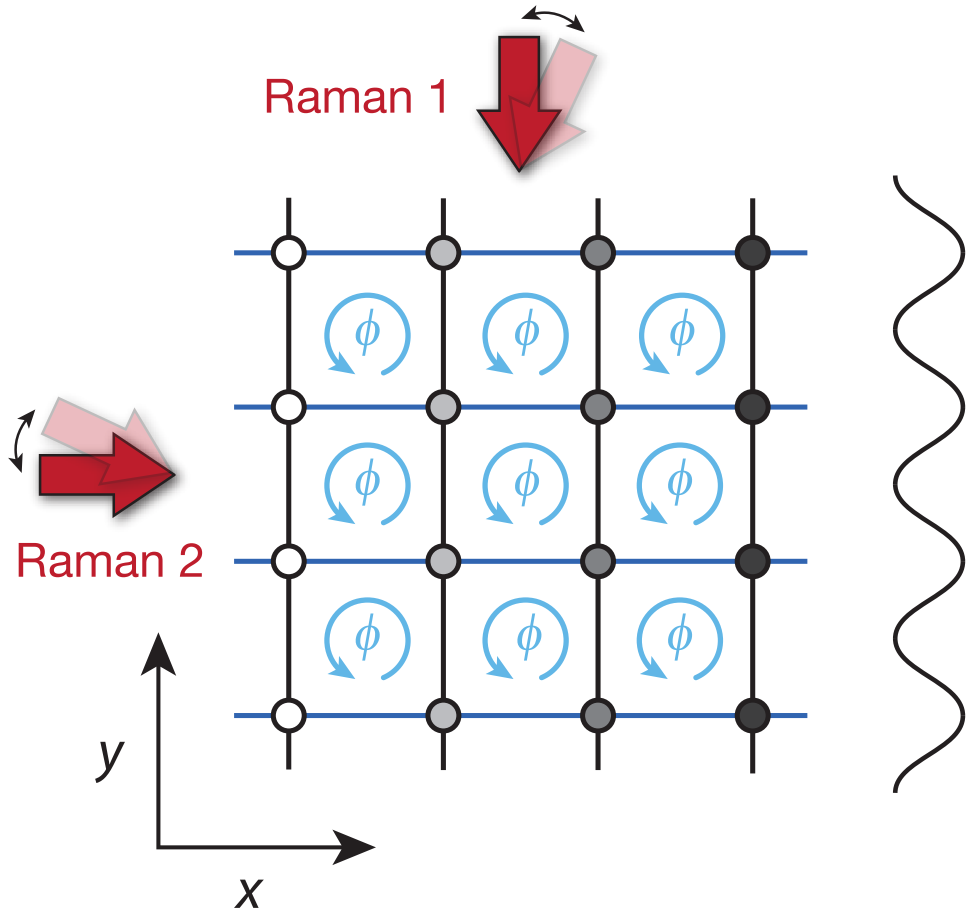
D. Jaksch & P. Zoller, NJP **5**, 56 (2003)

