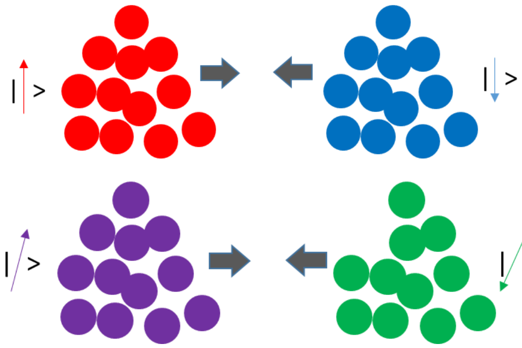
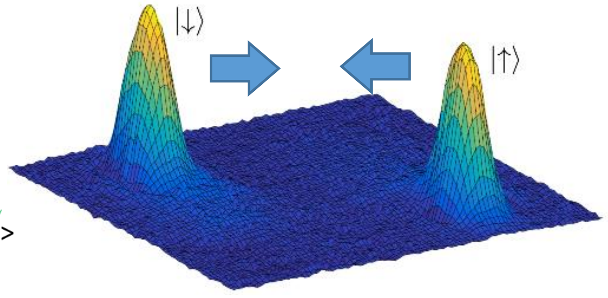
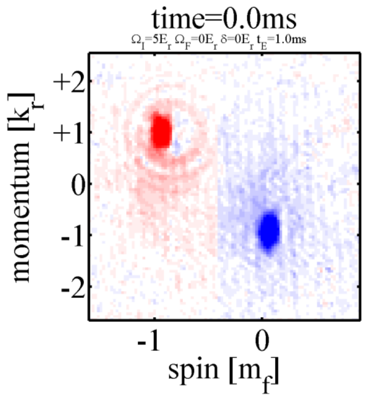
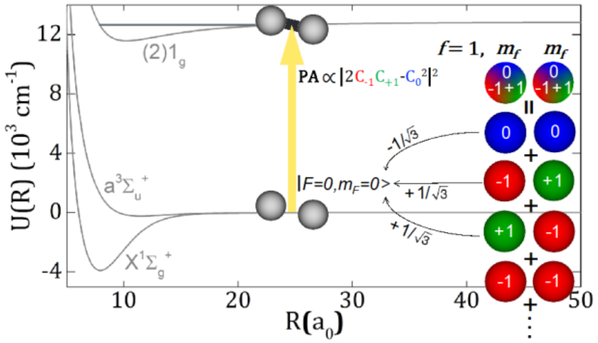
Euro Few-body Conference @ Surrey, 9/6/2019

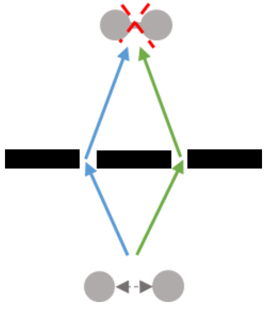
Spin-orbit-coupled Bose-Einstein Condensate as playground to explore quantum collision and chemistry











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(***starting a new lab & Villum Center for Hybrid Quantum Materials & Devices, from 2020***;
Looking for PhDs/postdocs/Assistant Profs, e.g. ***Quantum Optics****/Quantum Devices/Scanning Probe*)

Spin-orbit-coupled Bose-Einstein Condensate as playground to explore quantum collision and chemistry

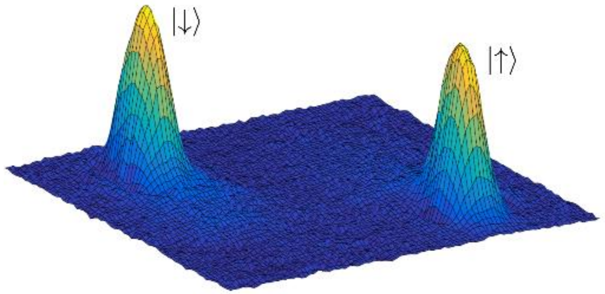
Outline

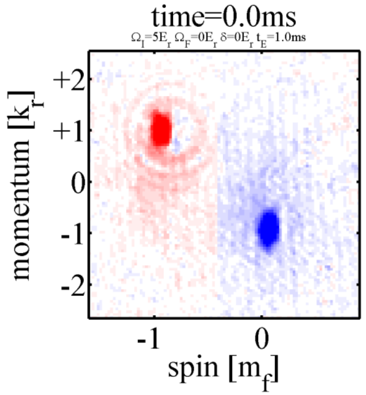
- Intro. to experimental platform: **“spin-orbit-coupled (SOC) BEC”**

  [“spin-helical atoms”] (by optical dressing)

- **(Spin) transport & Spinor BEC collider [how is it affected by SOC?]**

“2x2”



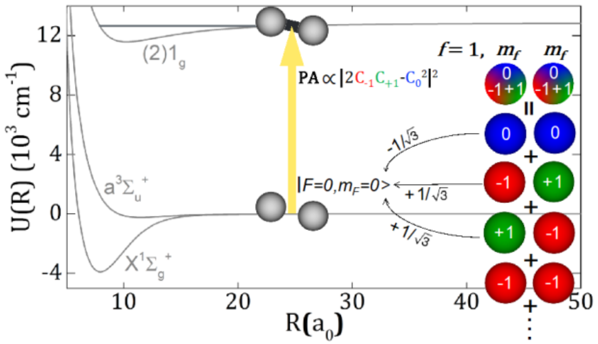


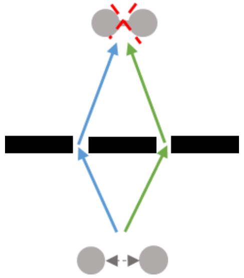
C. Li *et al.*, Nature Comm. 10, 375 (2019)

Chuan-Hsun Li

- **Quantum Synthesis: Interferometry in quantum (photo)chemistry**

“3x3”





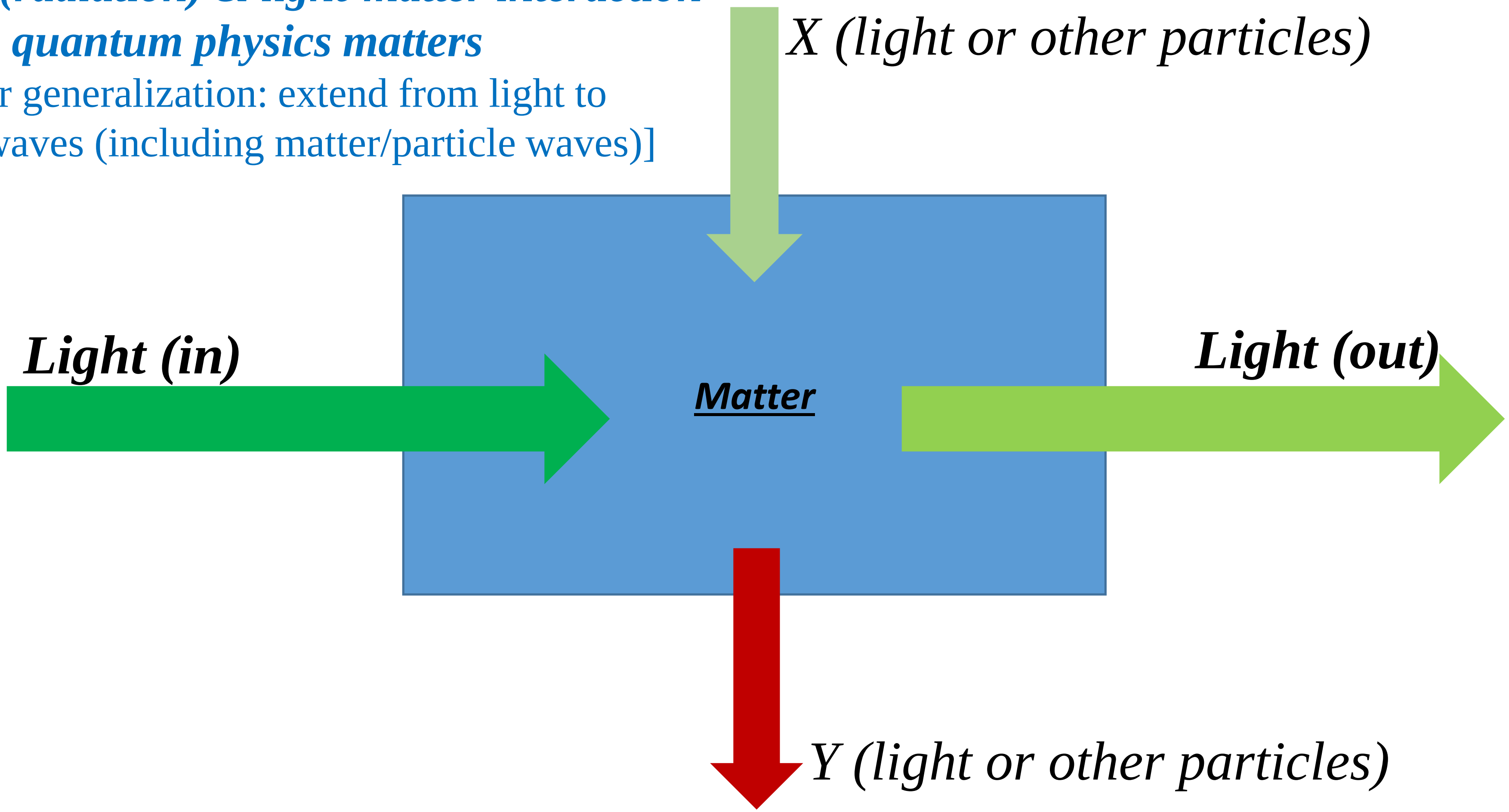
D.Blasing *et al.* PRL 121, 073202 (2018)

David Blasing
(→ Crane)

*Acknowledge Research Support by: Purdue Univ.; ARO; **NSF;DOE***

- **Light can probe, control & *create* new matter** (*coherent* light-matter interaction)

Quantum optics (broadly defined):
Light (radiation) & light-matter interaction where quantum physics matters
[further generalization: extend from light to other waves (including matter/particle waves)]

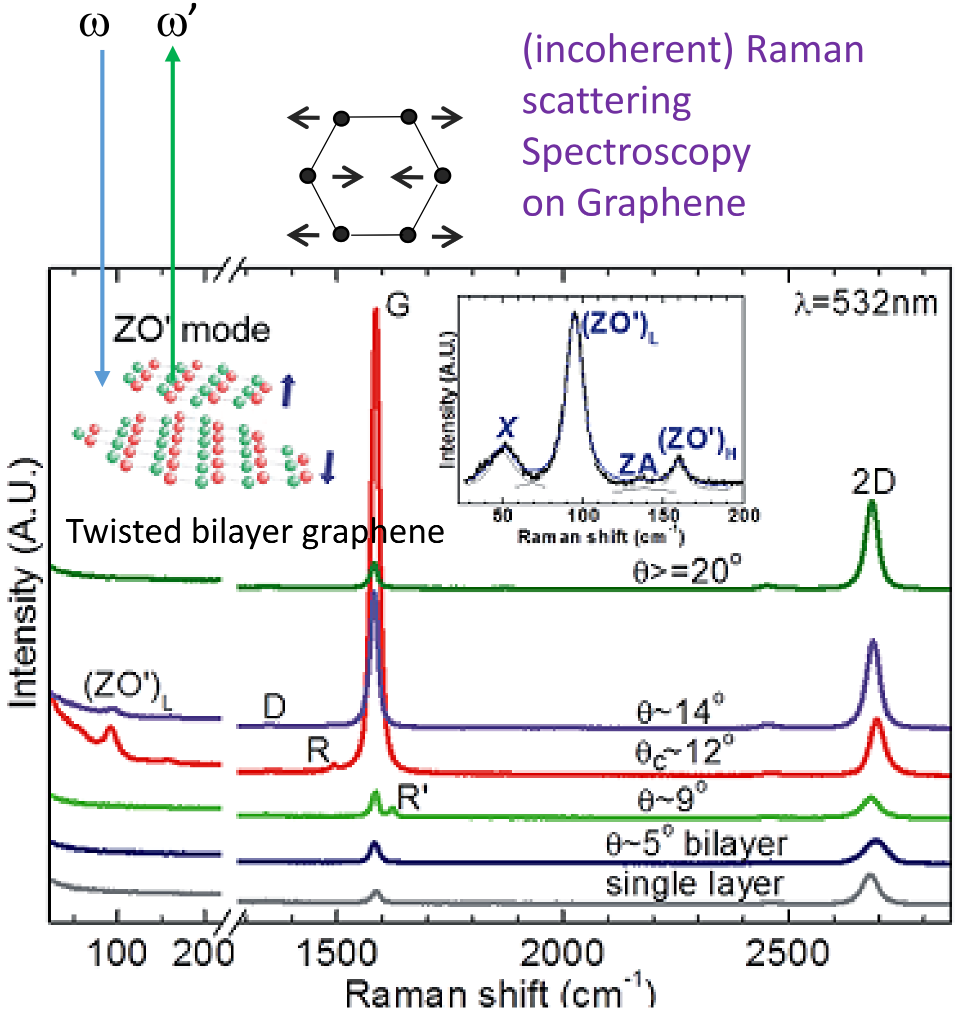


(from Y.Chen, Purdue PHYS 522 “Introduction to Quantum Optics and Quantum Photonics”)

Example: ***Raman** process* as light-matter interaction

--- from optical scattering (incoherent) to <u>optical dressing (coherent)</u>

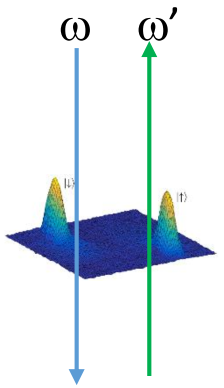
(incoherent) Raman scattering Spectroscopy on Graphene



R.He, T. F. Chung *et al.*, Nano Lett. 13, 3594 (2013)

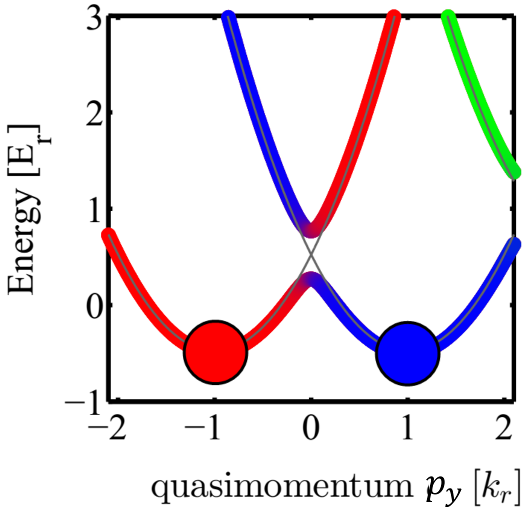
Can generalize to/realize 3x3, 4x4 .. NxN matrix Hamitonian…

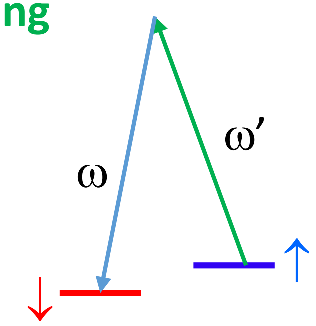
$$\begin{array}{cc} \text{“matter”} & \text{“light”} \\ \end{array}$$
$$\begin{pmatrix} \frac{\hbar^2}{2m}(p_y+k_r)^2 & \Omega \\ \Omega & \frac{\hbar^2}{2m}(p_y-k_r)^2 \end{pmatrix}$$



Raman (optical) dressing

→ Synthetic “bandstructure”/spin-orbit coupling

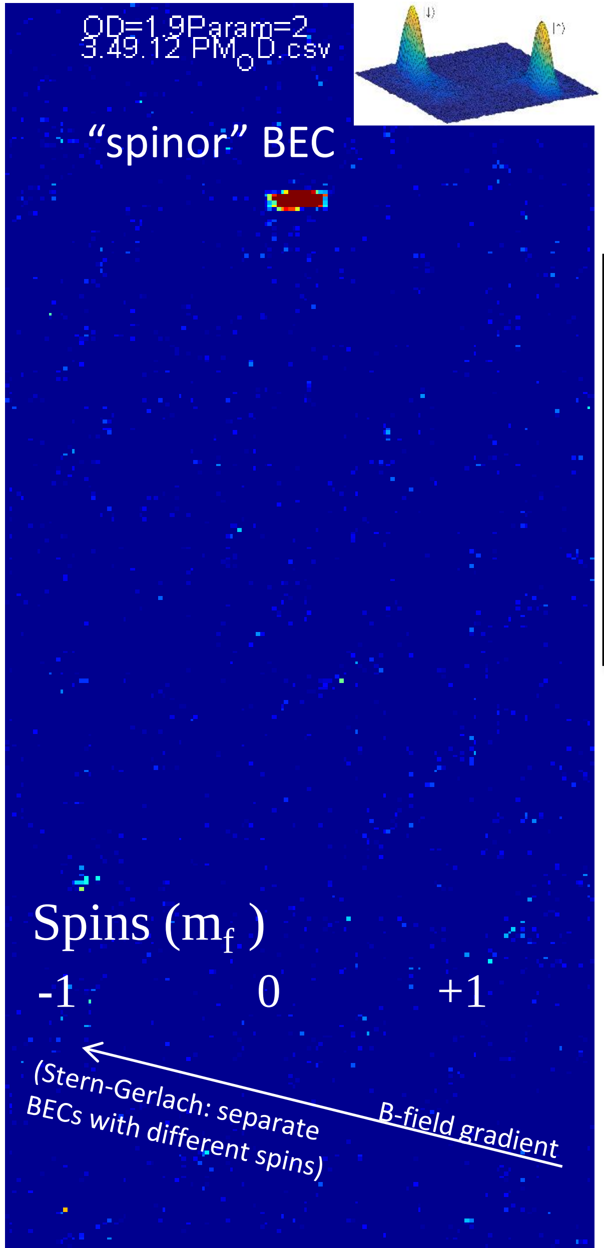




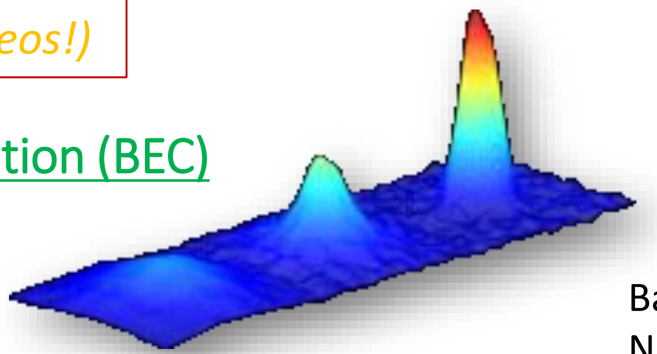
Eigenvalues E(Ω,p_y) and Eigenstate (“dressed state”): $\alpha(\Omega,p_y)|\downarrow,p_y+k_r\rangle+\beta(\Omega,p_y)|\uparrow,p_y-k_r\rangle$ dep on parameters (p, Ω)

cold atoms/BEC --- “seeing” quantum mechanics & dynamics!

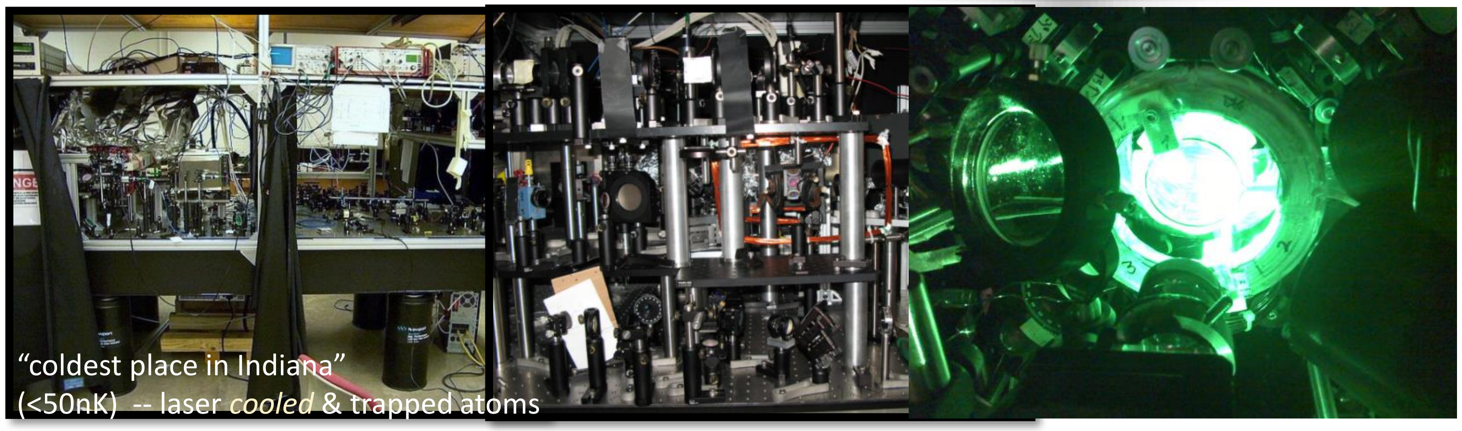
(“slowed down” and “blown up” so much that you can shoot photos & videos!)