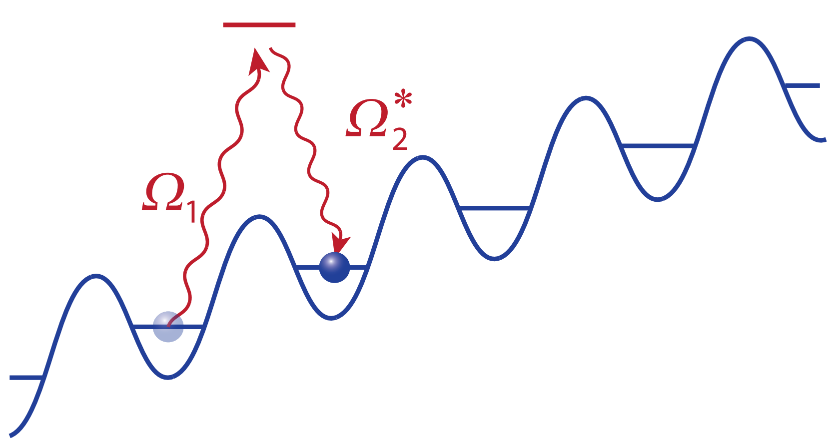


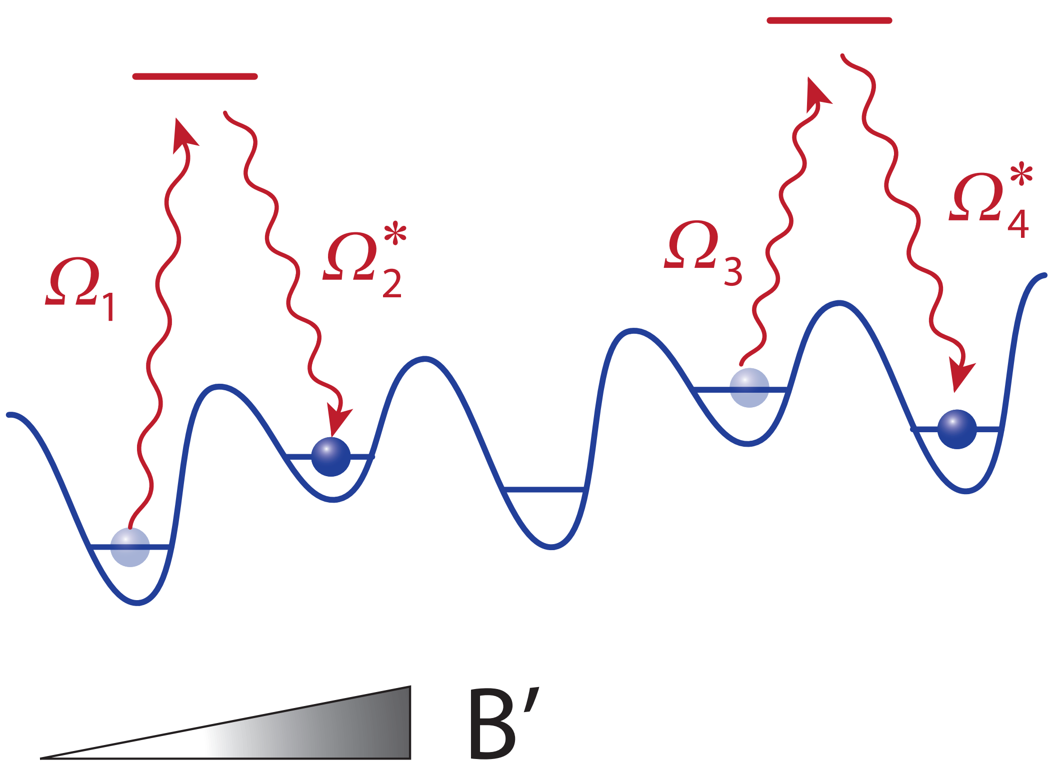
Using a superlattice

F. Gerbier & J. Dalibard, NJP **12**, 033007 (2010)

Outlook: Rectify the flux



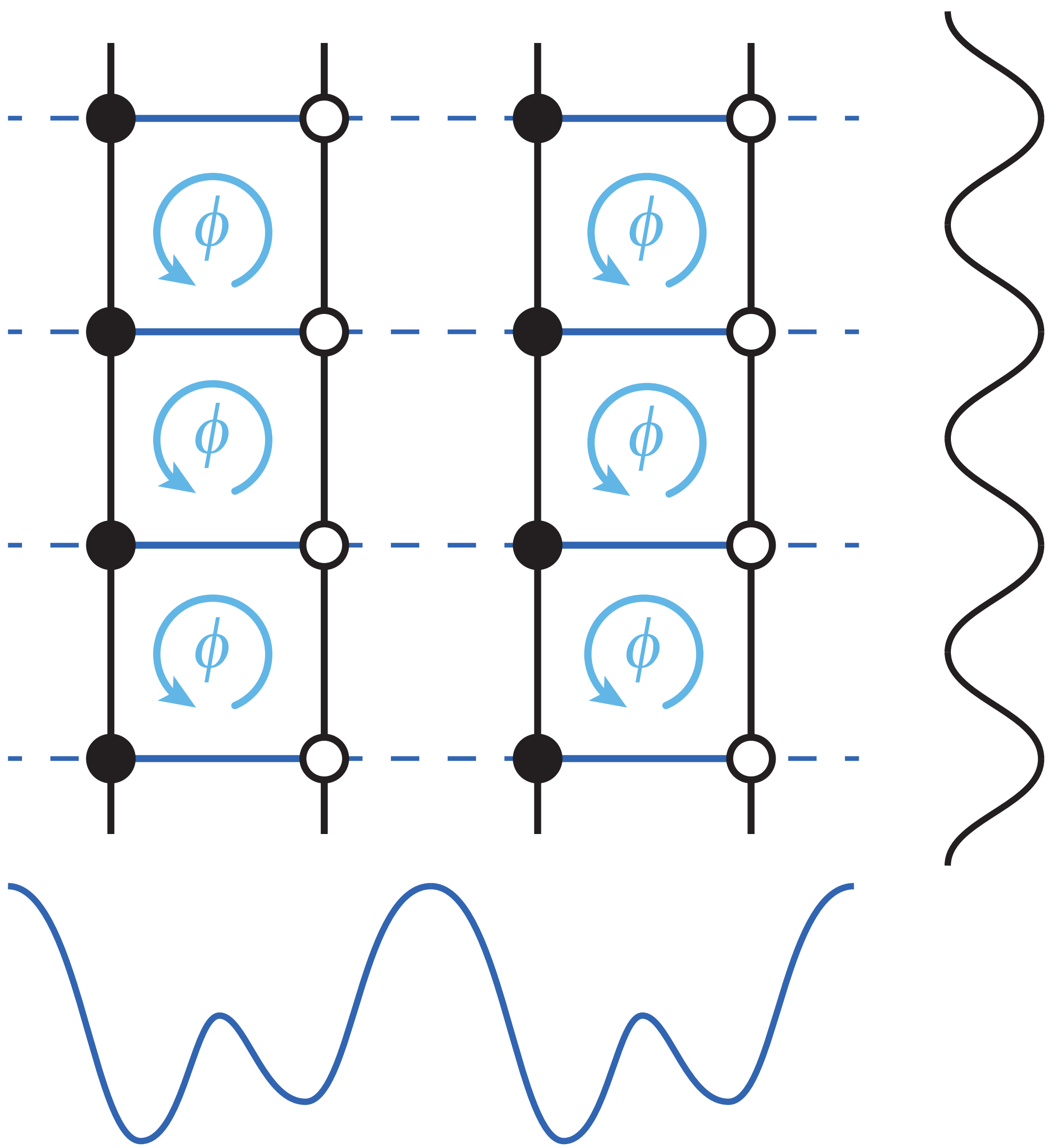




Using a linear potential
D. Jaksch & P. Zoller, NJP **5**, 56 (2003)

Using a superlattice + Gradient
F. Gerbier & J. Dalibard, NJP **12**, 033007 (2010)