Demo with our Bose-Einstein Condensation (BEC)

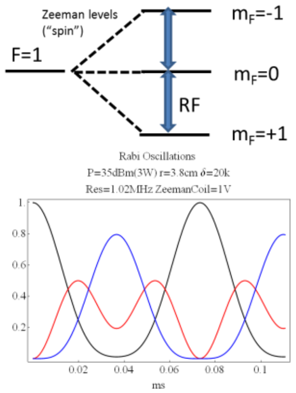


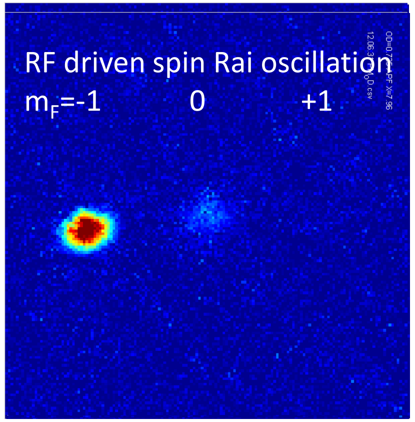
Purdue QMD’s “all-optical” Rb87 BEC apparatus with synthetic gauge fields and spin-orbit coupling



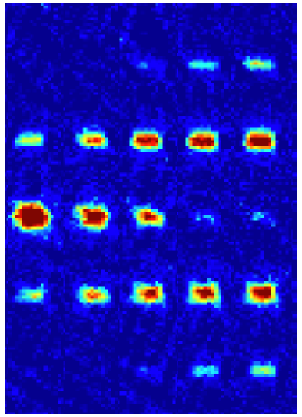
Based on several Nobel-prize technologies:

- Chu/Phillips /Cohen-Tannoudji’97;
- Cornell/Wieman /Ketterle’01;
- Ashkin’18

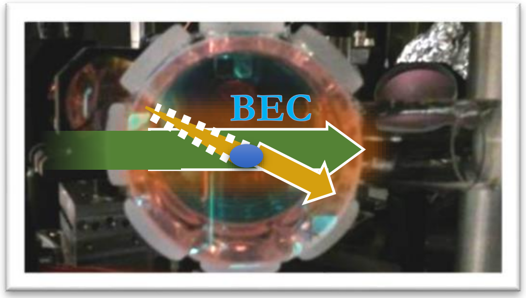




coherent oscillation of BEC between 3 spin states



BEC (matter wave) diffraction from laser standing wave (optical grating)

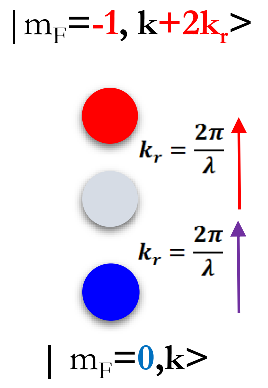


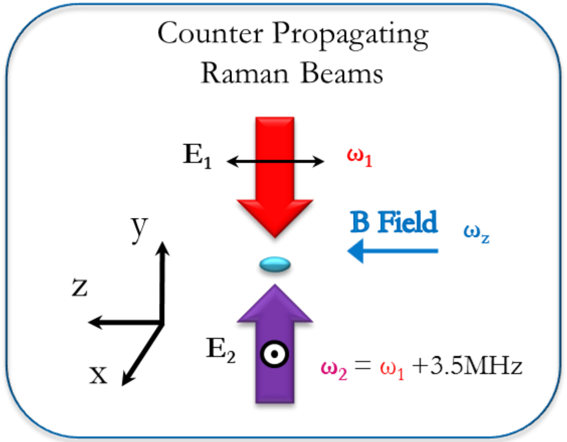
1550nm cross-beam optical trap (optical tweezer)

A.J. Olson *et al.*, PRA87, 053613 (2013) (exp. & modeling of efficient evaporative cooling in optical trap)

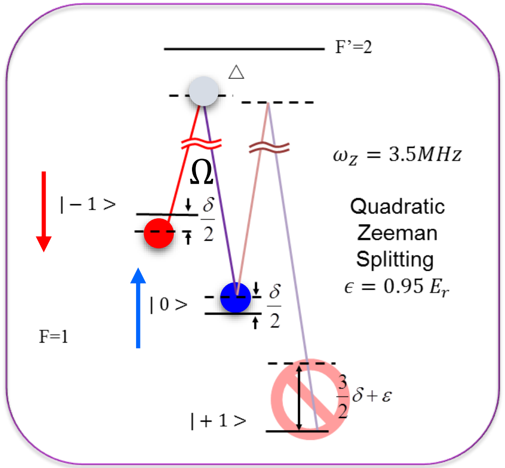
”discrete spots” → ” synthetic dimension/lattice!

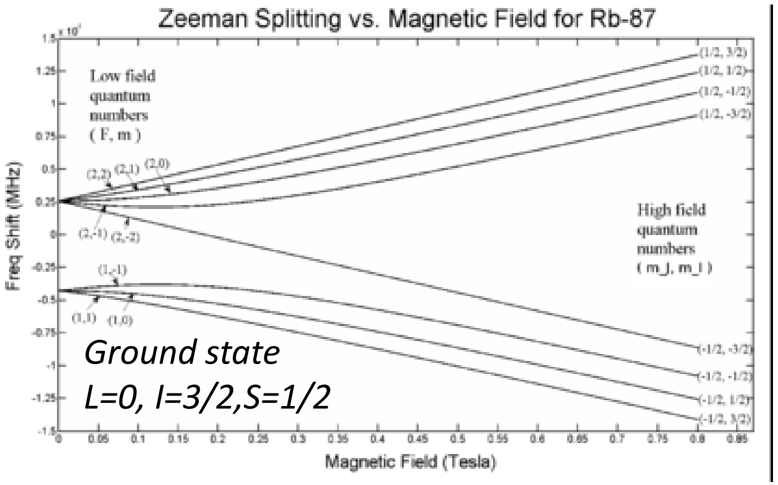
Synthetic Spin Orbit Coupling (SOC) by optical Raman coupling (spin-momentum)





[similar to Spielman/NIST'2011]



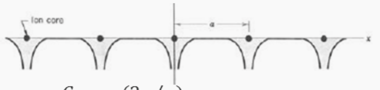


Synthetic (Dressed) bandstructure/SOC

$H_k\psi + V\psi = \varepsilon_k\,\psi$

Compare with bandstructure (due to coupling by periodic V)

$V(r) \sim \sum V_n e^{iG_n x}$ couples k with $k+G_n$

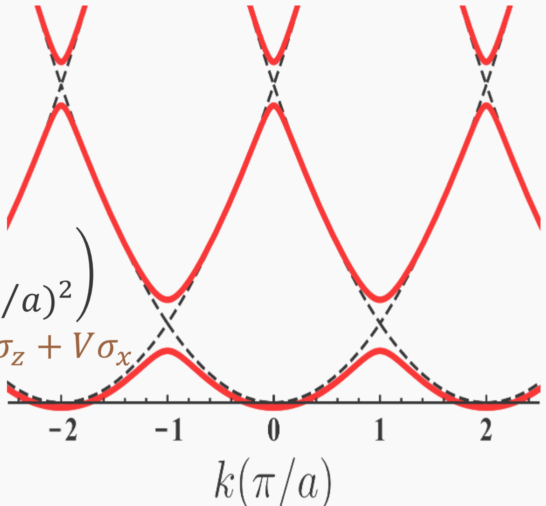


$G_n = n(2\pi/a)$

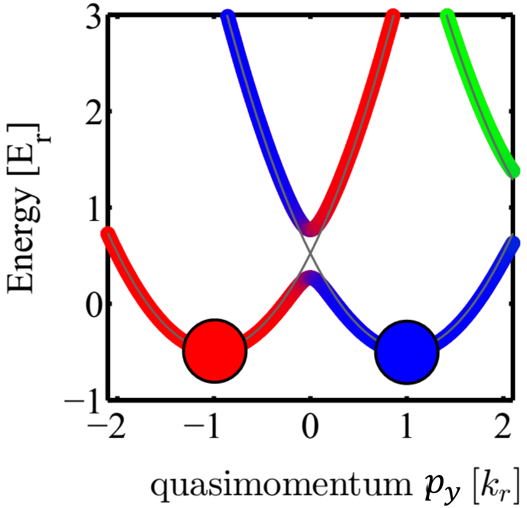
$\psi = e^{ikx}u(x) = e^{ikx}\left(\sum u_n e^{iG_n x}\right) = \sum u_n e^{i(k+G_n)x}$

$$\hat{H} = \begin{pmatrix} (k+\pi/a)^2 & V \\ V & (k-\pi/a)^2 \end{pmatrix}$$

$$= (k^2 + \pi^2/a^2)\mathrm{I} + 2(\pi/a)k\sigma_z + V\sigma_x$$



Ω=0.5E$_r$ δ=0E$_r$



$$\tilde{H} = \begin{pmatrix} \frac{\hbar^2}{2m}(p_y + k_r)^2 + \frac{\delta}{2} & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{\hbar^2}{2m}(p_y - k_r)^2 - \frac{\delta}{2} \end{pmatrix}$$

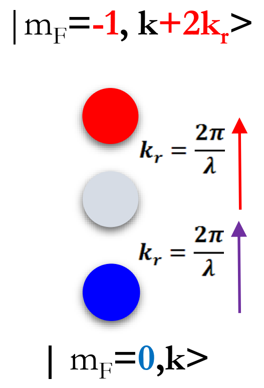
control knobs

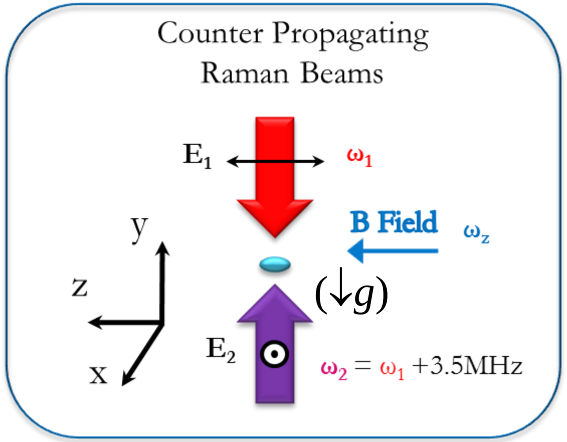
$$= \frac{\hbar^2 k_r^2}{2m} I + \boxed{\frac{\hbar^2}{2m} p_y^2 I + \frac{\hbar^2 k_r}{m} p_y \sigma_z + \frac{\Omega}{2}\sigma_x} + \frac{\delta}{2}\sigma_z$$

SOC "fictitious" B field

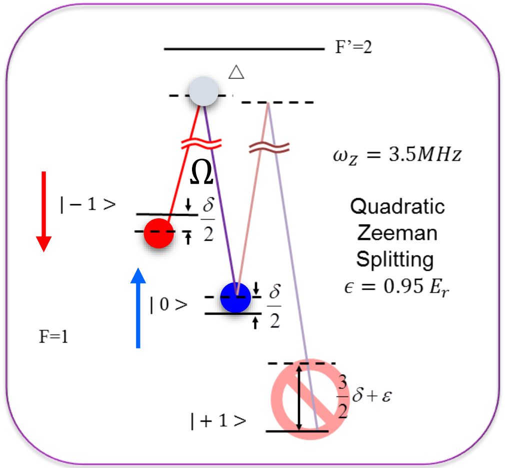
$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

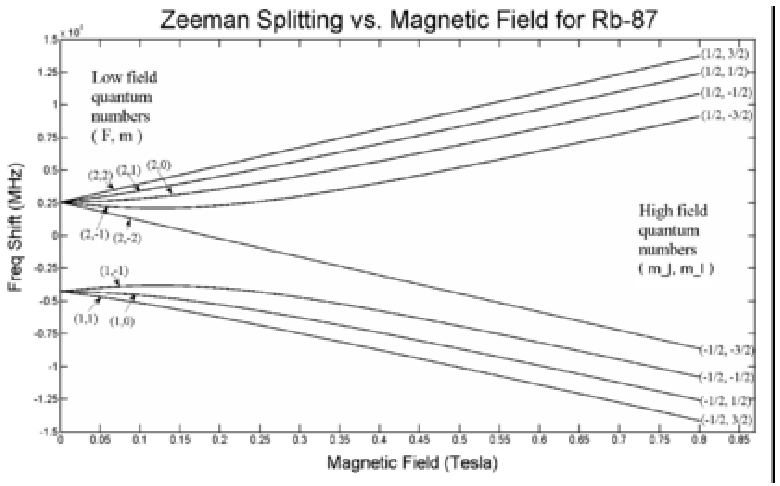
Synthetic Spin Orbit Coupling (SOC) by optical Raman coupling (spin-momentum)

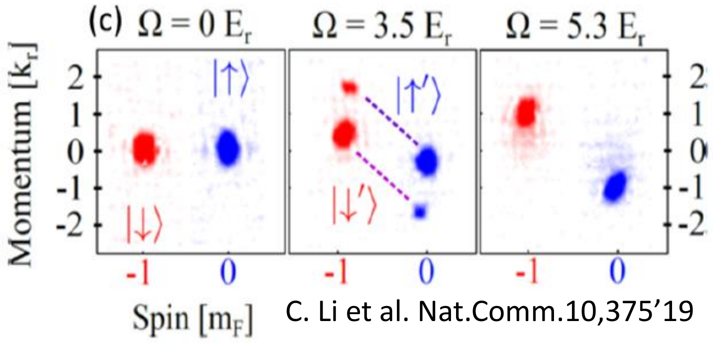




[similar to Spielman/NIST'2011]

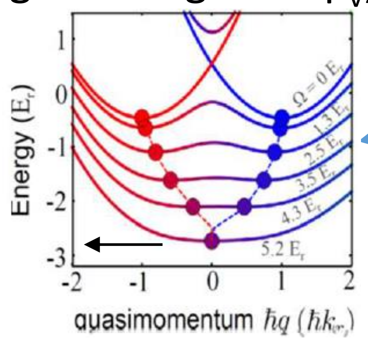






C. Li et al. Nat.Comm.10,375'19

Dressed bandstructure (Eigen-energies vs p_y)



$$\tilde{H} = \begin{pmatrix} \frac{\hbar^2}{2m}(p_y+k_r)^2+\frac{\delta}{2} & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{\hbar^2}{2m}(p_y-k_r)^2-\frac{\delta}{2} \end{pmatrix}$$

control knobs

$$= \frac{\hbar^2 k_r^2}{2m} I + \boxed{\frac{\hbar^2}{2m} p_y^2 I + \frac{\hbar^2 k_r}{m} p_y \sigma_z + \frac{\Omega}{2}\sigma_x} + \frac{\delta}{2}\sigma_z$$

SOC "fictitious" B field

Eigenstate ("dressed state"): $\alpha(p_y)\,|\downarrow, p_y+k_r\rangle + \beta(p_y)\,|\uparrow, p_y-k_r\rangle$

superposition of "bare state"

Synthetic Gauge Fields

$$H = \frac{(\vec{p} - q\vec{A})^2}{2m} \rightarrow \boxed{k_{y,\min} = \frac{qA_y}{\hbar}}$$

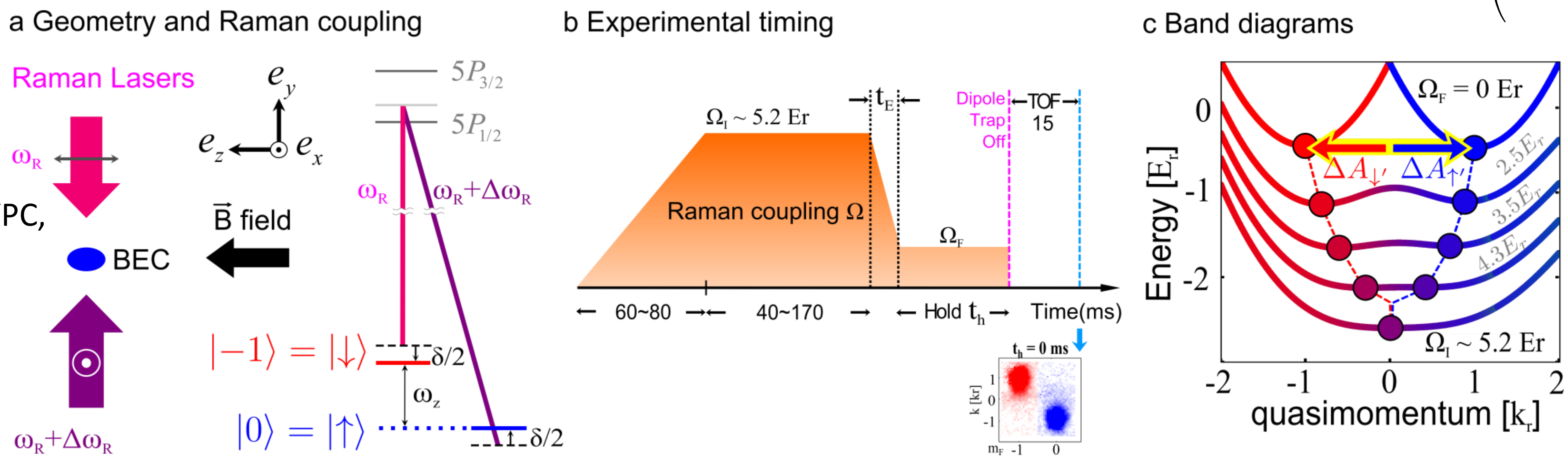
$$\frac{\partial A_y(t)}{\partial t} = E_y \qquad \frac{\partial A_y(x)}{\partial x} = B_z$$

(AC) spin current [spin-dipole mode] in trap

$$\begin{pmatrix} \frac{\hbar^2}{2m}(p_y+k_r)^2 & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{\hbar^2}{2m}(p_y-k_r)^2 \end{pmatrix}$$

Chuan-Hsun Li,
Chunlei Qu,
RJ Niffenegger, ..YPC,

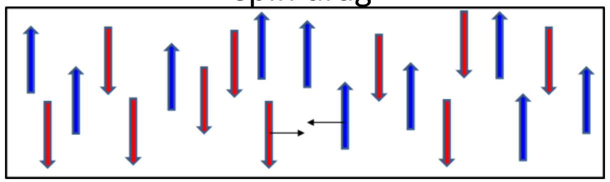
Nature Comm.
10, 375 (2019)



$$H = \frac{\hbar^2}{2m}p_y^2 I + \frac{\hbar^2 k_r}{m}p_y\sigma_z + \frac{\Omega}{2}\sigma_x$$

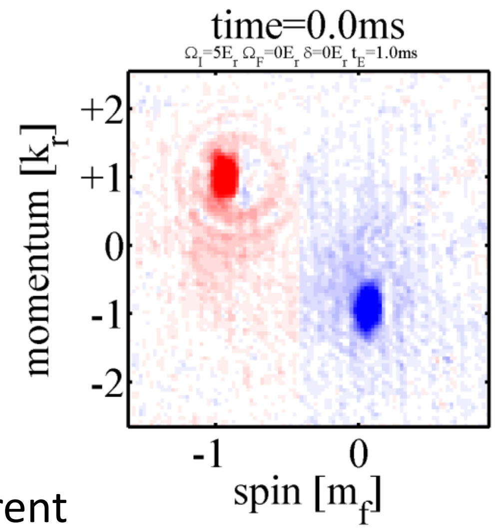
"quantum quench"

"spin drag"



$$\boxed{E_\sigma = \frac{\delta A_\sigma}{\delta t} \approx \frac{\Delta A_\sigma}{t_E}}$$

"Collide 2 spinor BECs in trap"



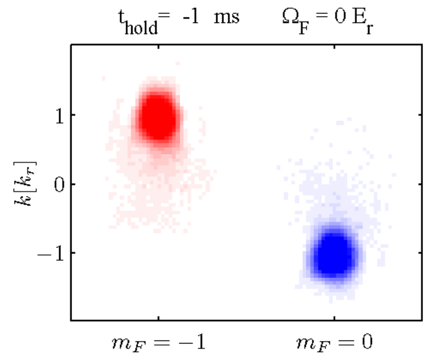
SDM previous studied in non SOC quantum gases,
eg. fermi gas: Sommer [Zwierlein] et al'11 by magnetic gradient
bosons: Koller et al'12; Maddaloni et al'00
theory (fermi gas): Stringari'99, etc. ["spin drag"]

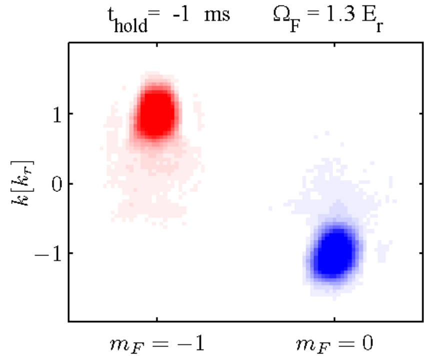
Spin Dipole Mode (SDM) --- AC spin current

What is the effect of SOC?