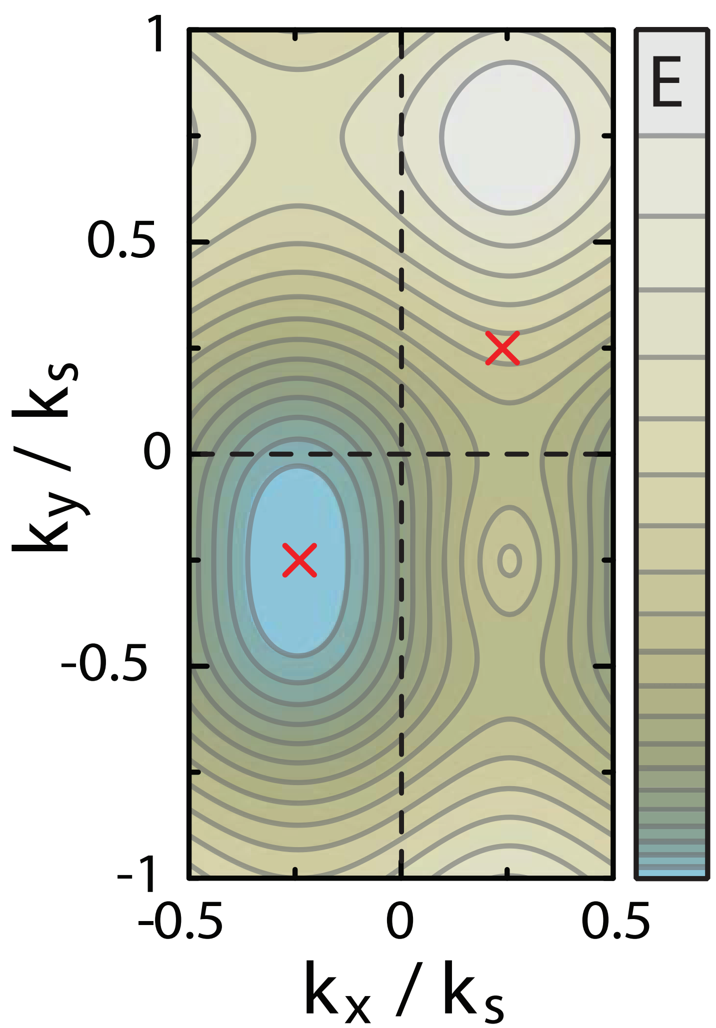
Outlook: Rectify the flux



Ladders in a magnetic field:

? Observables
? Edge current
? Bifurcation point
? Strong interaction
? Dirac point

Outlook: Rectify the flux



Ladders in a magnetic field:

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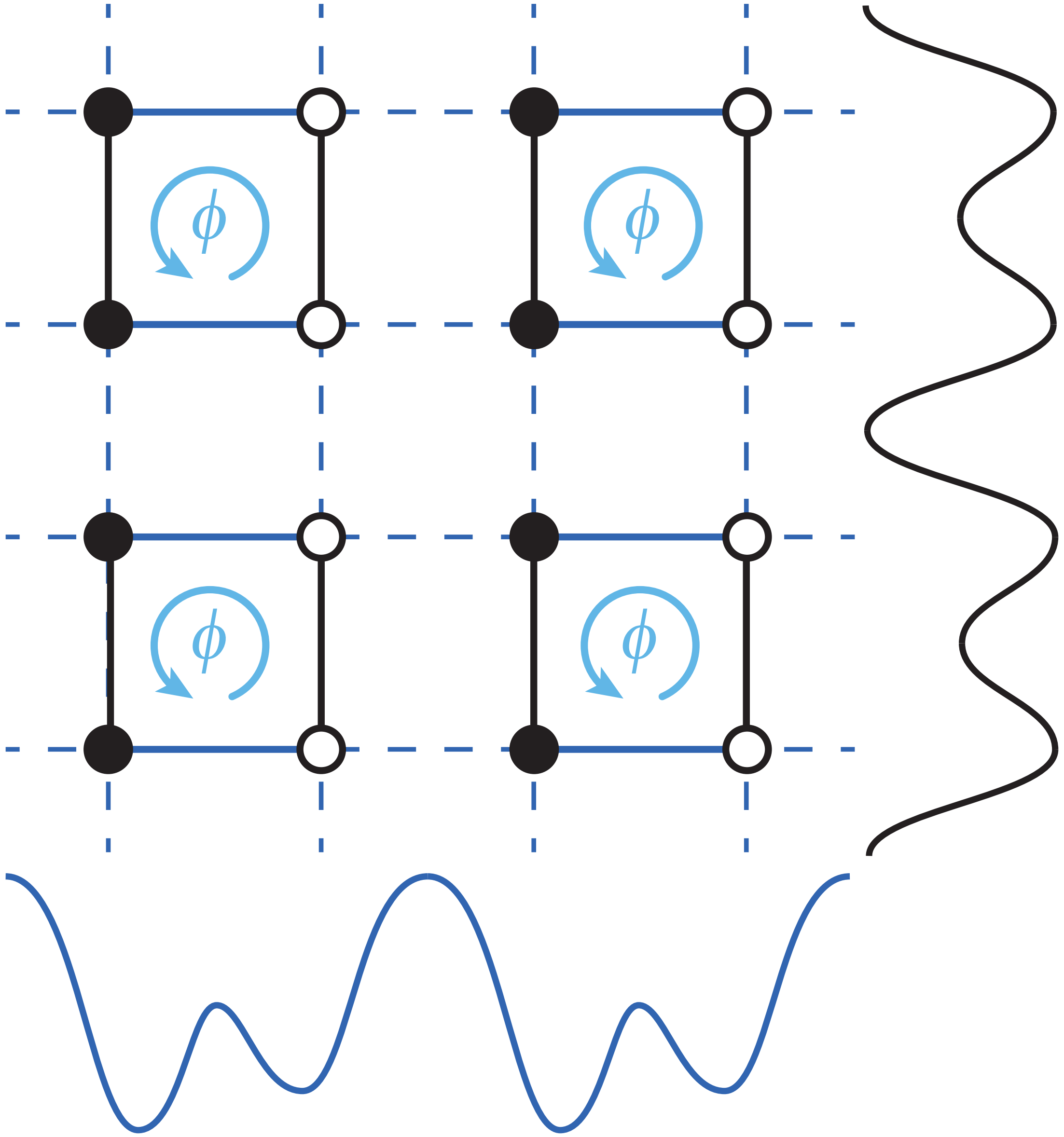