Spin Dipole Mode (AC Spin Current): no SOC vs SOC

Mechanical momentum

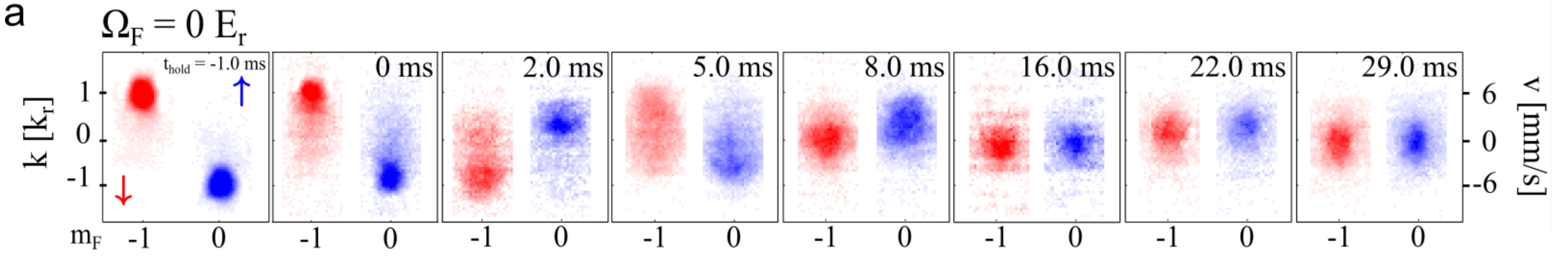


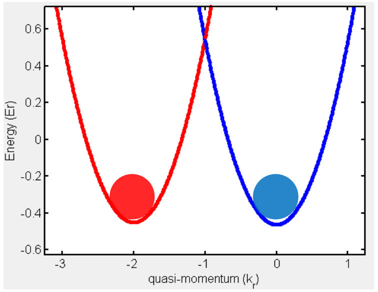


Bare case

Stronger thermalization

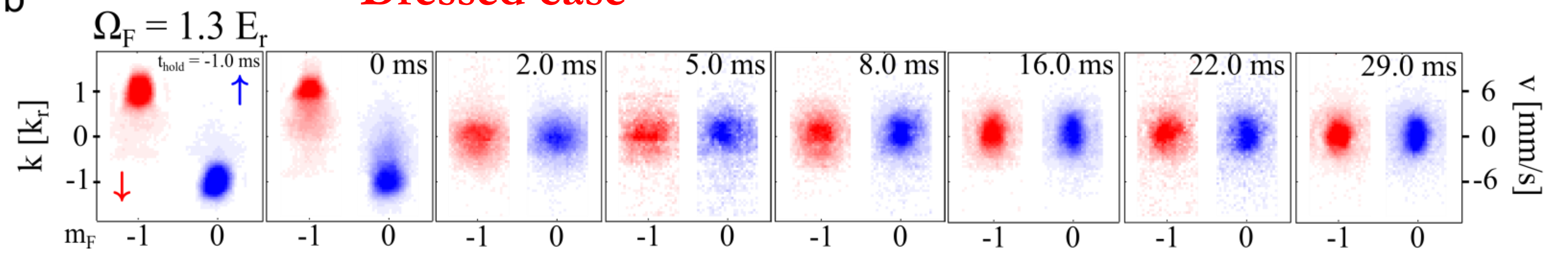
a

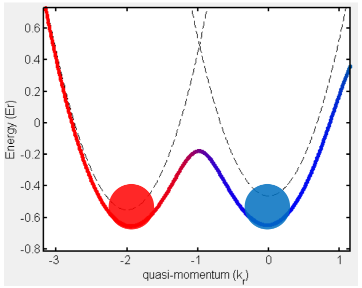




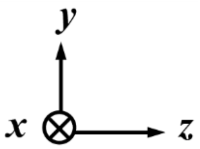
b

Dressed case





Stronger momentum damping, less thermalization

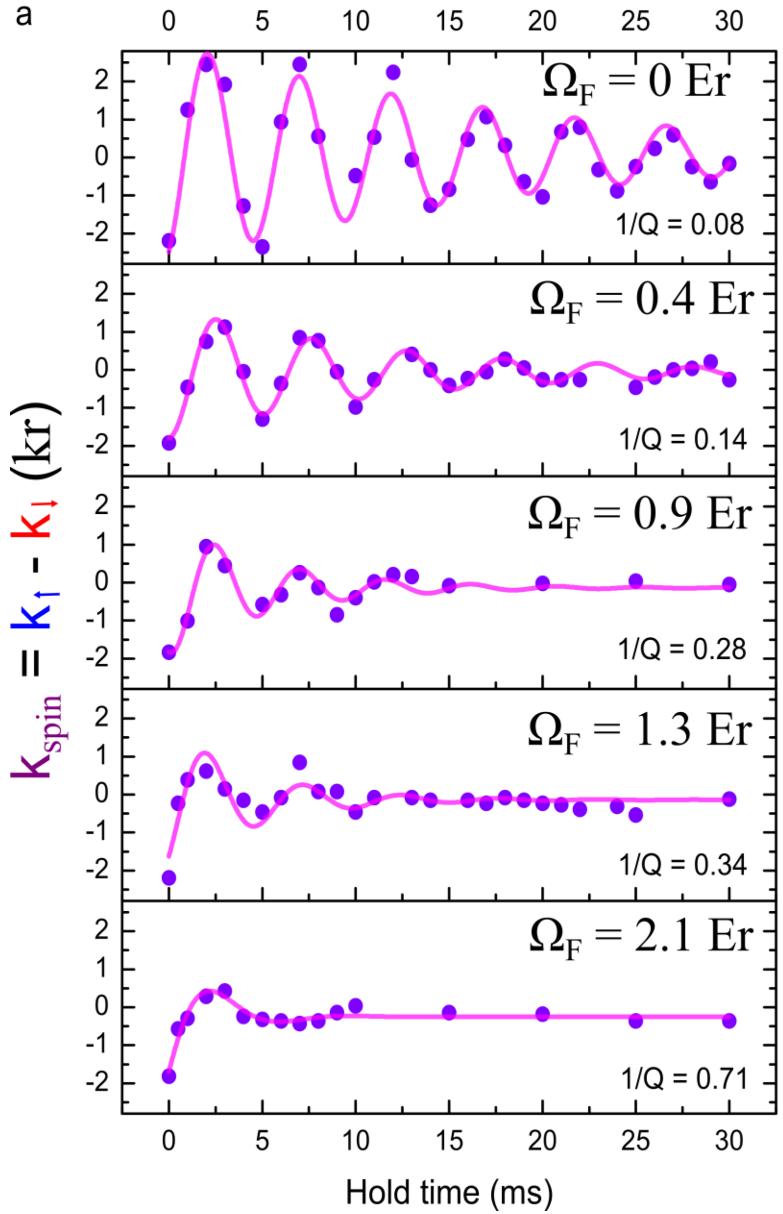


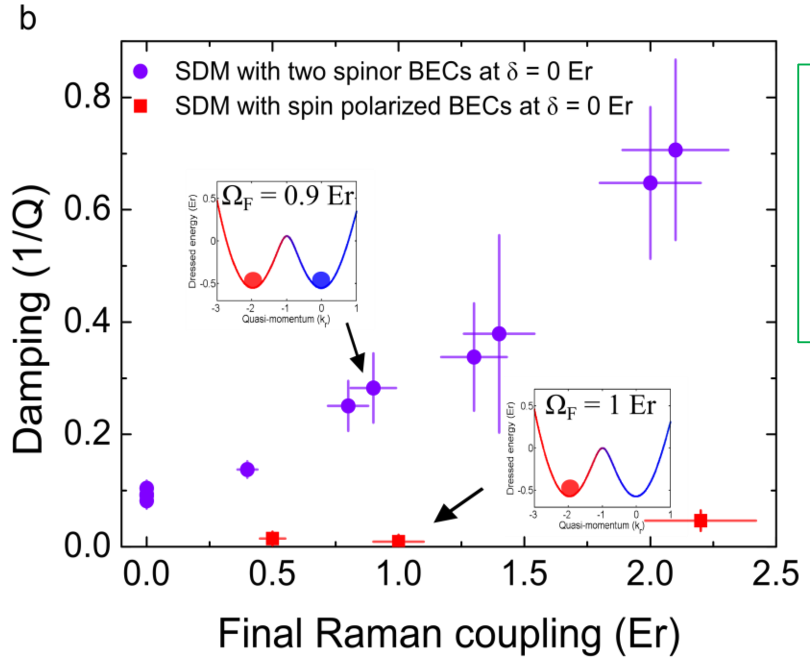
$$N_c \sim 1.3{-}1.6\times 10^4$$

$$\omega_z \sim 2\pi\times(37\pm 3)\ Hz$$

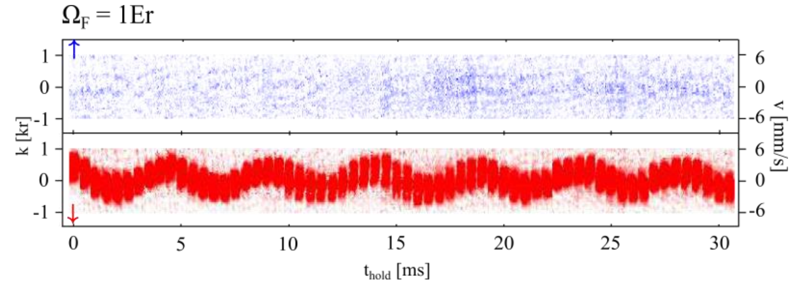
$$\omega_x \sim \omega_y \sim 2\pi\times(205\pm 15)\ Hz$$

Momentum Damping (1/Q) versus Final Raman coupling Ω_F





- Spin dipole mode/spin transport strongly damped by SOC)
- dipole mode/mass transport NOT damped by SOC)

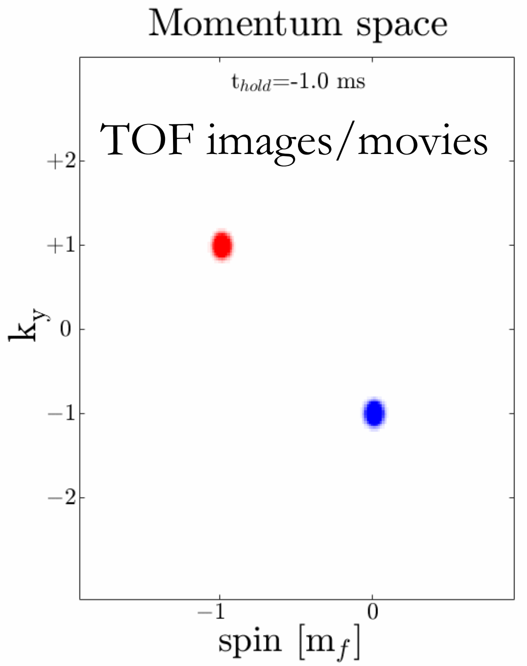


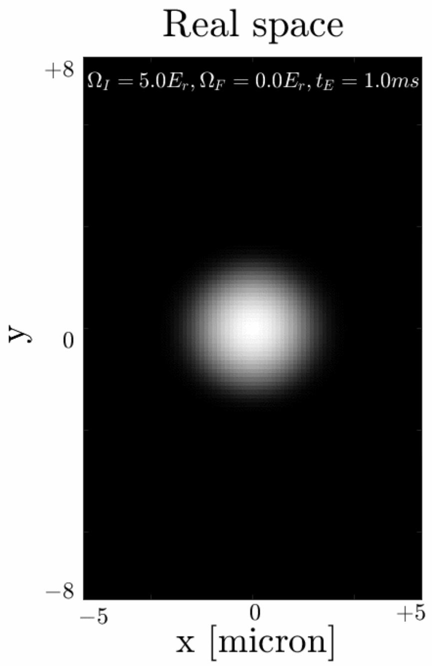
$$\frac{d^2y}{dt^2} = -\frac{1}{Q}\omega_0\frac{dy}{dt} - \omega_0^2 y$$

$$\frac{dy}{dt} = \frac{\hbar k}{m} \qquad \tau_{damp} = t_{trap}Q/\pi$$

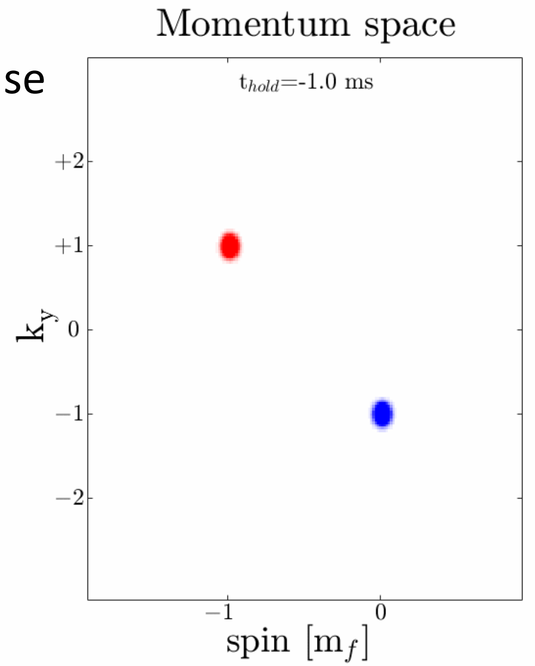
Damping factor (1/Q) increases as damping increases

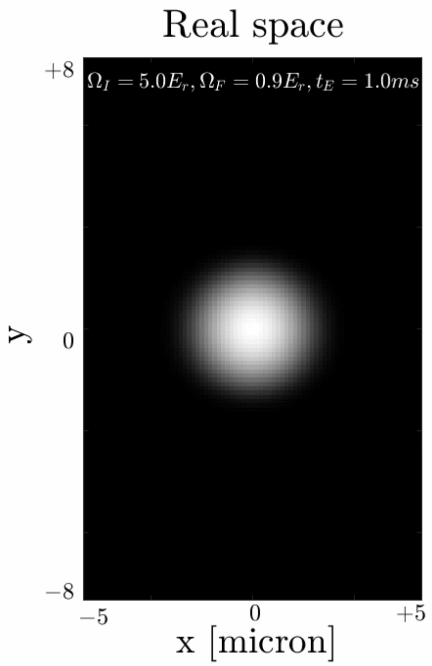
Bare case





Dressed case





GPE Simulation of SDM:
In-situ images/movies

GPE done by Chunlei Qu & Chuanwei Zhang (UT Dallas)

$$\Psi = \begin{pmatrix} \psi_\downarrow \\ \psi_\uparrow \end{pmatrix} = \begin{pmatrix} \sqrt{n_\downarrow(\mathbf{r},t)}e^{i\phi_\downarrow(\mathbf{r},t)} \\ \sqrt{n_\uparrow(\mathbf{r},t)}e^{i\phi_\uparrow(\mathbf{r},t)} \end{pmatrix}$$

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = H_{\mathrm{tot}}\Psi(\mathbf{r},t)$$
$$= \left(\frac{\hat{p}_x^2}{2m} + \frac{\hat{p}_z^2}{2m} + H_{\mathrm{SOC}} + V_{\mathrm{trap}} + V_{\mathrm{int}}\right)\Psi(\mathbf{r},t)$$

$$\hat{p}_y/\hbar = -i\frac{\partial}{\partial y}$$

$$\boxed{H_{\mathrm{SOC}} = \begin{pmatrix} \frac{\hbar^2}{2m}(q_y + k_{\mathrm{r}})^2 - \delta_{\mathrm{R}} & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{\hbar^2}{2m}(q_y - k_{\mathrm{r}})^2 \end{pmatrix}}$$

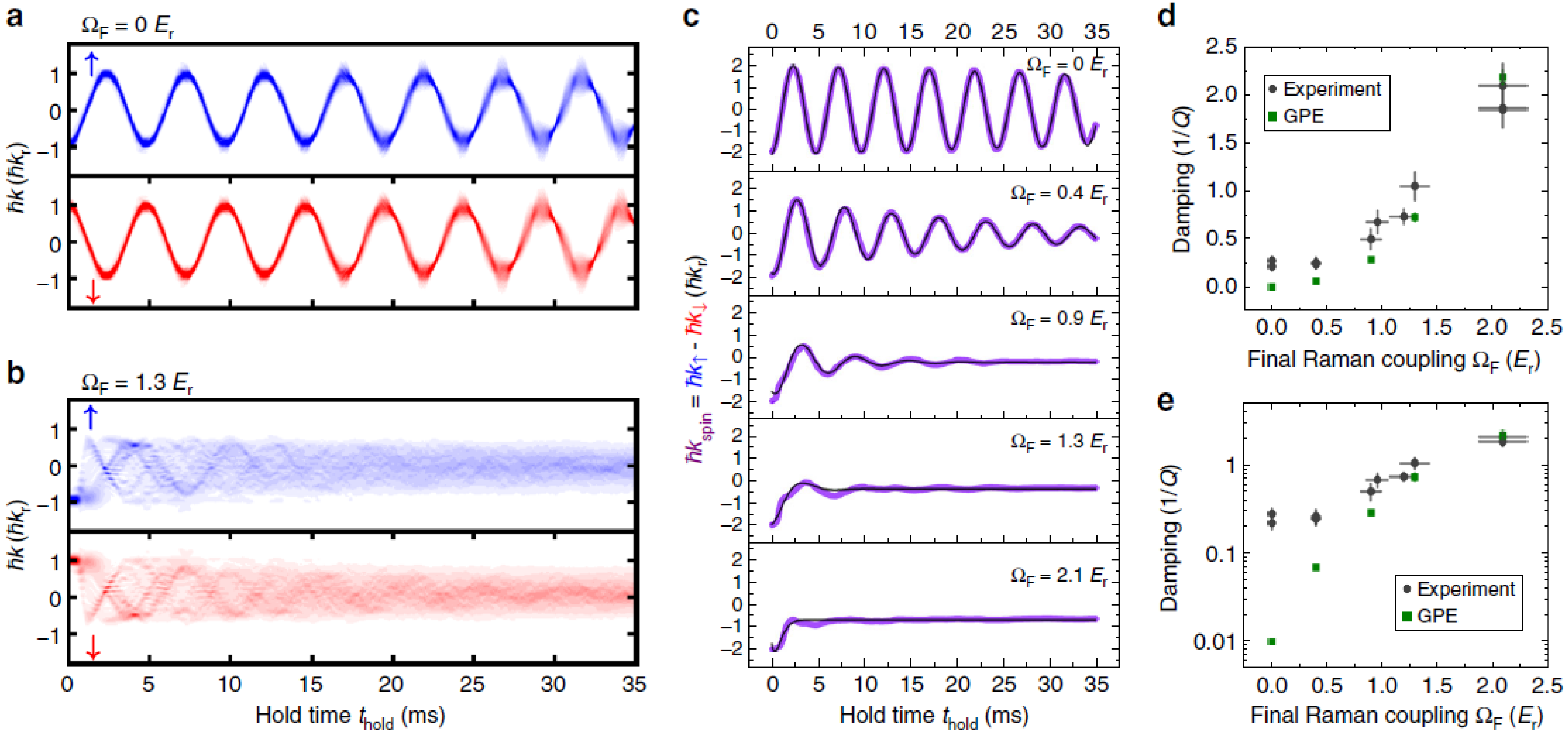
$$V_{\mathrm{trap}} = \frac{1}{2}m\omega_x^2x^2 + \frac{1}{2}m\omega_y^2y^2 + \frac{1}{2}m\omega_z^2z^2$$

$$V_{\mathrm{int}} = \begin{pmatrix} g_{\downarrow\downarrow}|\psi_\downarrow|^2 + g_{\downarrow\uparrow}|\psi_\uparrow|^2 & 0 \\ 0 & g_{\uparrow\uparrow}|\psi_\uparrow|^2 + g_{\uparrow\downarrow}|\psi_\downarrow|^2 \end{pmatrix}$$

$$g_{\downarrow\downarrow} = g_{\downarrow\uparrow} = g_{\uparrow\downarrow} = \frac{4\pi\hbar^2(c_0 + c_2)}{m} \qquad c_2 = -0.46a_0$$

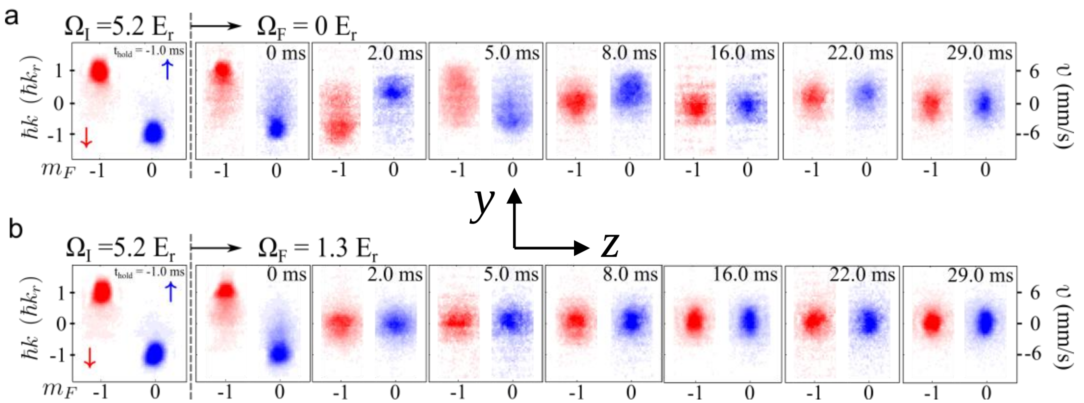
$$g_{\uparrow\uparrow} = \frac{4\pi\hbar^2 c_0}{m} \qquad c_0 = 100.86a_0$$

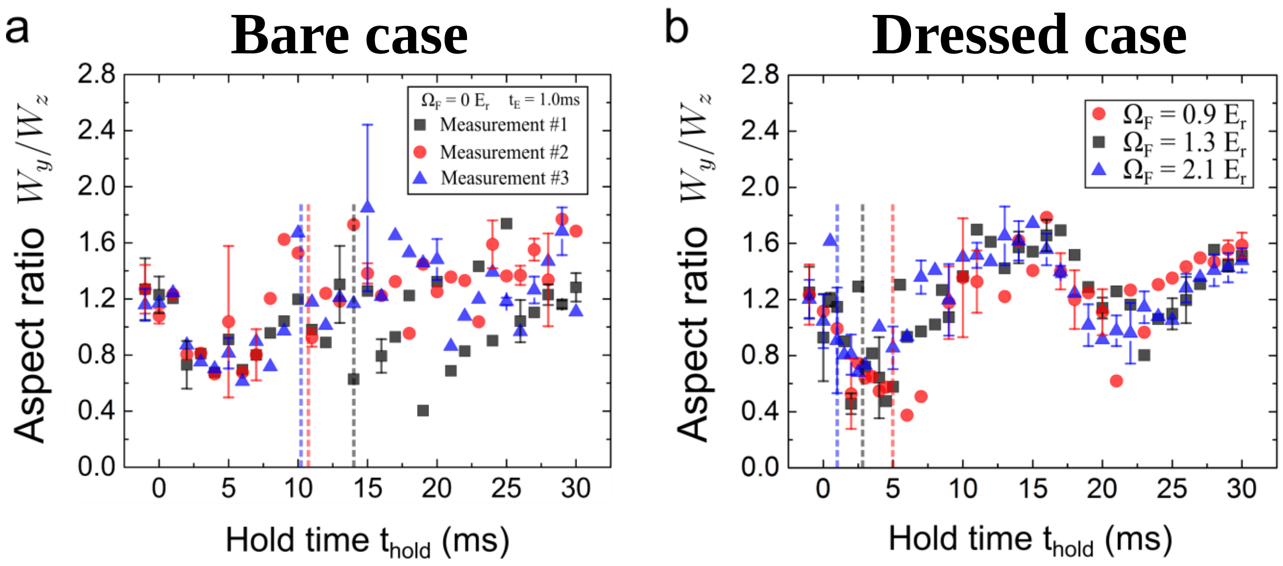
GPE simulation qualitatively explains damping

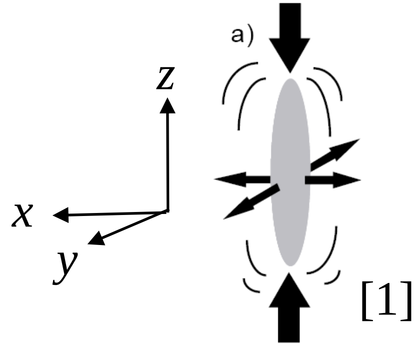


Observation of BEC Shape Oscillations (Quadrupole Modes)

We also study shape oscillations, which is an example of the kinetic energy that does not contribute to the global BEC motion.







$\omega_z \sim 2\pi \times (37 \pm 3)\ Hz$

$\omega_x \sim \omega_y \sim 2\pi \times (205 \pm 15)\ Hz$

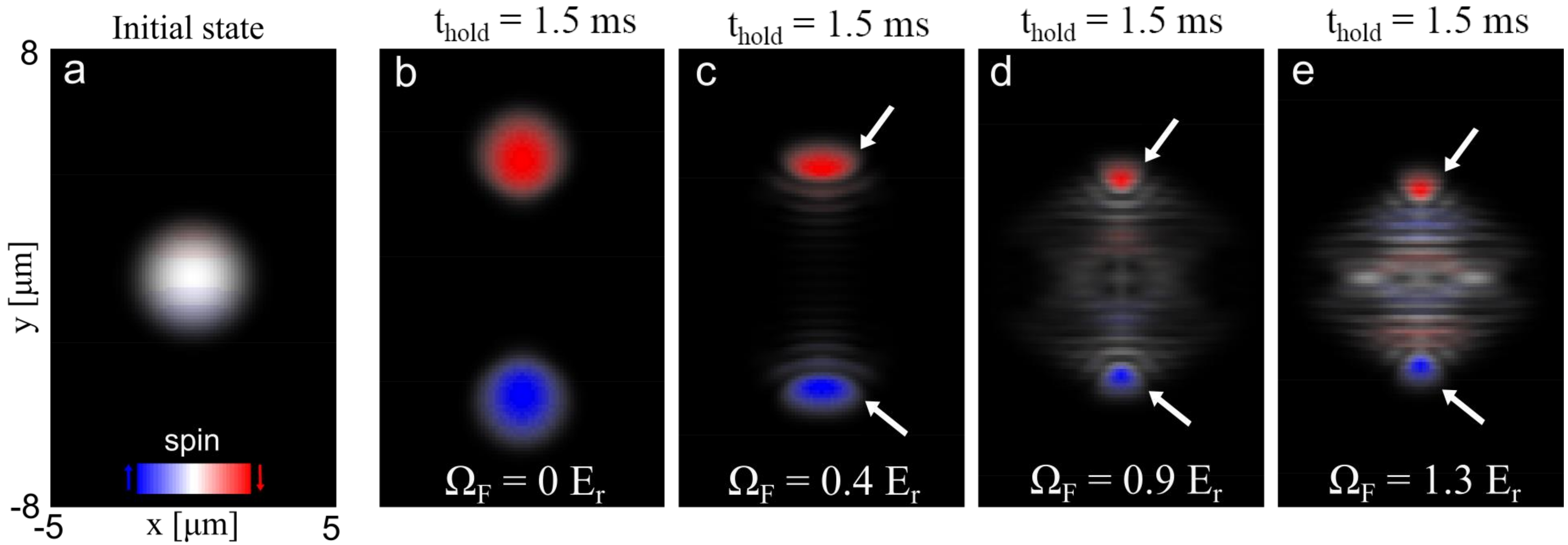
Oscillations do not seem to possess a well-defined frequency.

Oscillations have a well-defined average frequency of 58 Hz, consistent with the predicted frequency of the m=0 quadrupole mode: $f_{m=0} = \sqrt{2.5}\omega_z/(2\pi) \sim 59$ Hz for a cigar shape BEC.

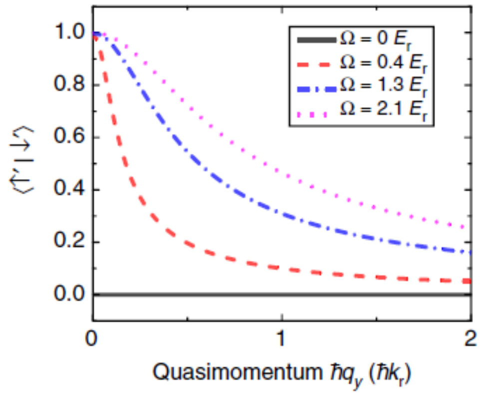
[1] W. Ketterle et al, arXiv:cond-mat/9904034

Understanding the SDM damping

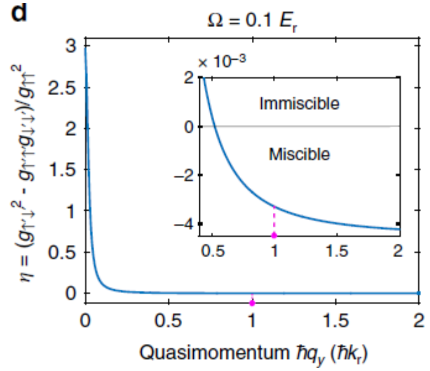
GPE Simulation of SDM:
In-situ images
GPE done by Chunlei Qu
& Chuanwei Zhang (UT Dallas)



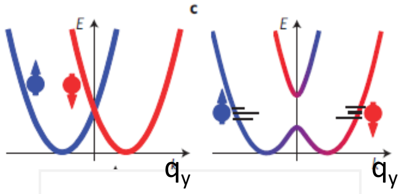
When two dressed spins collide: increased interaction energy, formation of density modulation, excitation of other collective modes (eg. quadrupole mode)



(M.He & Q.Zhou)



$$H = \frac{\hbar^2}{2m} q_y^2 I + \frac{\hbar^2 k_r}{m} q_y \sigma_z + \frac{\Omega}{2} \sigma_x$$



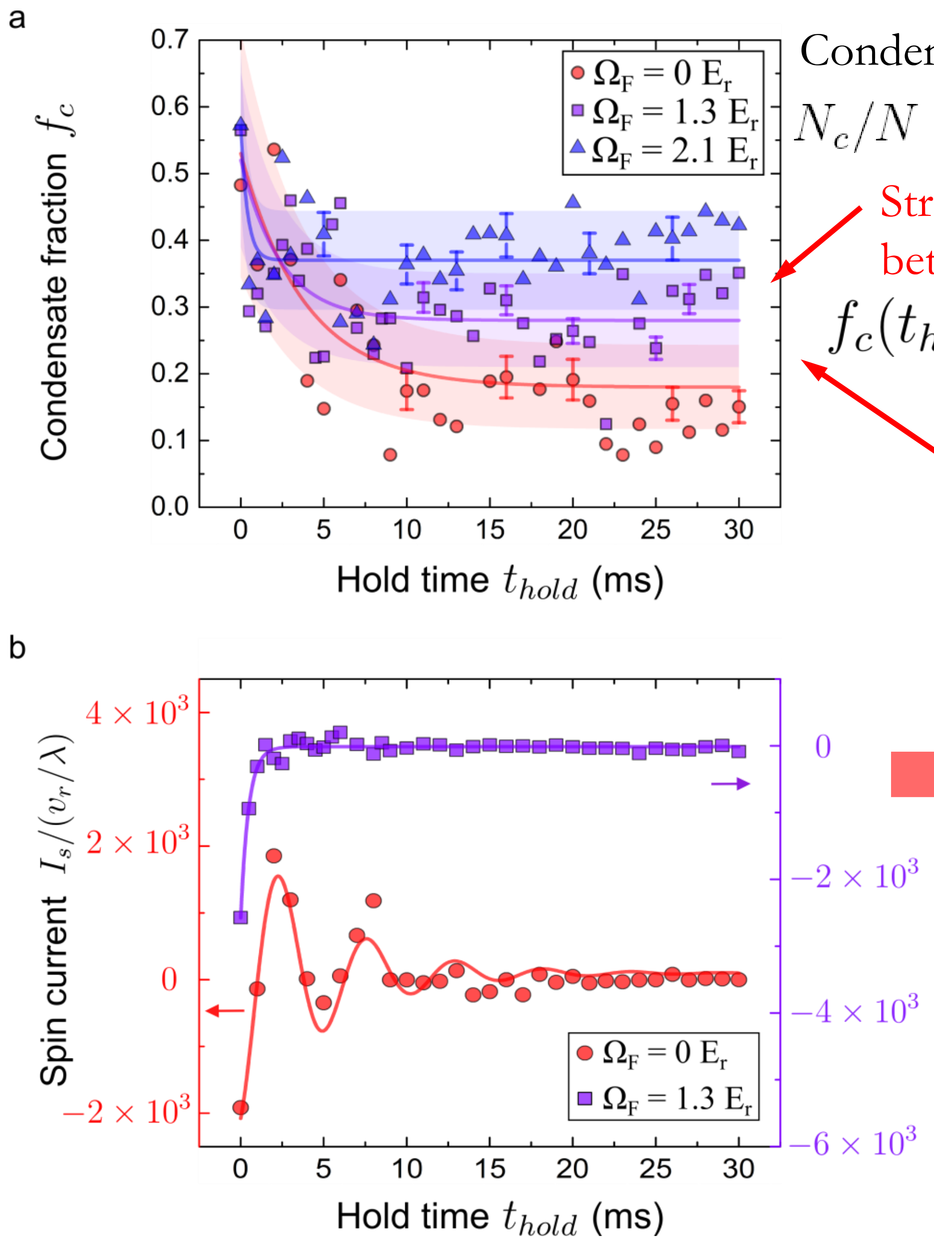
Eigenstate ("dressed state"): $\alpha(q_y)|\downarrow, q_y + k_r\rangle + \beta(p_y)|\uparrow, q_y - k_r\rangle$

Acknowledge discussion with Hui Zhai et al.

At Ω>0 (dressed), spin part no longer orthogonal, the wavefunction interference leads to enhanced interaction, which excites breathing mode (decay channel of SDM) and leads to strong damping of SDM; this strong damping gives less oscillation thus less heating

Other important factor: (enhanced) immiscibility of dressed BECs when moving (q →0)

Thermalization and Spin Current Relaxation



Condensate fraction:

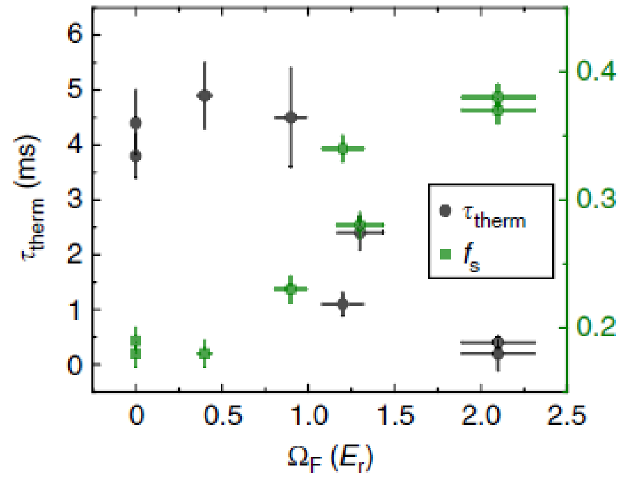
$$N_c/N = (N_c^{\uparrow} + N_c^{\downarrow})/(N_c^{\uparrow} + N_{therm}^{\uparrow} + N_c^{\downarrow} + N_{therm}^{\downarrow})$$

Stronger momentum damping stops the collision between different spins earlier.

$$f_c(t_{hold}) = f_s + (f_i - f_s)\exp(-t_{hold}/\tau_{therm})$$

Thermalization

Momentum damping



Spin current: $I_s = I_{\uparrow} - I_{\downarrow}$

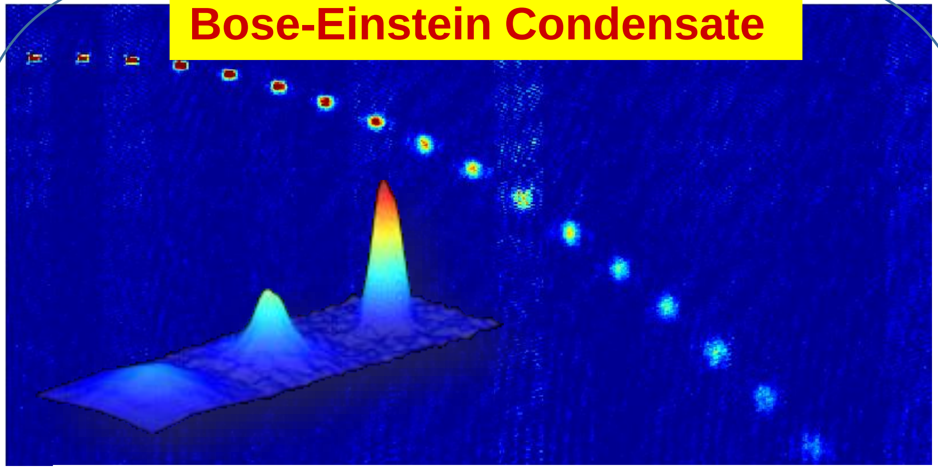
$$I = \frac{N_c}{L} v = \boxed{f_c} \cdot \boxed{v} \cdot \frac{N}{L}$$

Effects of SOC on spin current relaxation:

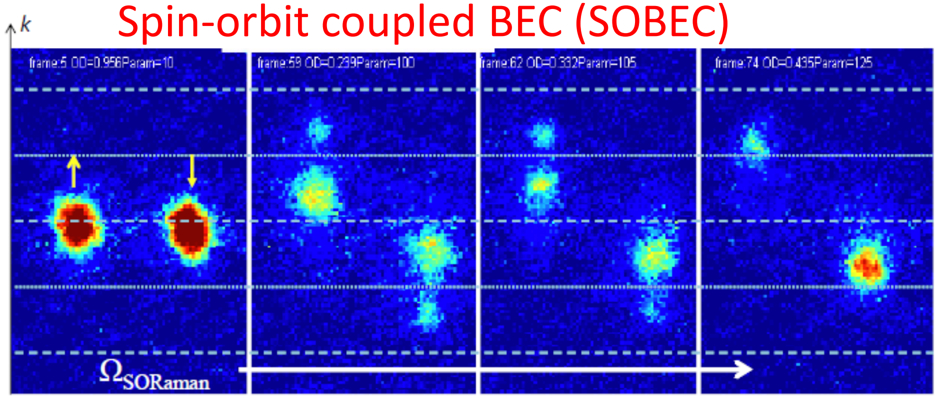
1. Stronger momentum damping
2. Less thermalization

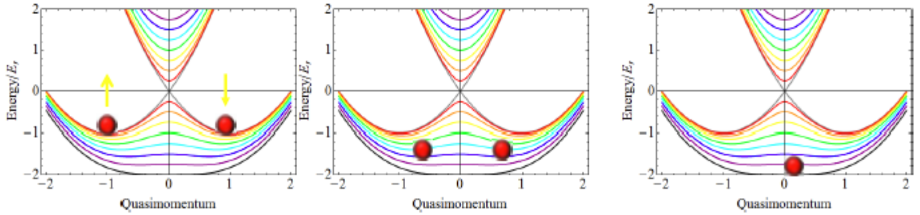
AMO Research in Quantum Matter and Device (QMD) Laboratory

Bose-Einstein Condensate



Spin-orbit coupled BEC (SOBEC)



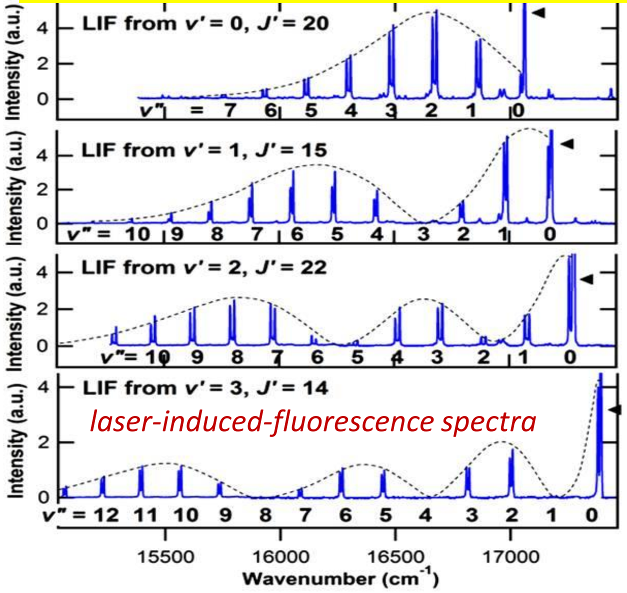


"synthetic" gauge fields & (dressed) bandstructures

- **Quantum transport & dynamics**
- **Photoassociation**

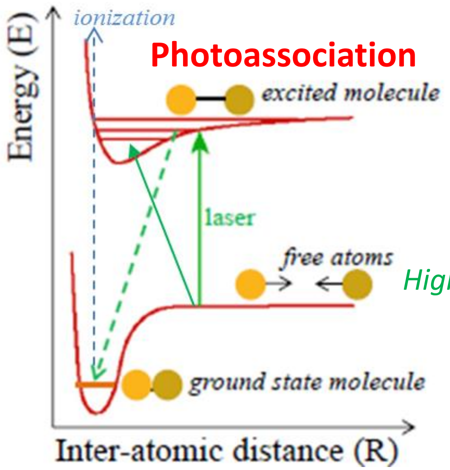
http://www.physics.purdue.edu/quantum/bec.php

(Cold/Polar) LiRb Molecules

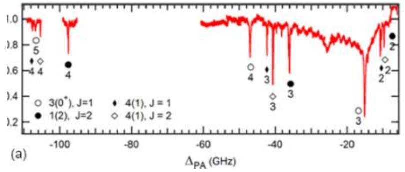


S. Dutta et al. CPL 511, 7 (2011)

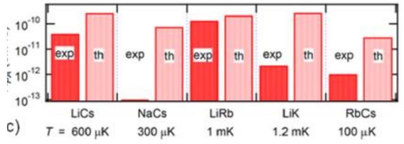
Joint experiment with Dan Elliott (Purdue)



*First **LiRb cold molecules***



Highest PA rate among bi-alkalis!



S. Dutta et al. EPL 104, 63001(2013); PRA 89,020702(2014)

D. Blasing et al. PRA 94, 062504 (2016) [short-range PA]

http://www.physics.purdue.edu/quantum/mol.php

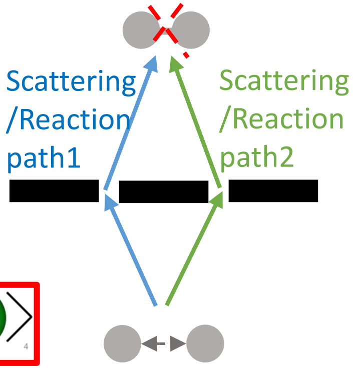
Effects of quantum superposition and interference in spin-dependent photoassociation of ^{87}Rb Bose-Einstein condensates

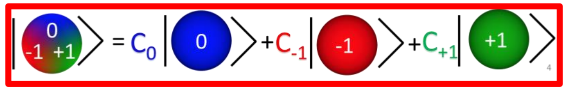
David Blasing
(→ Crane)

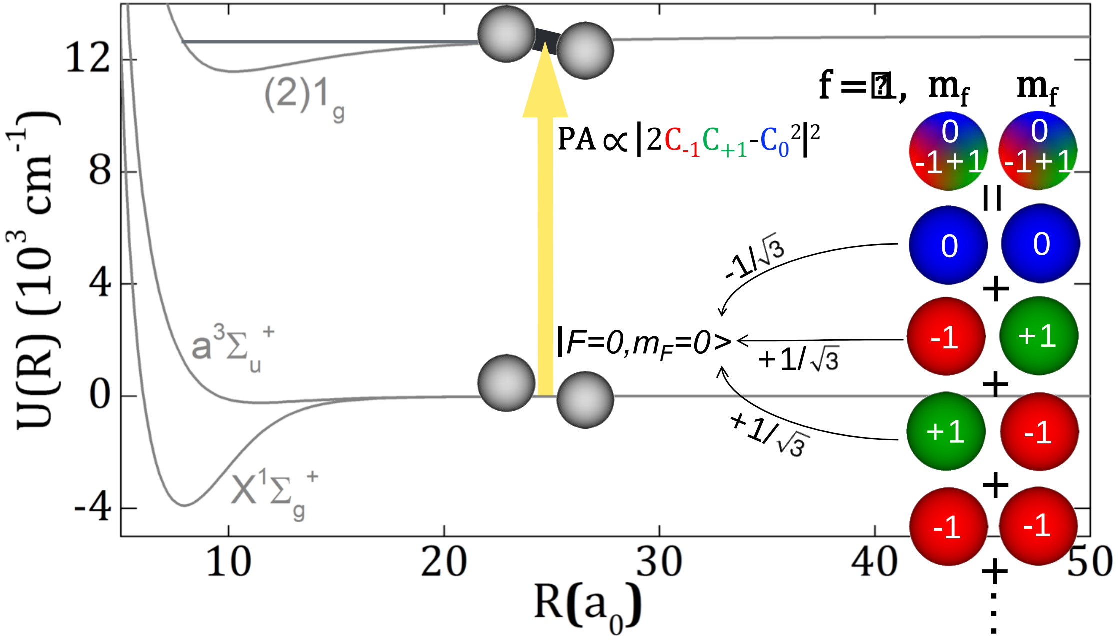
PHYSICAL REVIEW LETTERS **121**, 073202 (2018)

Observation of Quantum Interference and Coherent Control in a Photochemical Reaction

David B. Blasing,[1] Jesús Pérez-Ríos,[2] Yangqian Yan,[1] Sourav Dutta,[1,3,†]
Chuan-Hsun Li,[4] Qi Zhou,[1,5] and Yong P. Chen[1,4,5,*]