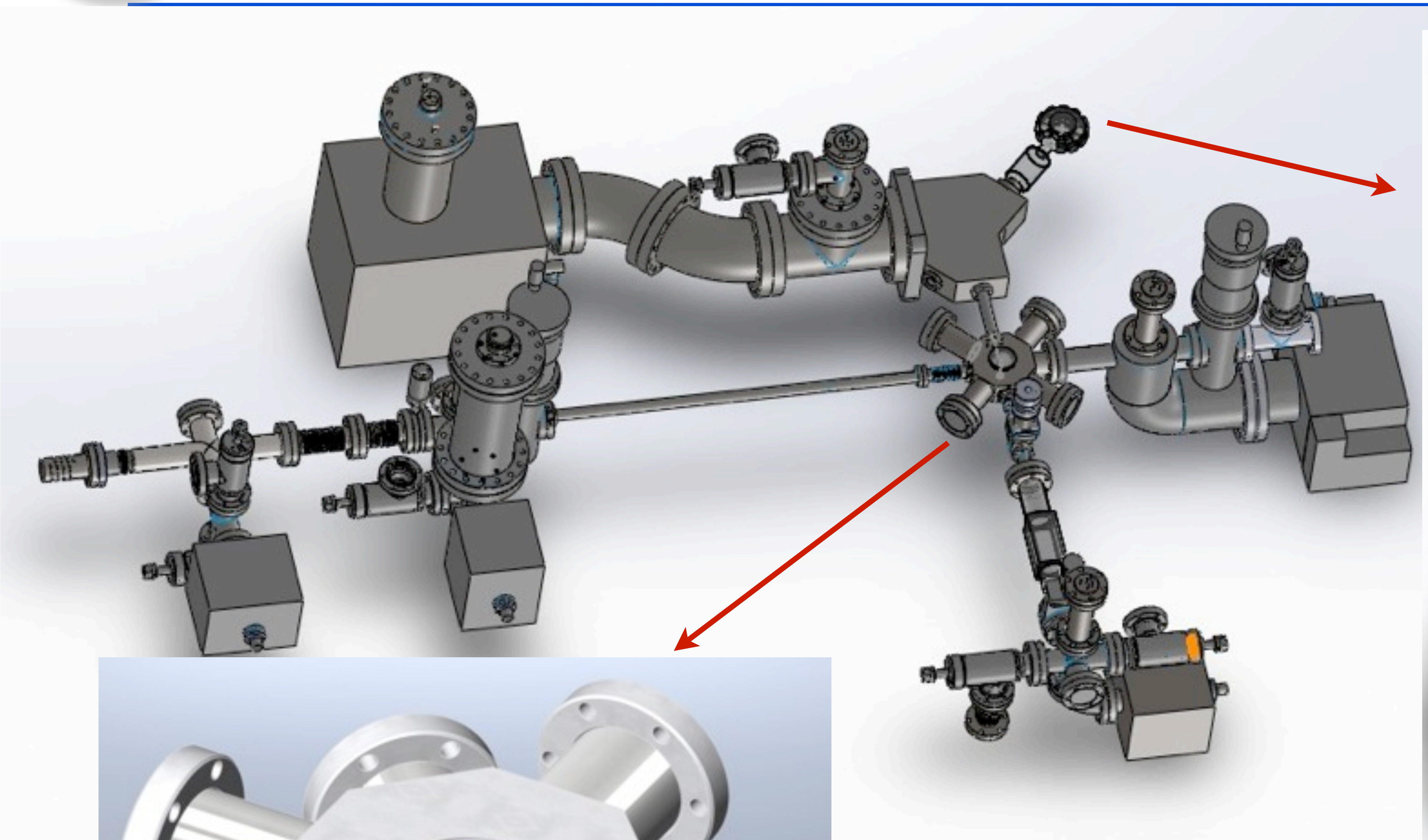
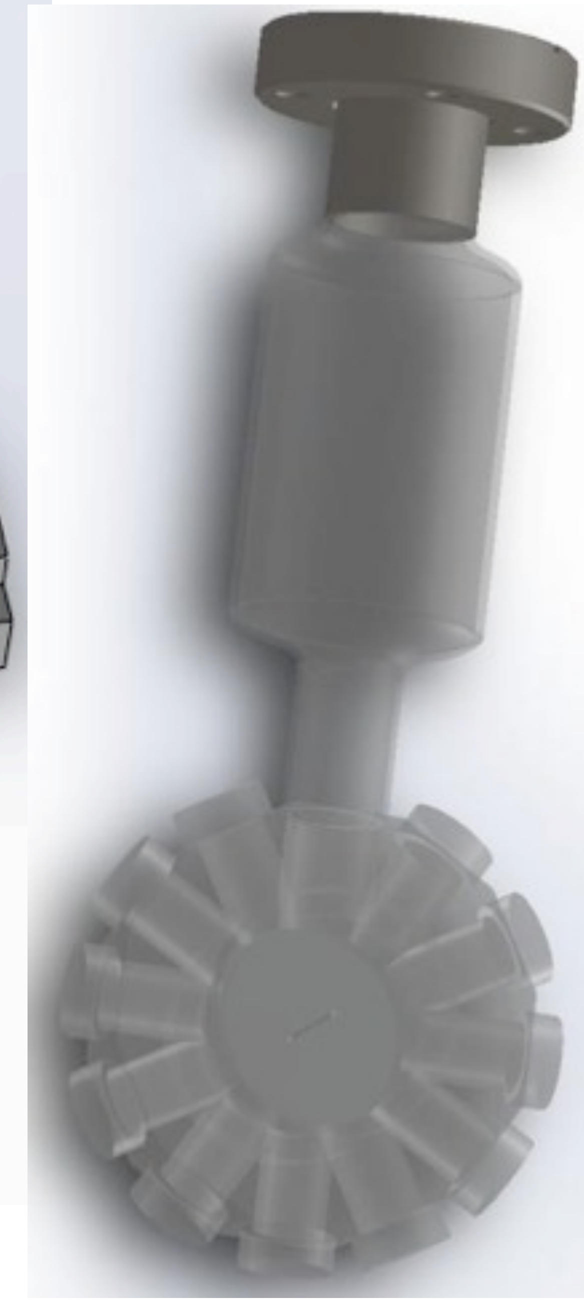