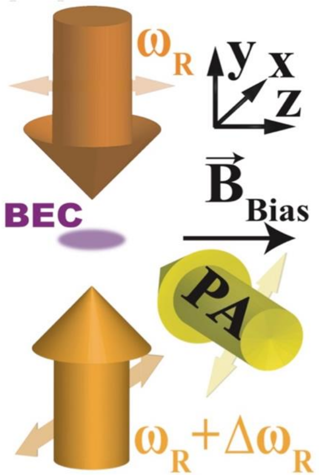


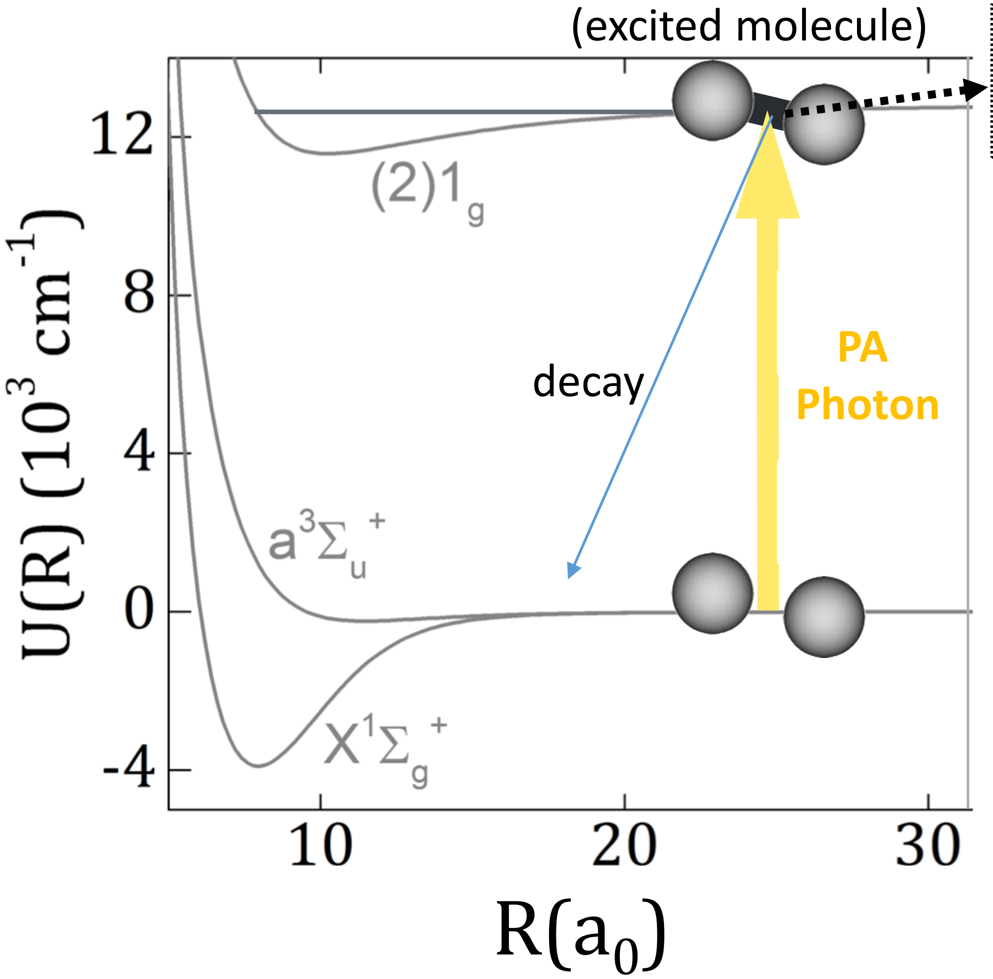


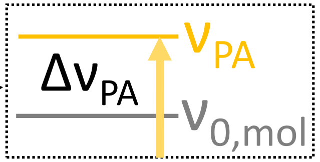
New approach for
"coherent photochemistry"
(not using pulsed/interfering lasers)

(we will also move onto 3x3 matrices..)

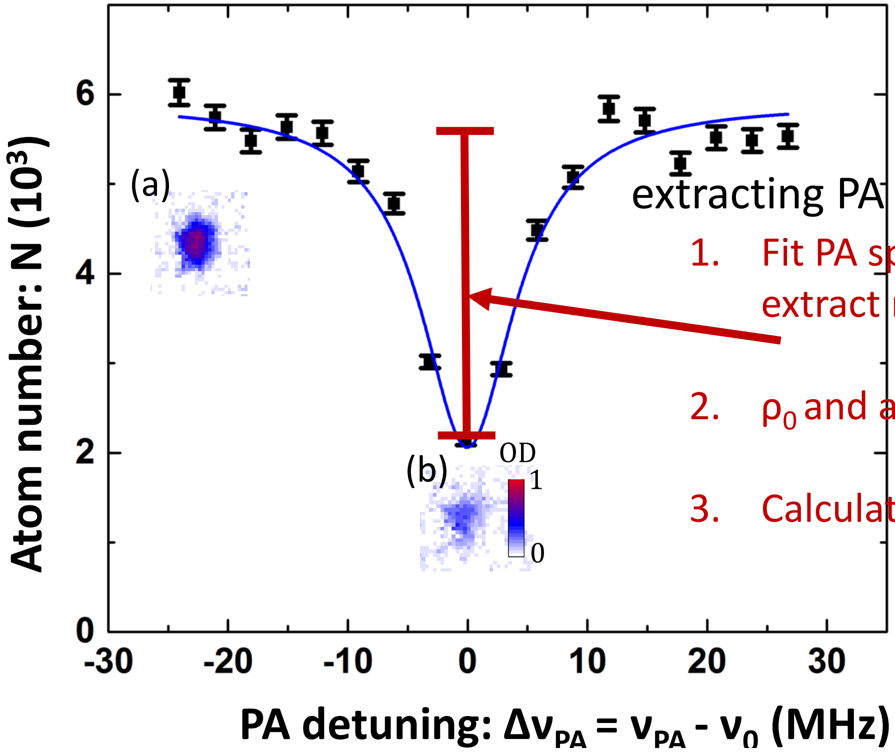
Photoassociation (PA) – loss of atoms from trap







Note: PA can measure "Tan's contact"



extracting PA rate k_{PA}

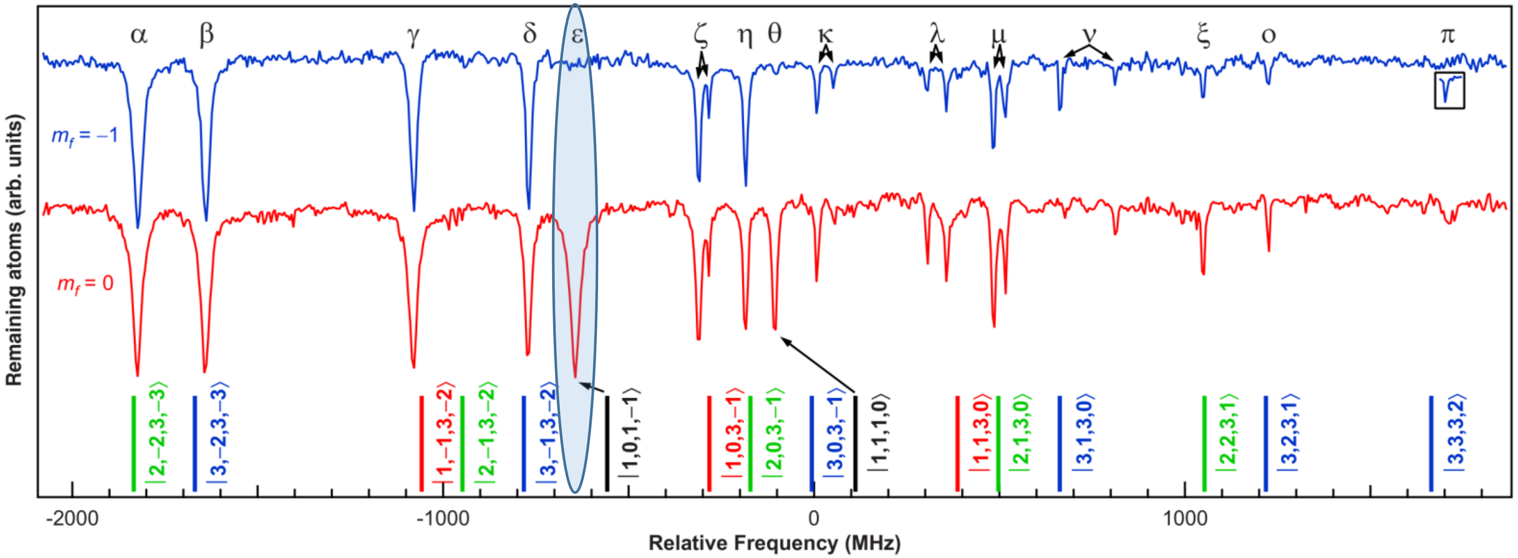
1. Fit PA spectra and extract $\eta = k_{PA}\rho_0 t_{pa}$
2. ρ_0 and and t_{pa} known
3. Calculate $k_{PA}=\eta/\rho_0 t_{pa}$

^{87}Rb potentials from Allouche, et al., J. Chem. Phys. **136**, 114302 (2012).

$$d\rho(t,\vec{r})/dt = -k_{PA}\rho^2(t,\vec{r}) \quad N(\eta) = N_0 \frac{15}{2}\eta^{-5/2}[\eta^{1/2} + \frac{1}{3}\eta^{3/2} - (1+\eta)^{1/2}\tanh^{-1}(\sqrt{\eta/(1+\eta)})].$$

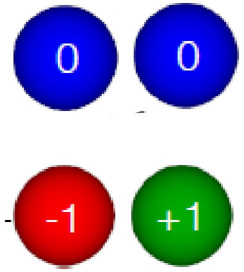
C. McKenzie et al., Phys. Rev. Lett. **88**, 120403 (2002).

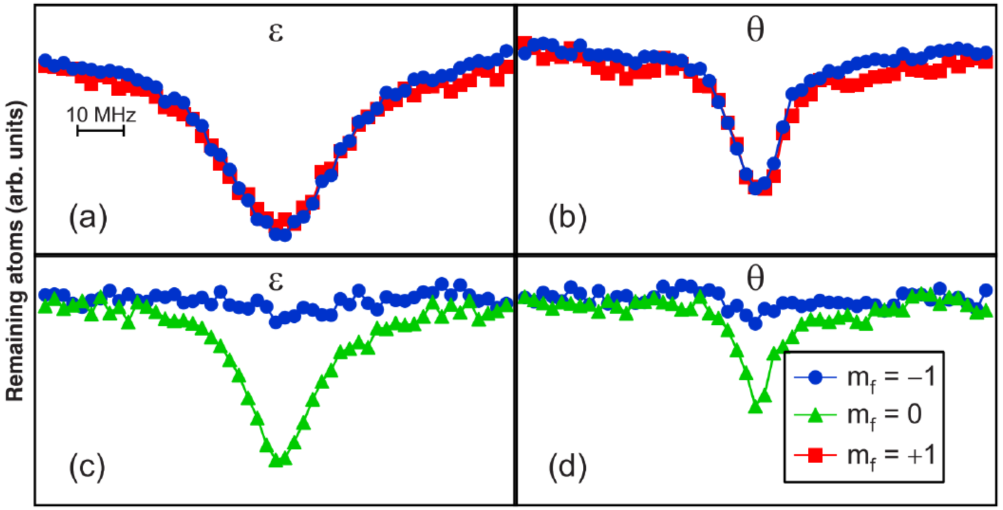
Photoassociation can be spin-dependent



Key point: choose PA line that require colliding atoms (reactants) must have $m_{f,1} + m_{f,2} = 0$

|f=1,m$_f$> pairs:

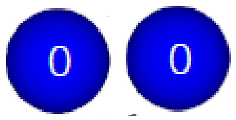


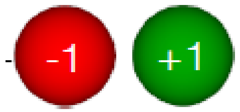


C. Hamley [M.Chapman], et al., Phys. Rev. A **79**, 23401 (2009).

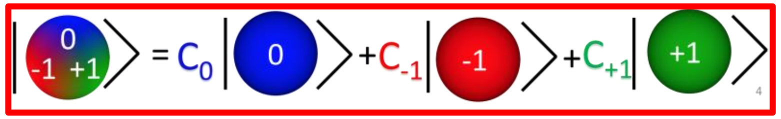
“spin-dependent” Photoassociation

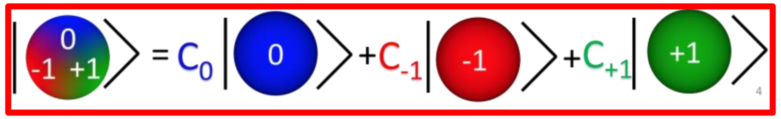
Key point: for our PA line, colliding atoms must have $m_{f,1} + m_{f,2} = 0$





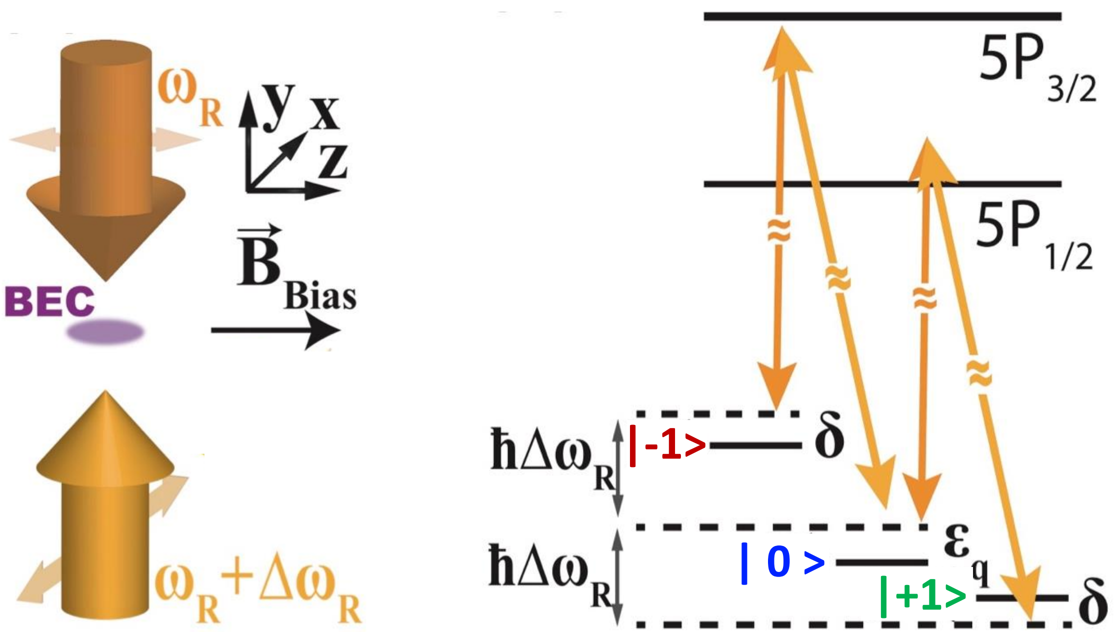
Question: atoms in spin superpositions simultaneously access multiple spin-pathways, what is PA process like?



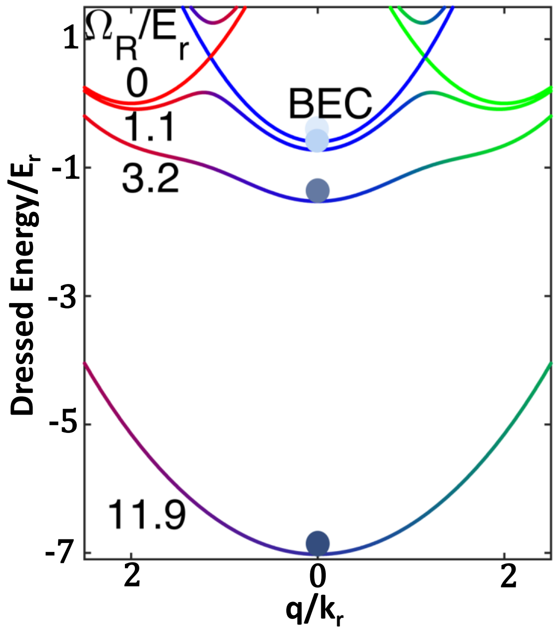


D. Blasing *et al*., “Observation of Quantum Interference and Coherent Control in a Photo-Chemical Reaction”, Phys. Rev. Lett. 121, 073202 (2018)

Spin(-momentum) superposition states



Rep. bandstructures at δ=0

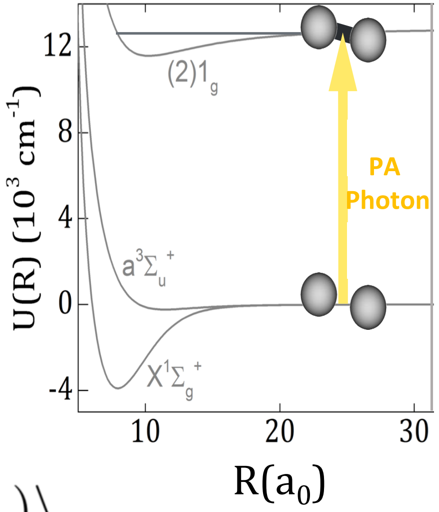


More information on our SOC BEC: A. Olson et al. PRA'14; PRA'17

$$\begin{pmatrix} \frac{\hbar^2}{2m}(q+2k_r)^2-\delta & \frac{\Omega_R}{2} & 0 \\ \frac{\Omega_R}{2} & \frac{\hbar^2}{2m}q^2-\epsilon_q & \frac{\Omega_R}{2} \\ 0 & \frac{\Omega_R}{2} & \frac{\hbar^2}{2m}(q-2k_r)^2+\delta \end{pmatrix}$$

Lin/Spielman[NIST], PRL'09

q: quasimomentum
k_r: recoil momenta
δ: Raman detuning
Ω_R: Raman coupling
ε_q: quadratic shift



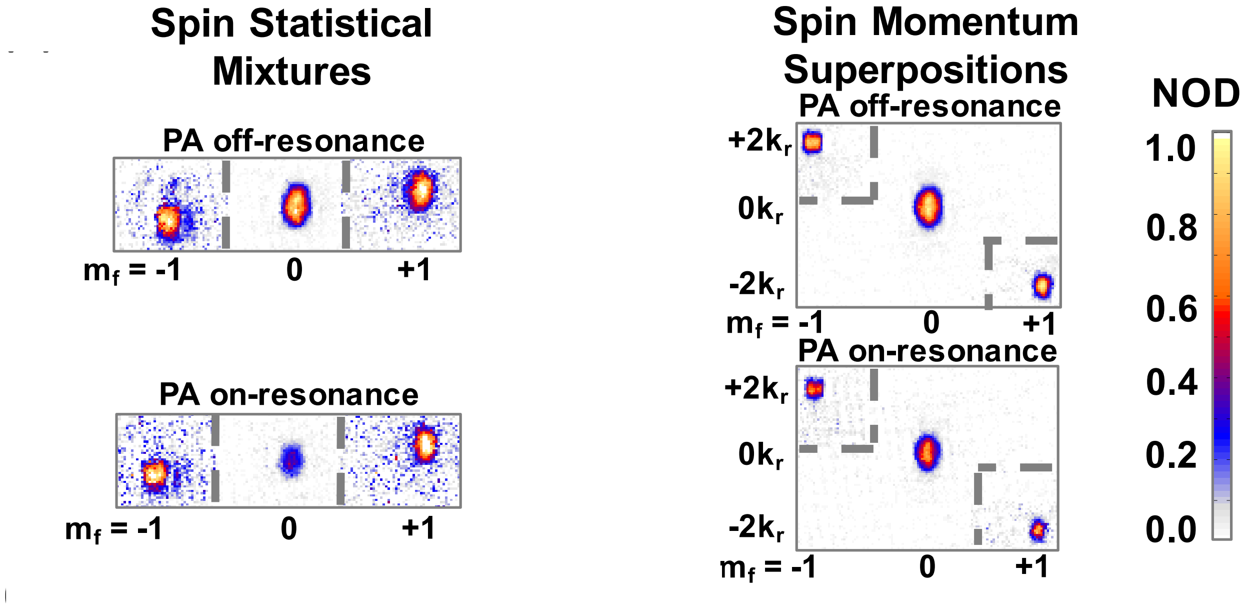
Creates spin-momentum superpositions :

$$\sum_{i=1}^{3} C_i \left|m_f, p\right\rangle_i = C_{-1}\left|-1, \hbar(q+2k_r)\right\rangle + C_0\left|0, \hbar q\right\rangle + C_{+1}\left|+1, \hbar(q-2k_r)\right\rangle$$

Note: momentum part of the superposition do not affect PA (length scale << $1/k_r$)

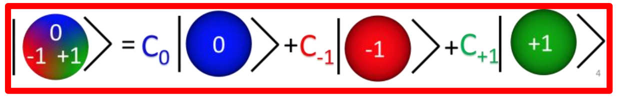
PA on spin(-momentum) superpositions

Evidence for superposition state (all components undergo PA together!)



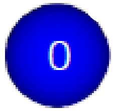
D. Blasing *et al*., “Observation of Quantum Interference and Coherent Control in a Photo-Chemical Reaction”, Phys. Rev. Lett. 121, 073202 (2018)

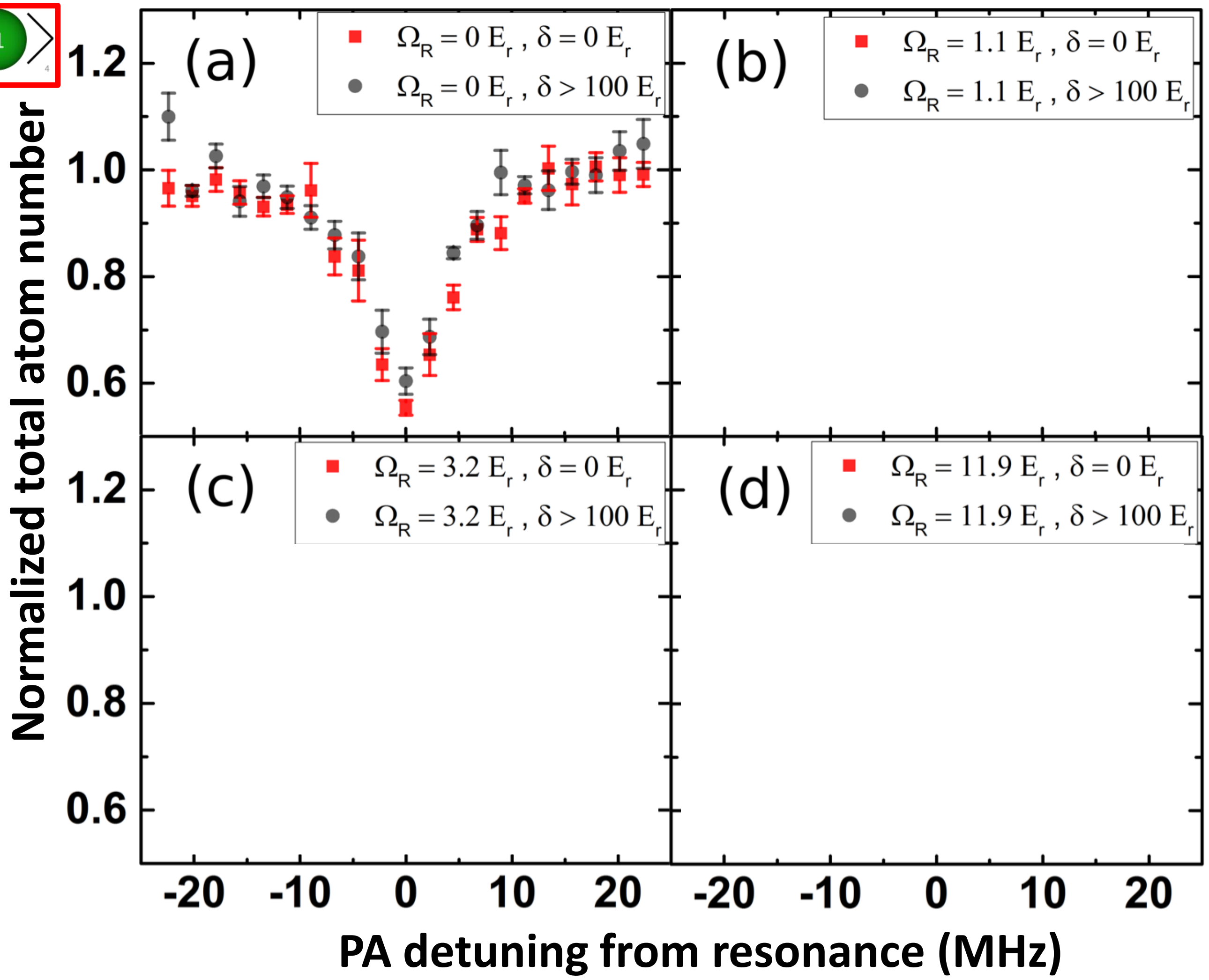
PA on spin(-momentum) superpositions with increasing Ω_R



(a) → (d): turning on the spin-momentum superpositions

(a) → (d): control, no spin-momentum superpositions [bare BEC of m_F=0]





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→ ***red and black curves diverge: PA significantly modified for dressed BEC (superposition), even ~ completely "turned off" at large Ω_R !***

PA on spin(-momentum) superpositions

$$\psi_{scat} \propto \sum_{i=-1}^{+1}\sum_{j=-1}^{+1} C_i C_j \, |f=1, m_f=i\rangle_a \otimes |f=1, m_f=j\rangle_b$$

$$k_{ine} \propto |\langle \psi_{mol} | \vec{d}\cdot\vec{E} | \psi_{scat}\rangle|^2$$

f, m_f

$$|1,0\rangle \otimes |1,0\rangle = \sqrt{\tfrac{2}{3}}|2,0\rangle - \sqrt{\tfrac{1}{3}}|0,0\rangle$$

opposite CG coefficient!

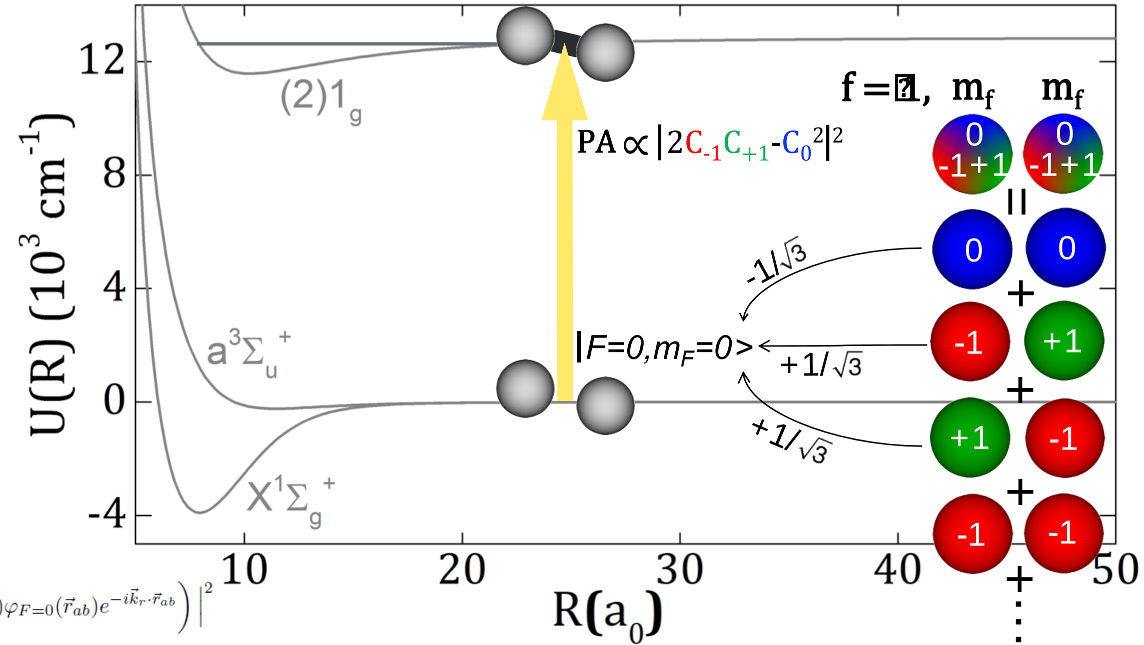
Total F, m_F

$$|1,-1\rangle \otimes |1,-1\rangle = \sqrt{\tfrac{1}{6}}|2,0\rangle - \sqrt{\tfrac{1}{2}}|1,0\rangle + \sqrt{\tfrac{1}{3}}|0,0\rangle$$

$$\propto |2C_{-1}C_{+1} - C_0^2|^2$$

$$k_{sup} = k_{0,0}(|c_0^2|^2 + 4|c_{-1}c_{+1}|^2 - 4\Re(c_0^2 c_{-1} c_{+1}))$$

Prediction: PA rate for spin superpositions modified over bare rate

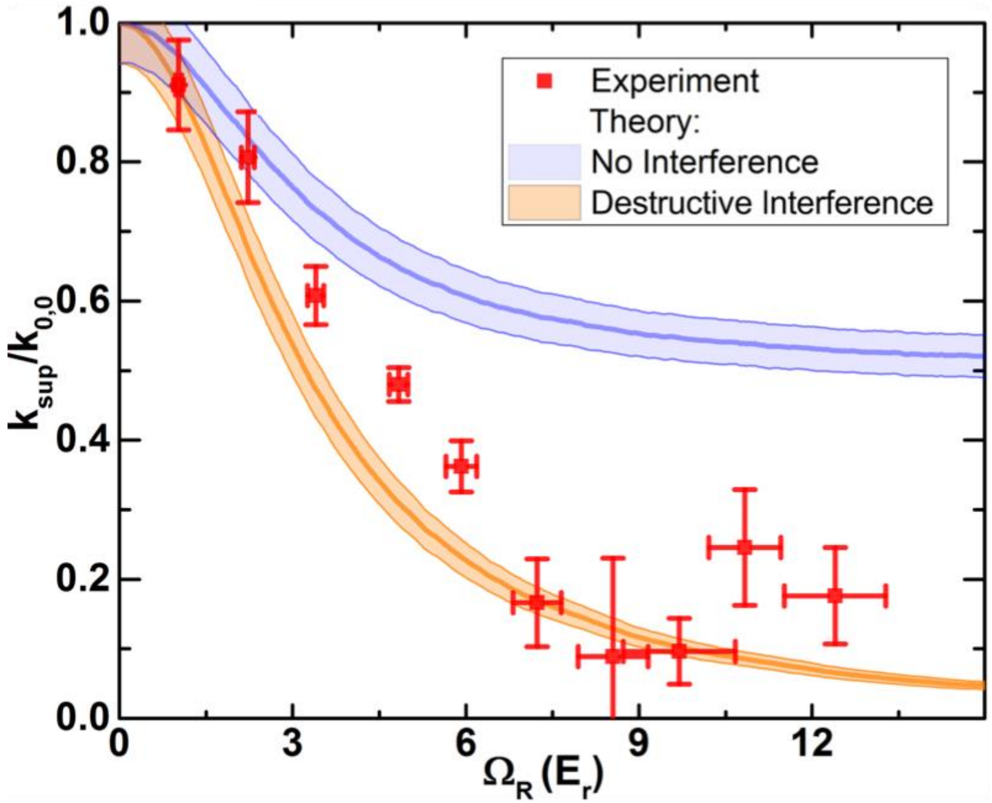


$$\Gamma_{sup} \propto \left| -\frac{C_0^2}{\sqrt{3}}\left(\int d\vec{r}_{ab}\varphi_m^*(\vec{r}_{ab})\varphi_{F=0}(\vec{r}_{ab})\right) + \frac{C_1 C_{-1}}{\sqrt{3}}\left(\int d\vec{r}_{ab}\varphi_m^*(\vec{r}_{ab})\varphi_{F=0}(\vec{r}_{ab})e^{i\vec{k}_r\cdot\vec{r}_{ab}} + \int d\vec{r}_{ab}\varphi_m^*(\vec{r}_{ab})\varphi_{F=0}(\vec{r}_{ab})e^{-i\vec{k}_r\cdot\vec{r}_{ab}}\right)\right|^2$$

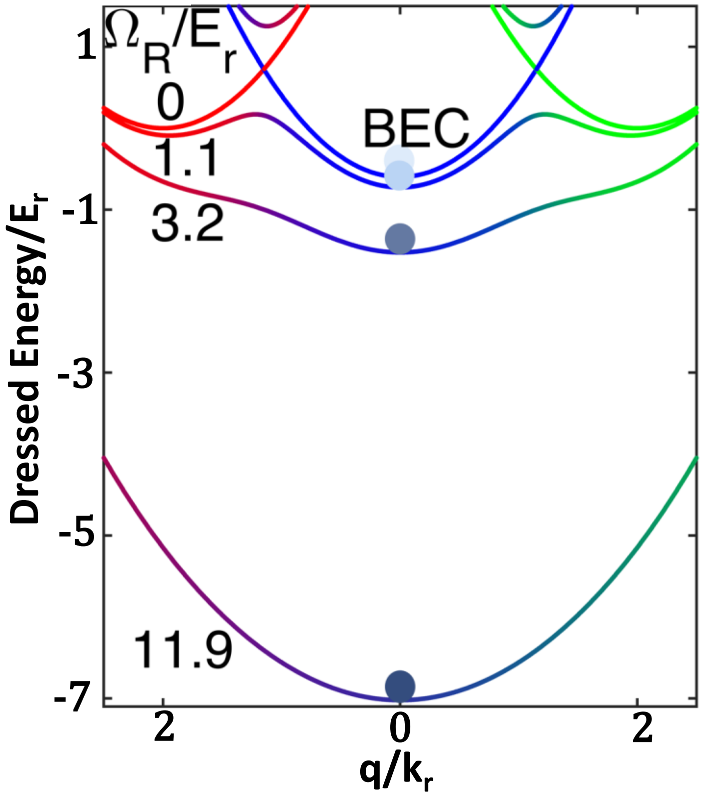
PA on spin(-momentum) superpositions

$$k_{sup} = k_{0,0}(|c_0^2|^2 + 4|c_{-1}c_{+1}|^2 - 4\Re(c_0^2 c_{-1}^* c_{+1}^*))$$

Various Ω_R at $\delta = 0$



Rep. bandstructures



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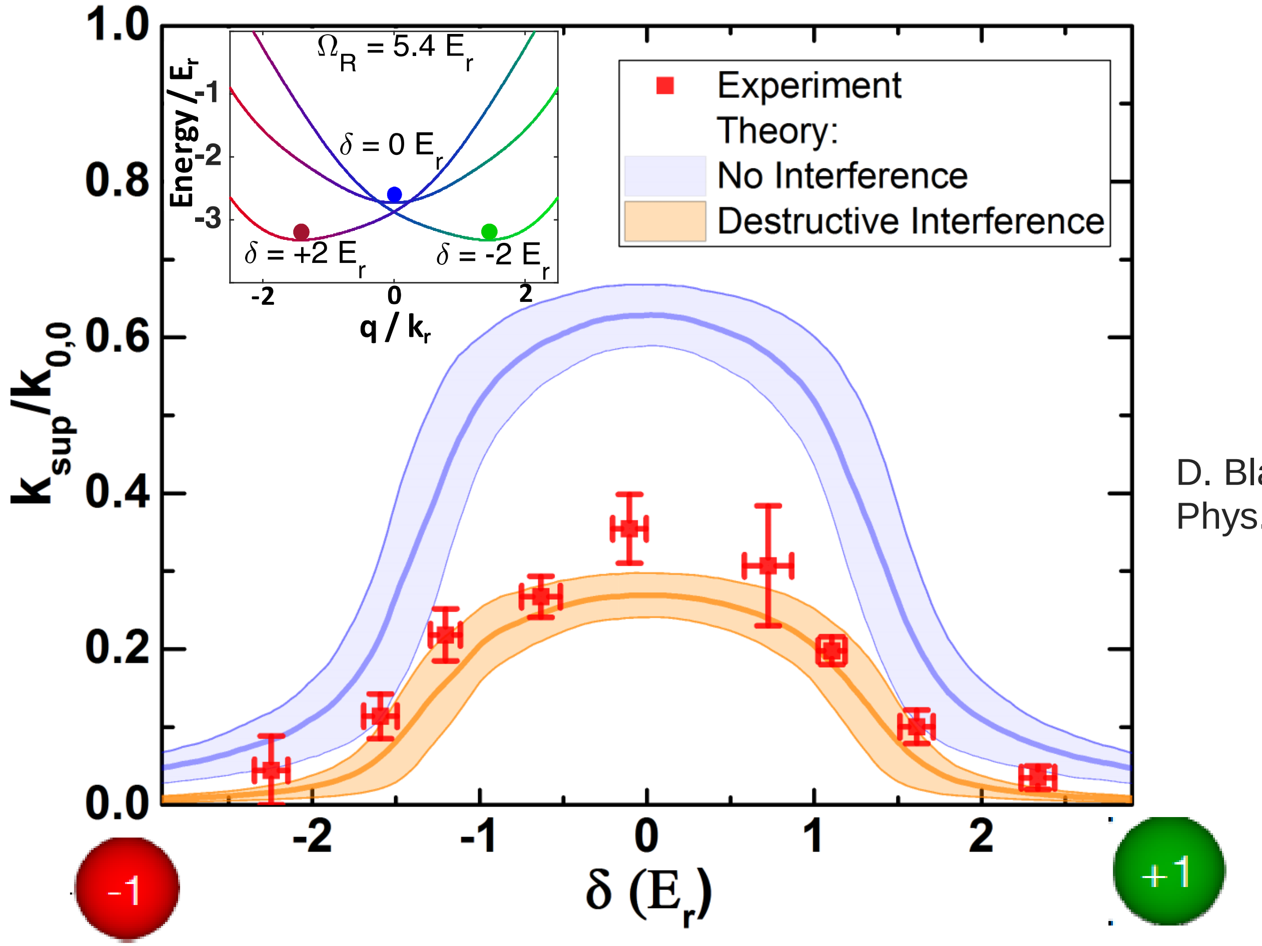
at large $\Omega_R \rightarrow$ $C_0 = \frac{1}{\sqrt{2}}$; $C_{-1} = C_{+1} = \frac{1}{2}$: $k \rightarrow 0$!

PA on spin(-momentum) superpositions

$$k_{sup} = k_{0,0}(|c_0^2|^2 + 4|c_{-1}c_{+1}|^2 - 4\Re(c_0^2 c_{-1}^* c_{+1}^*))$$

Various $\delta = 0$ at $\Omega_R = 5.4\ E_r$



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“using chemistry to probe physics?”
(quantum condensed matter)

Summary & Outlook

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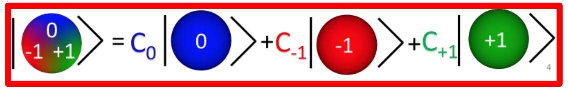
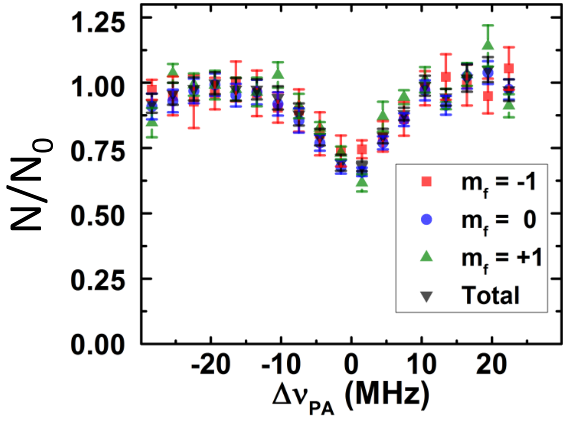
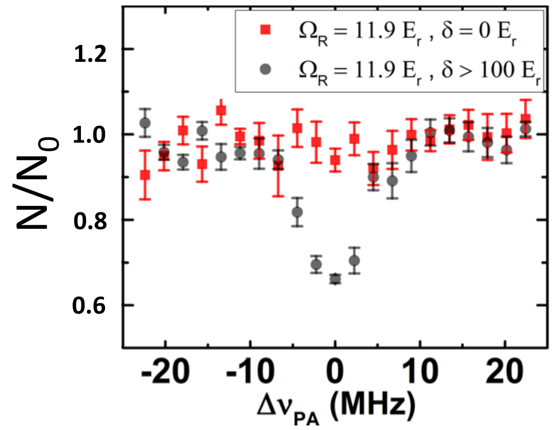
Novel “light-dressed” reactants
(in superposition state)



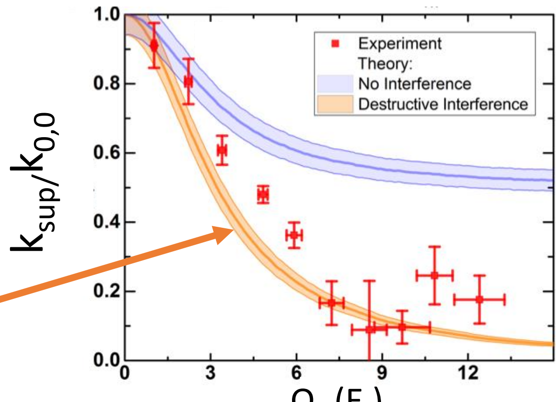


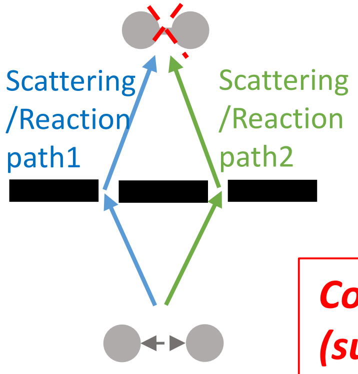
Observations indicate destructive interference



Agrees with theoretical model

$$k_{sup} = k_{0,0}(|c_0^2|^2 + 4|c_{-1}c_{+1}|^2 - 4\Re(c_0^2 c_{-1}^* c_{+1}^*))$$

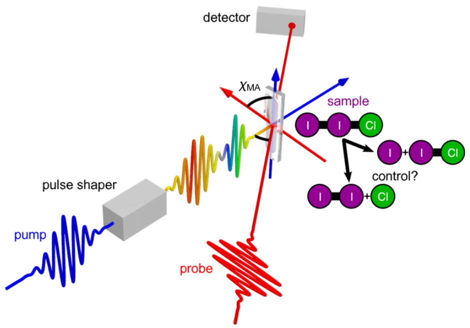


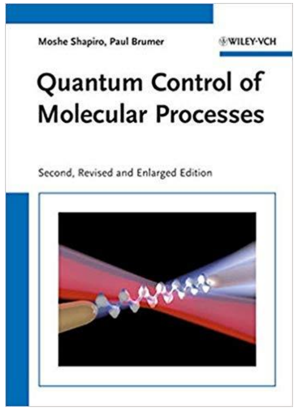


Two-pathway interference in Chemical space (reaction paths)

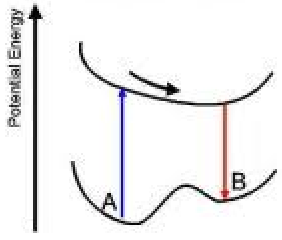
Control reactants’ quantum (superposition) states [high-dim Hilbert space]

New approach for “coherent photochemistry”
(not using pulsed/interfering lasers)

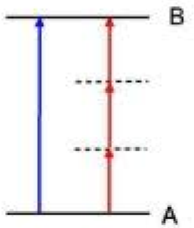




Tannor-Rice



Brumer-Shapiro



Spin-orbit-coupled Bose-Einstein Condensate as playground to explore quantum collision and chemistry

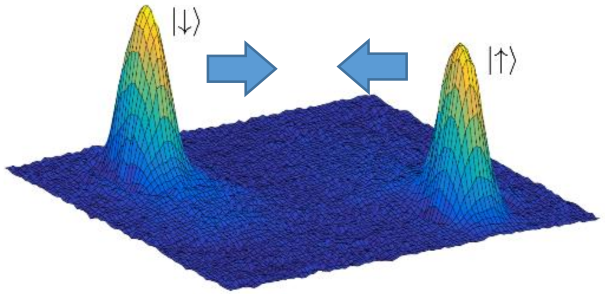
Outline

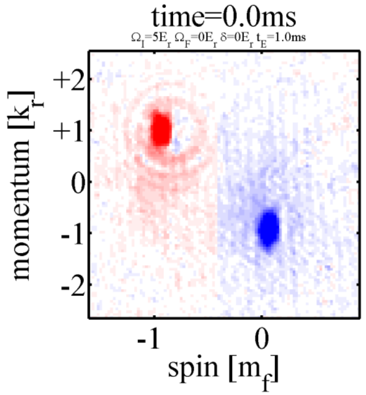
- Intro. to experimental platform: **"spin-orbit-coupled (SOC) BEC"**

  ["spin-helical atoms"] (by optical dressing)

- **(Spin) transport & Spinor BEC collider [how is it affected by SOC?]**

"2x2"



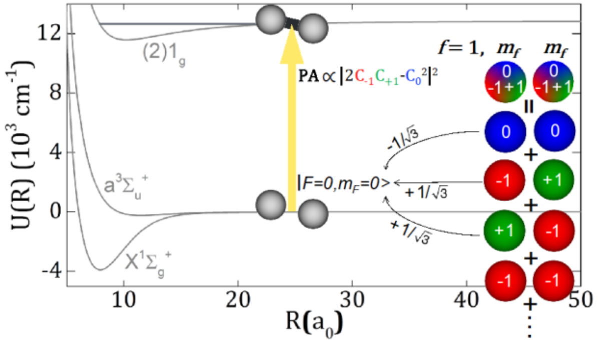


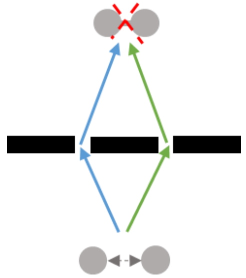
C. Li *et al.*, Nature Comm. 10, 375 (2019)

Chuan-Hsun Li

- **Quantum Synthesis: Interferometry in quantum (photo)chemistry**

"3x3"





D.Blasing *et al.* PRL 121, 073202 (2018)

David Blasing
(→ Crane)

Acknowledge Research Support by: Purdue Univ.; ARO; ***NSF;DOE***

(move onto 4x4 matrices..)