Detection of a vortex prepared in isolated 4-site plaquettes

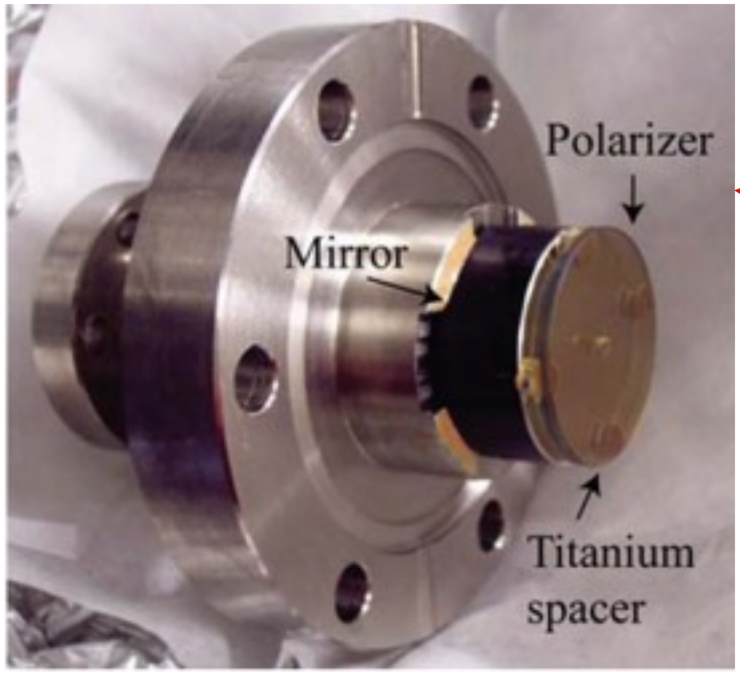
Ongoing Project: Fermi-Fermi Mixture in OLs