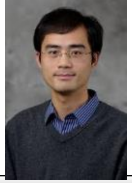
A Bose-Einstein Condensate on a Synthetic Hall Cylinder

arXiv:1809.02122, under review (2018)

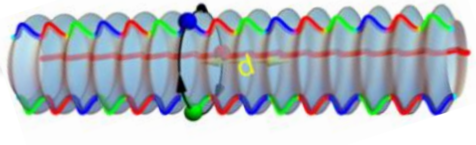
Chuan-Hsun Li,[1] Yangqian Yan,[2] Sayan Choudhury[2], David B. Blasing[2], Qi Zhou[2,3,*], and Yong P. Chen[2,1,3,†]

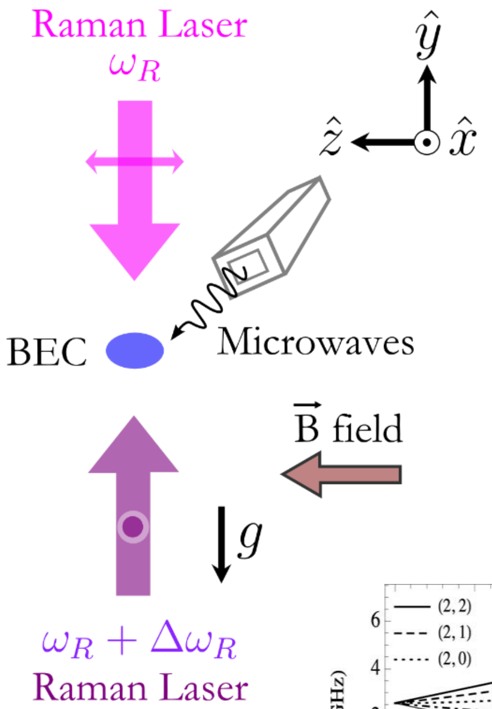
(experiment)

(proposal/prediction: Qi Zhou: arXiv:1810.12331)



"emergent" lattice (no external optical lattice)

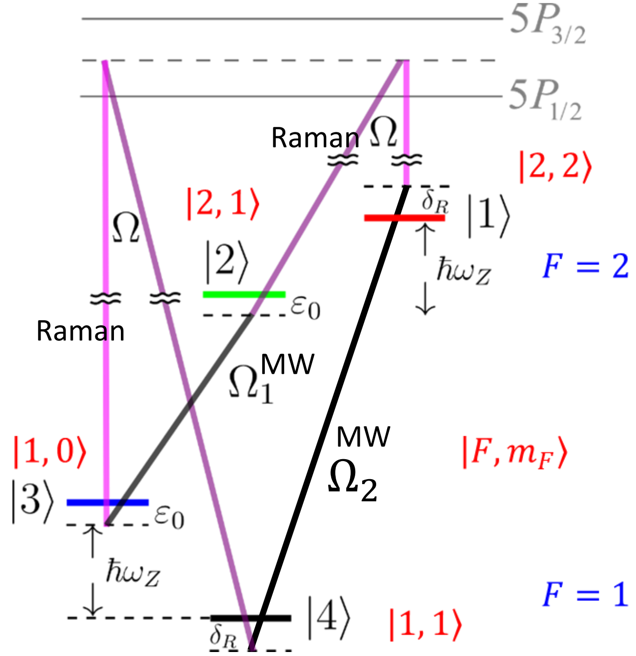


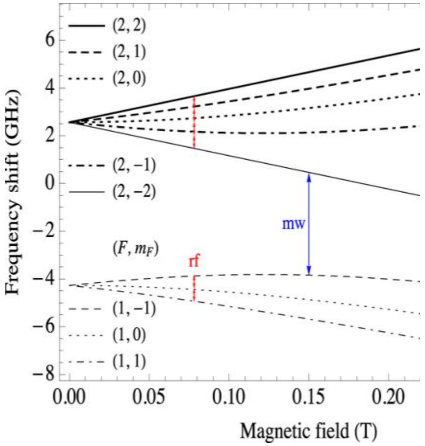


$\lambda \approx 790\ nm$

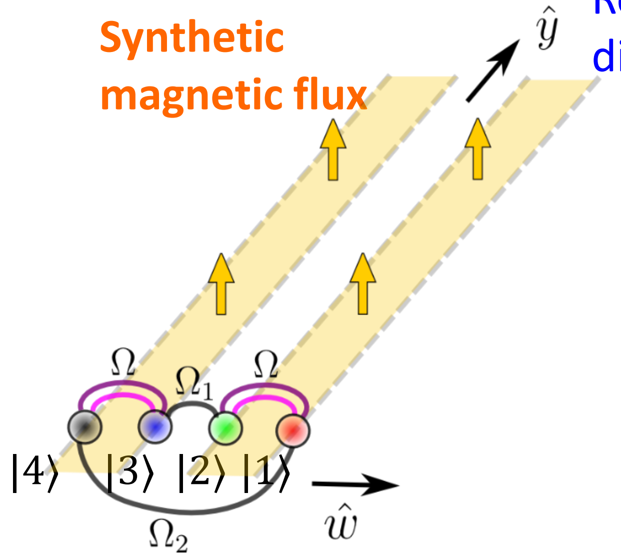
$k_r = 2\pi/\lambda$

$K = 2k_r$





***Hall ribbon** (periodic boundary condition):*

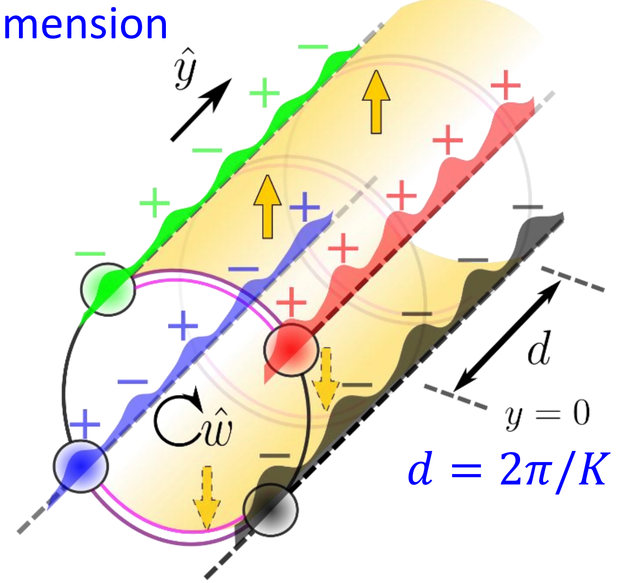


Synthetic dimension

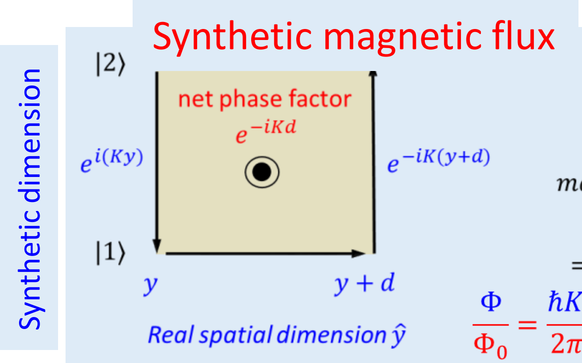
[Lewenstein et al'14; Spielman'15; Fallani'15…]

Real spatial dimension

Hall cylinder



$d = 2\pi/K$

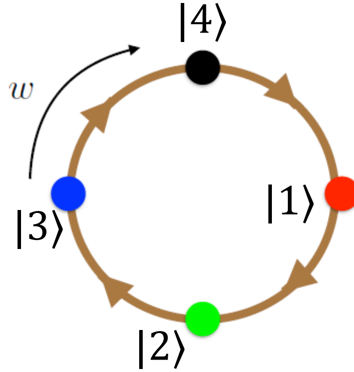


$(phase)_i = \frac{q}{\hbar}\int_i \vec{A}\cdot d\vec{l}$

$magnetic\ flux\ \Phi = \int \vec{B}\cdot d\vec{S}$

$= \oint \vec{A}\cdot d\vec{l} = \frac{\hbar}{q}\sum (phase)_i$

$\frac{\Phi}{\Phi_0} = \frac{\hbar K d/q}{2\pi\hbar/e} = \frac{Kd}{2\pi} = 1 \quad (q \equiv -e)$



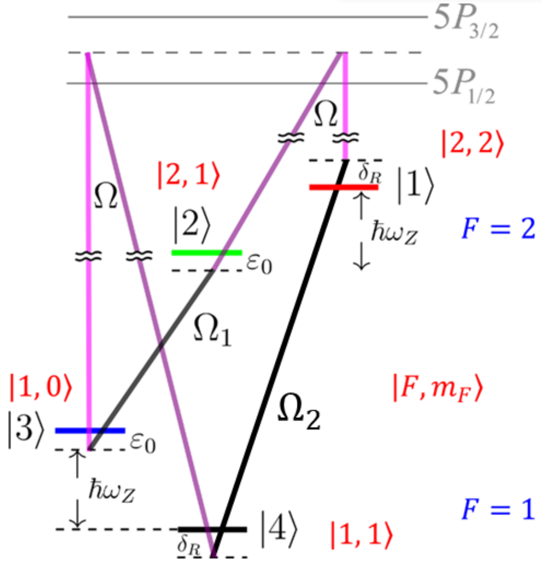
cyclic coupled spin ("**synthetic circle**")

e^{2iKy} phase accumulated

Net momentum transfer=$2K=4k_r$

Hall cylinder → emergent lattice & band structure

nonsymmorphic symmetry → topological protected bandcrossing



$$H = \frac{\hat{p}_y^2}{2m}\mathrm{I} + \begin{array}{ccccc} |1\rangle & |2\rangle & |3\rangle & |4\rangle & \\ \left(\begin{array}{c} -\delta_R \\ \frac{\Omega^*}{2}e^{-i(Ky)} \\ 0 \\ \frac{\Omega_2^*}{2} \end{array}\right. & \begin{array}{c} \frac{\Omega}{2}e^{i(Ky)} \\ \varepsilon_0 \\ \frac{\Omega_1^*}{2} \\ 0 \end{array} & \begin{array}{c} 0 \\ \frac{\Omega_1}{2} \\ \varepsilon_0 \\ \frac{\Omega^*}{2}e^{-i(Ky)} \end{array} & \left.\begin{array}{c} \frac{\Omega_2}{2} \\ 0 \\ \frac{\Omega}{2}e^{i(Ky)} \\ \delta_R \end{array}\right) & \begin{array}{c} |1\rangle \\ |2\rangle \\ |3\rangle \\ |4\rangle \end{array} \end{array}$$

$d = 2\pi/K$

(Hamiltonian's period)

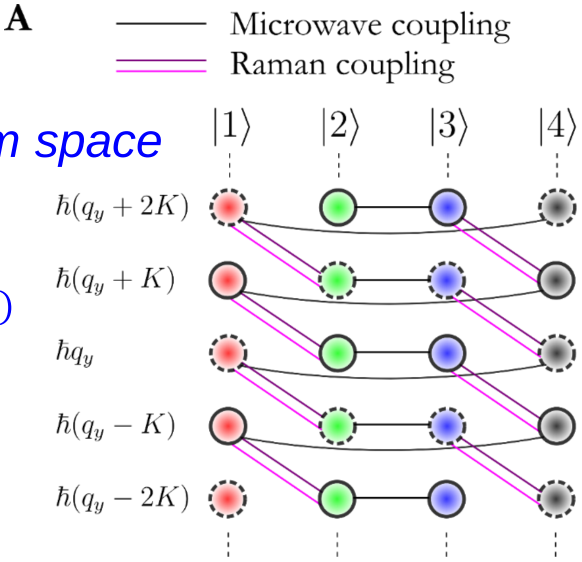
H is invariant under translation $d/2$ + a discrete unitary transformation ("rotation") (|2>,|3> flip signs)

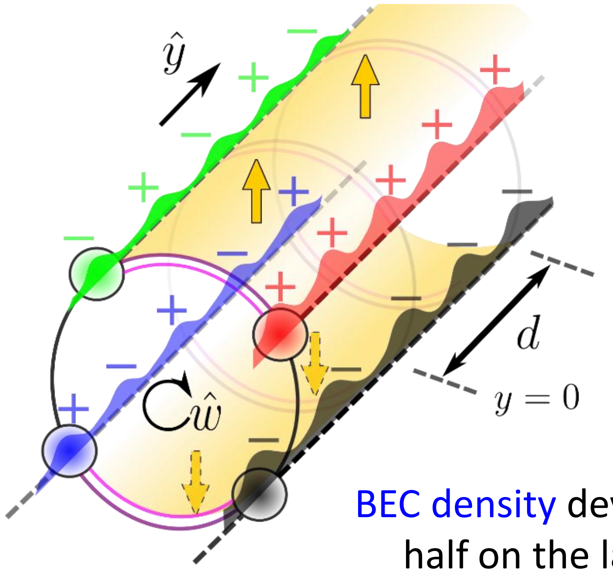
nonsymmorphic symmetry

Plane waves $\{|\hbar(q_y + nK); m\rangle\} = \{e^{i(q_y+nK)y}|m\rangle\}$

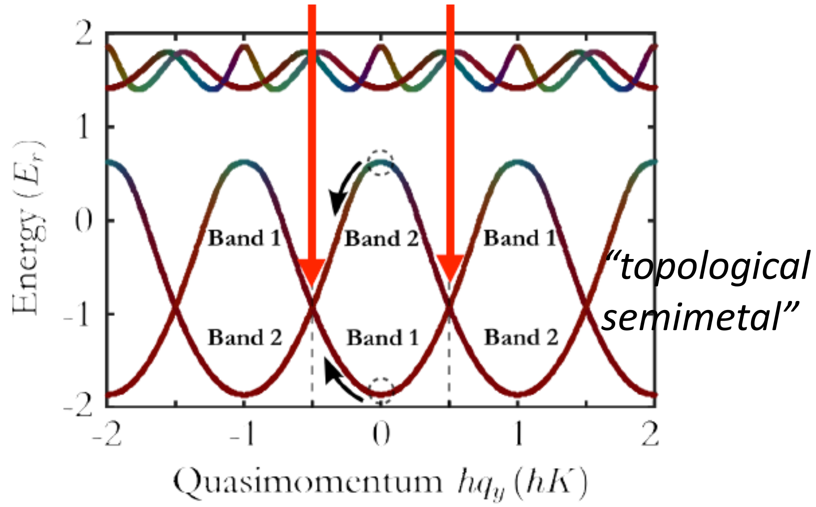
momentum space

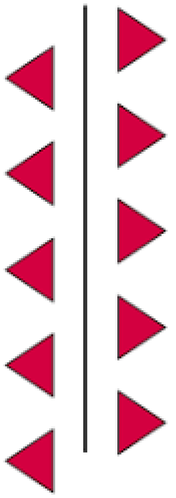
$\hbar(q_y + nK)$





Symmetry protected band crossings

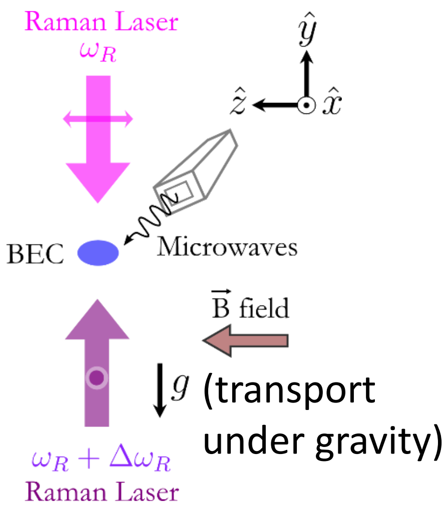


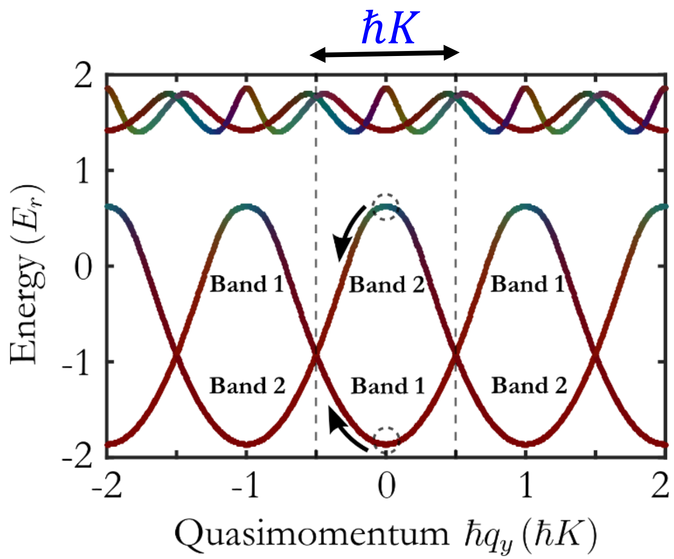


BEC density develops a crystalline order with a periodicity of $d/2$, half on the lattice period d (phase's period = d or $d/2$).

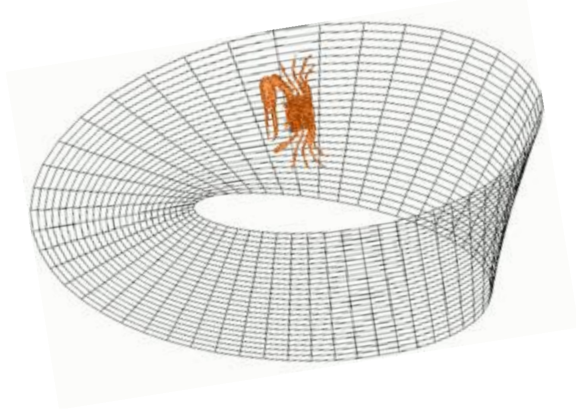
C. Li *et al.* arXiv:1809.02122

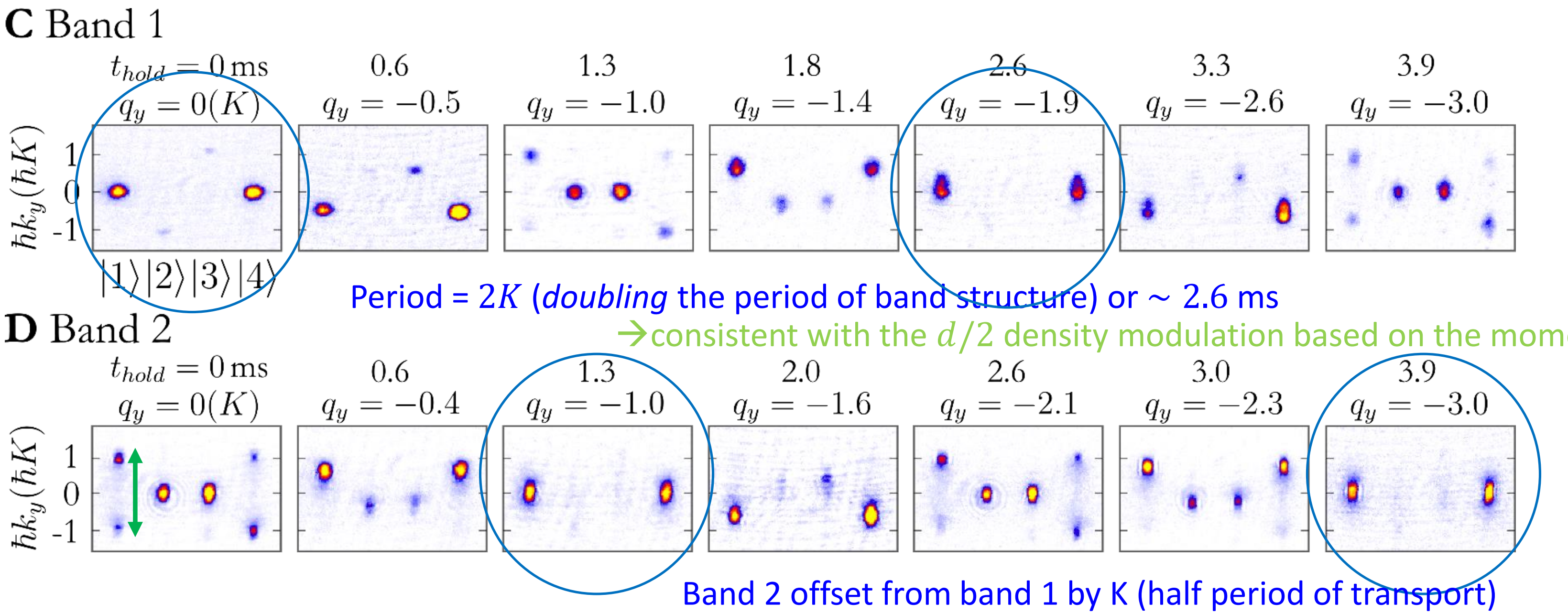
Quantum Transport in Emergent Lattice/Band → **Bloch oscillations**





quantum transport in each band:
analogous to (momentum space) Mobius-strip!