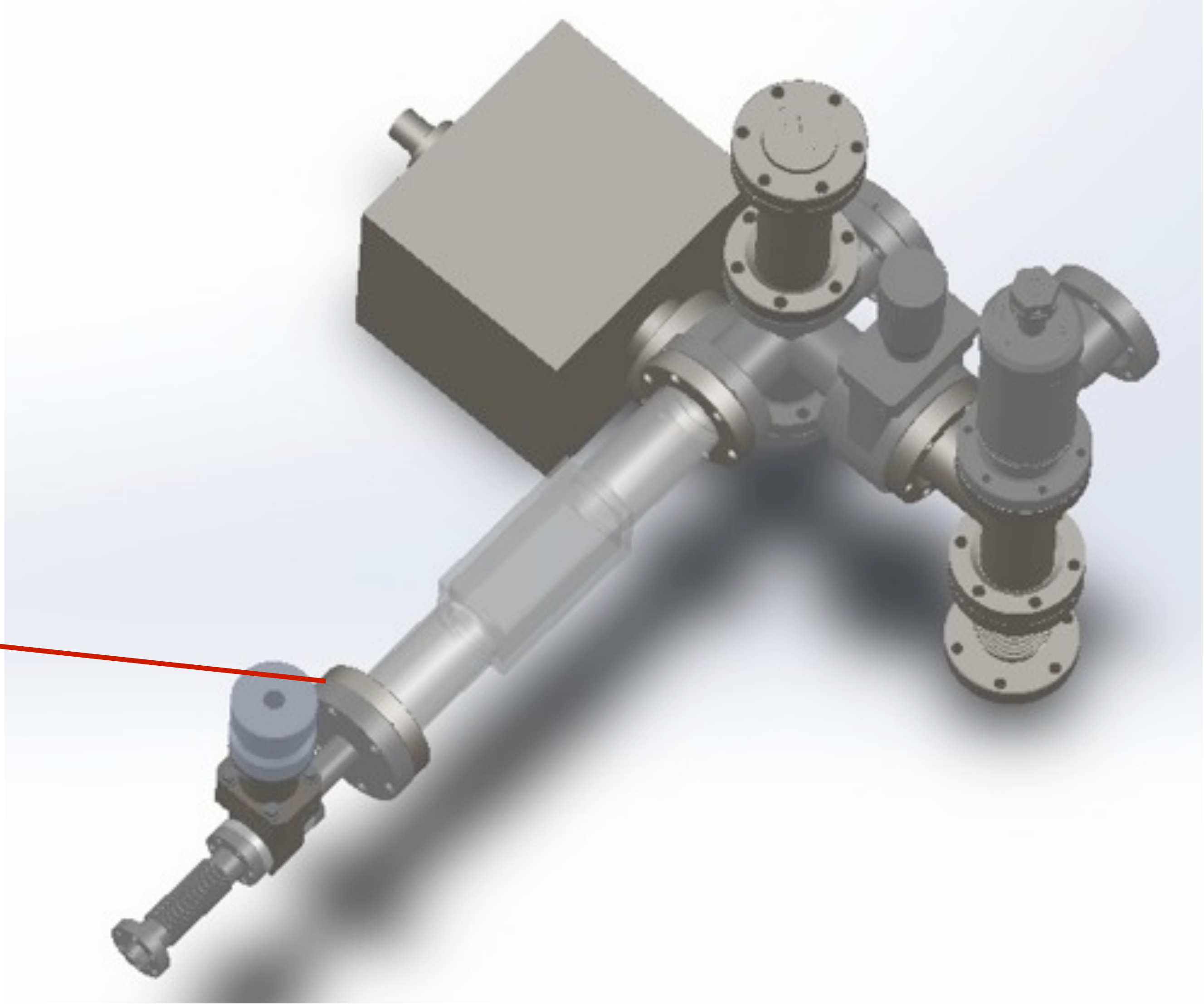




Ongoing Project: Fermi-Fermi Mixture in OLs

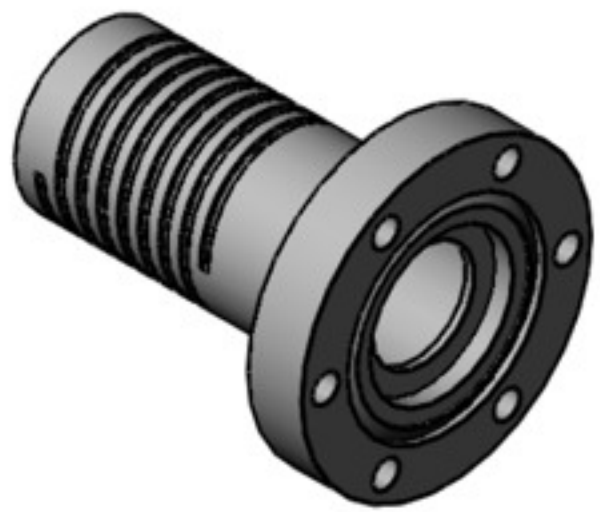
Vacuum design——2D+MOT for K40



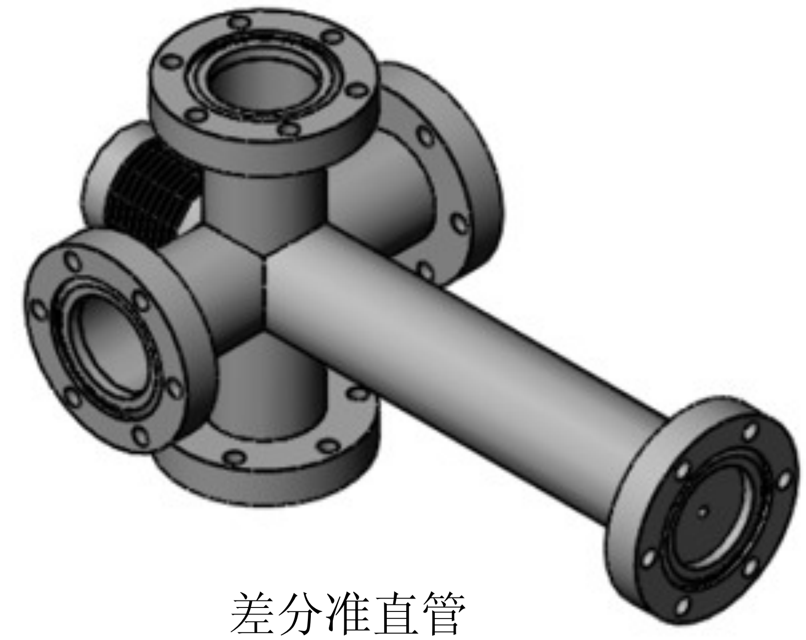


Ongoing Project: Fermi-Fermi Mixture in OLs

Vacuum design——Collimated Li6 atom beam

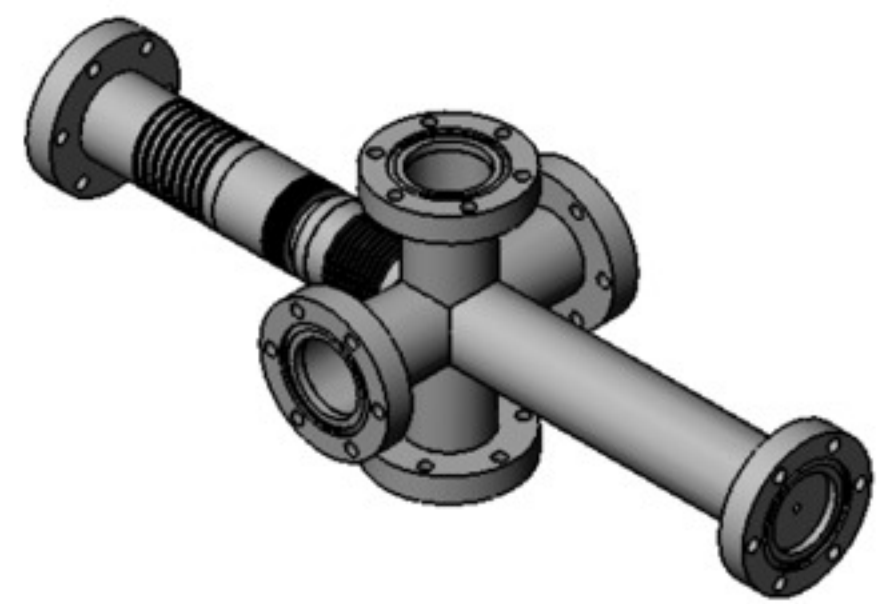


Li烤炉



差分准直管

回流炉



输出准直后的高
通量Li原子束