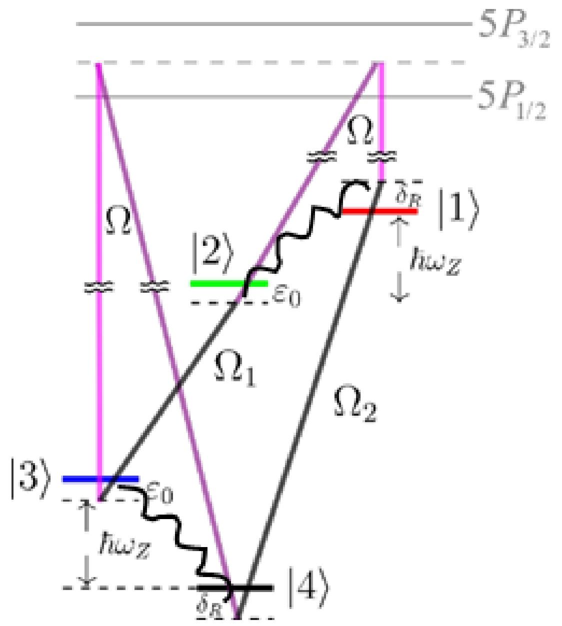
Period = $2K$ (*doubling* the period of band structure) or ~ 2.6 ms

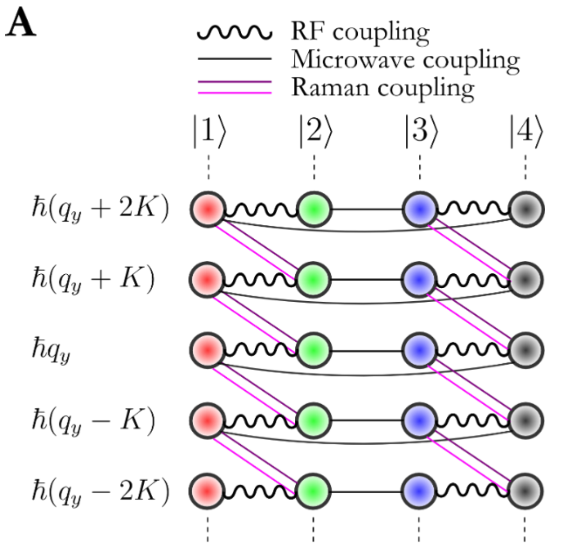
→consistent with the $d/2$ density modulation based on the momentum-position duality.

Band 2 offset from band 1 by K (half period of transport)

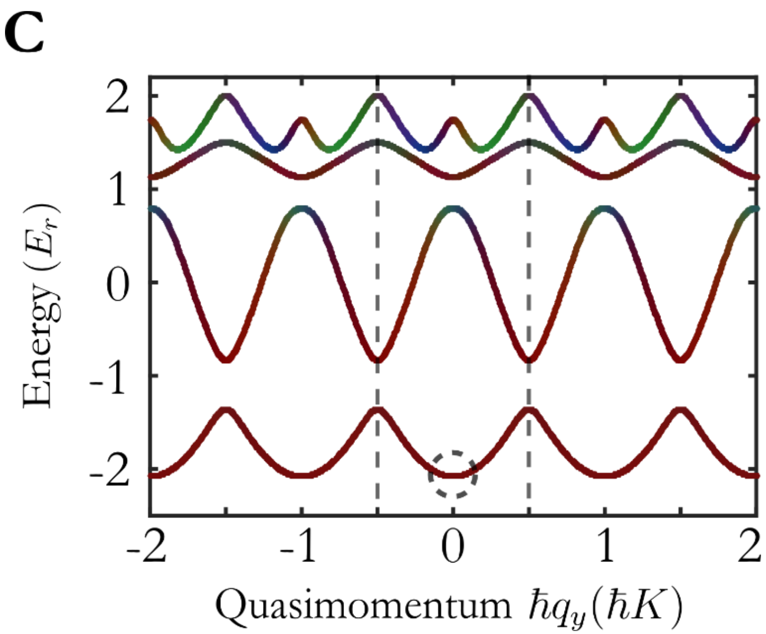
C. Li *et al*. arXiv:1809.02122

Breaking the nonsymmorphic symmetry → open gaps @ the crossings



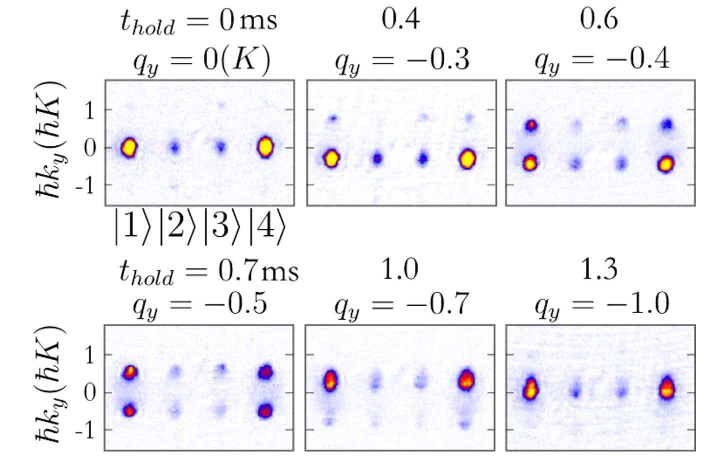


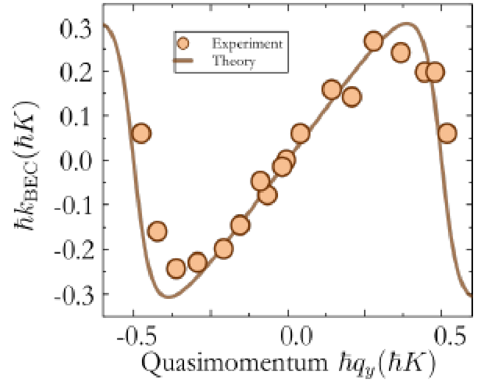
a topological change
In the band structure



arXiv:1809.02122

D Period = $\hbar K$ or ~ 1.3 ms





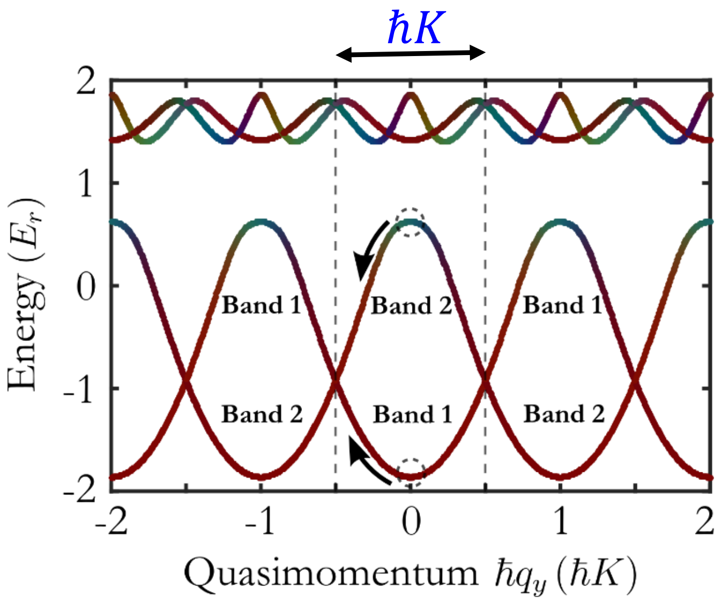
$$H=\frac{\hat{p}_y^2}{2m}\mathrm{I}+\begin{pmatrix} -\delta_R & \overset{+\Omega_{rf}}{\frac{\Omega}{2}e^{i(Ky)}} & 0 & \frac{\Omega_2}{2} \\ \frac{\Omega^*}{2}e^{-i(Ky)} & \varepsilon_0 & \frac{\Omega_1}{2} & 0 \\ 0 & \frac{\Omega_1^*}{2} & \varepsilon_0 & \frac{\Omega}{2}e^{i(Ky)} \\ \frac{\Omega_2^*}{2} & 0 & \underset{+\Omega_{rf}}{\frac{\Omega^*}{2}e^{-i(Ky)}} & \delta_R \end{pmatrix}\begin{array}{l} |1\rangle \\ |2\rangle \\ |3\rangle \\ |4\rangle \end{array}$$

→ "untwist" the Mobius strip
(in the momentum space)

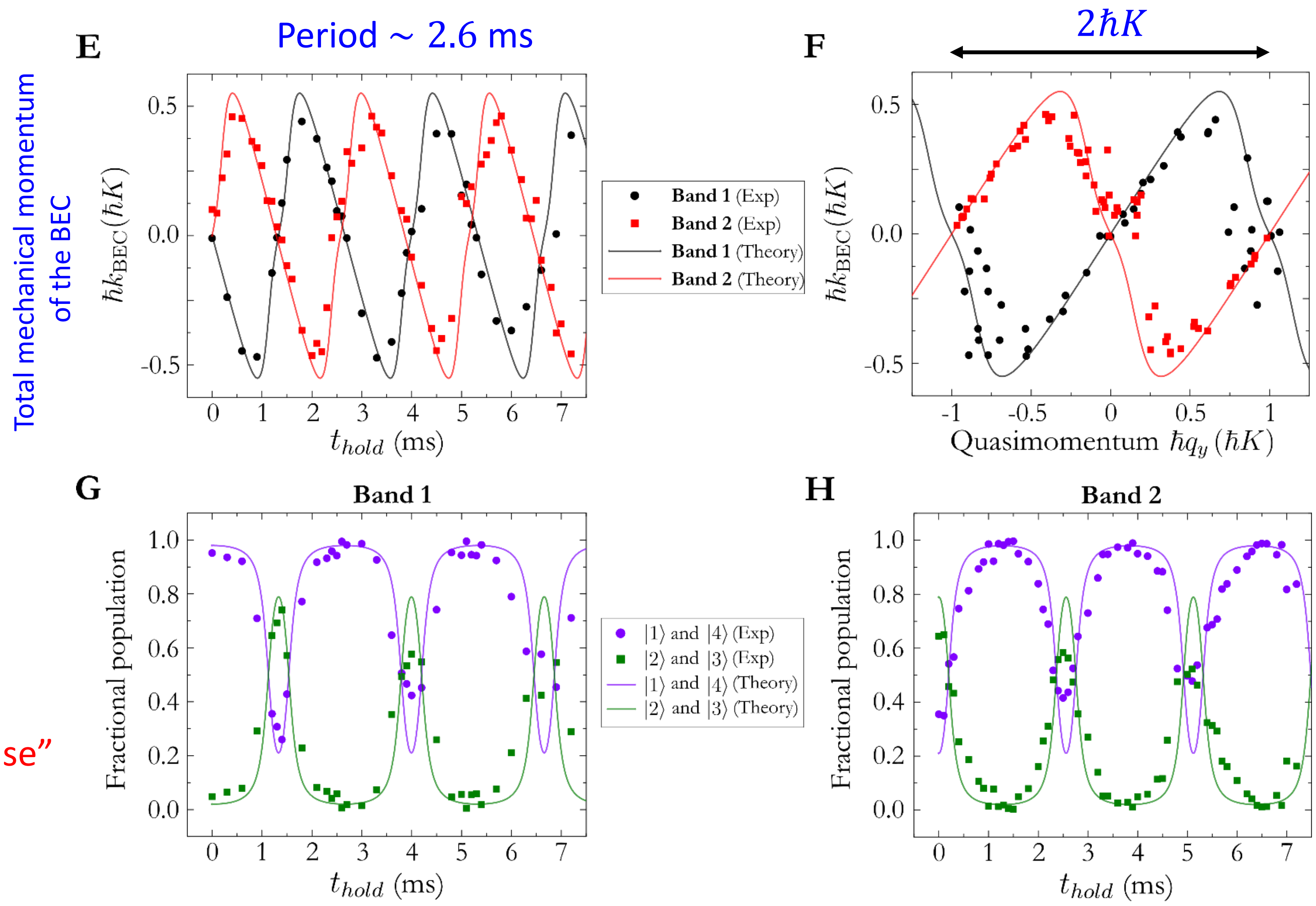
Analysis of Bloch oscillations -> mapping band structure

Consistent with the (topologically protected) band crossings!

Similar observation under different parameters (crossing protected by nonsymmorphic symmetry)

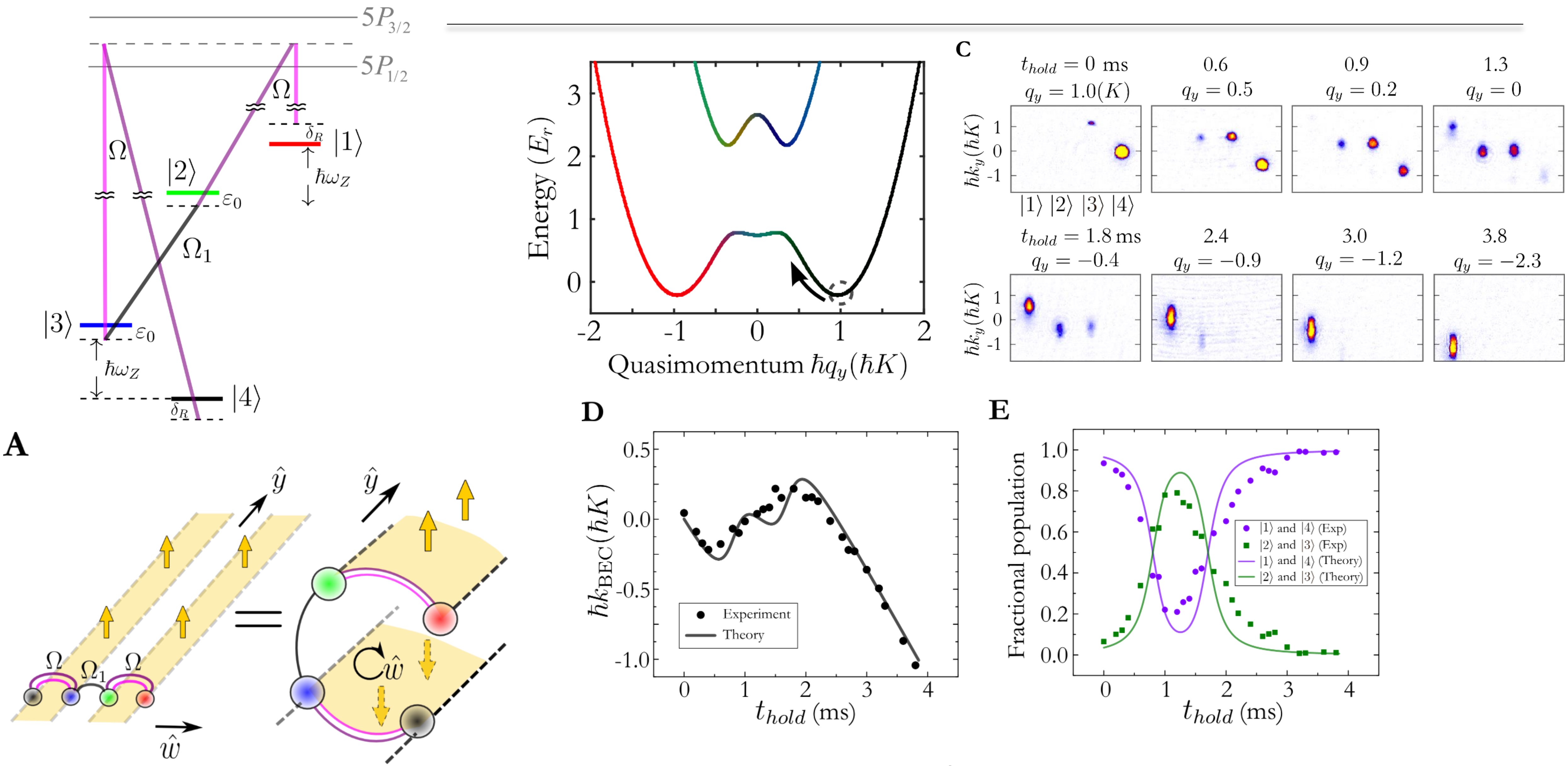


A “symmetry protected topological phase” (for bosons)



C. Li *et al*. arXiv:1809.02122, under review (2018)

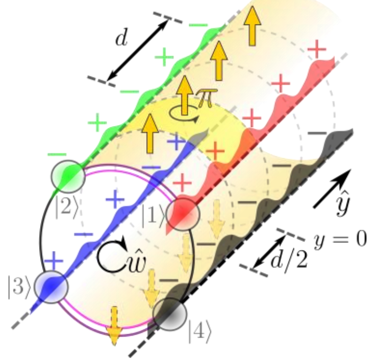
Unzipped cylinder: Emergent lattice and Bloch oscillations disappear

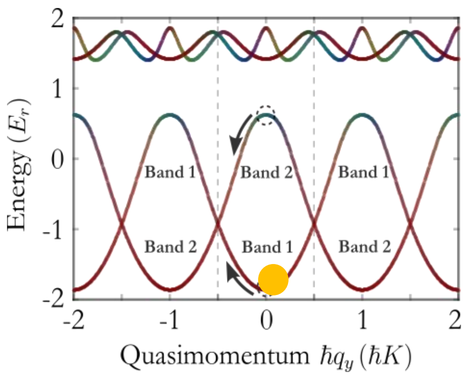


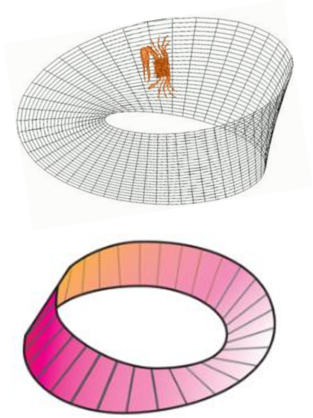
arXiv:1809.02122

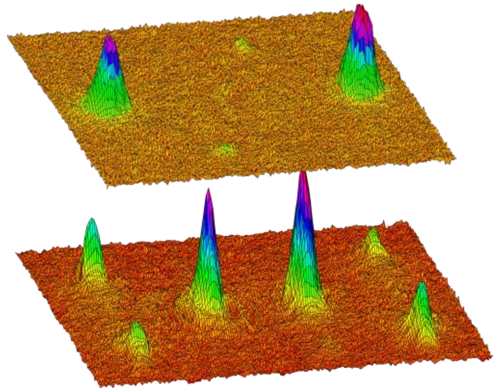
Summary: Emergent symmetry-protected (bosonic) topological states

arXiv:1809.02122

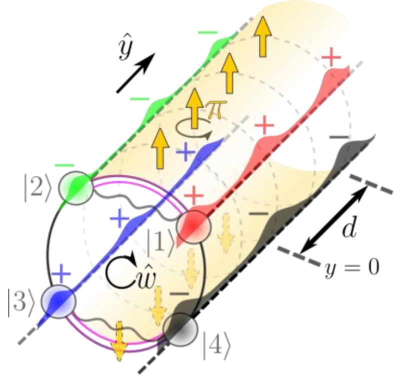


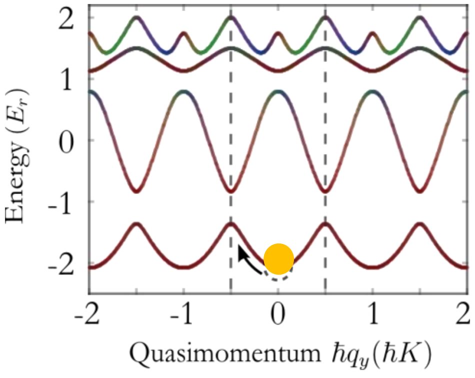


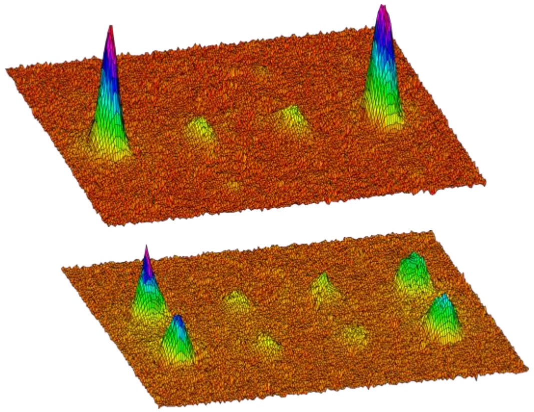




Breaking the symmetry





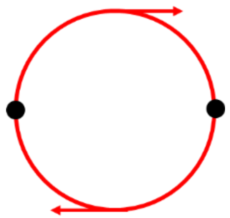


Next:Can particle-particle interactions change the topology?

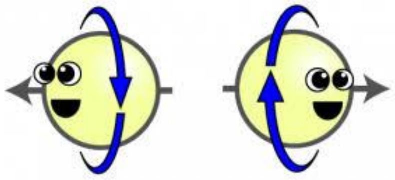
Symmetry-Protected Topological Orders in Interacting Bosonic Systems

Xie Chen,[1,2] Zheng-Cheng Gu,[3] Zheng-Xin Liu,[4,2] Xiao-Gang Wen[5,2,4*] 10.1126/science.1227224

https://physics.aps.org/articles/v1/6

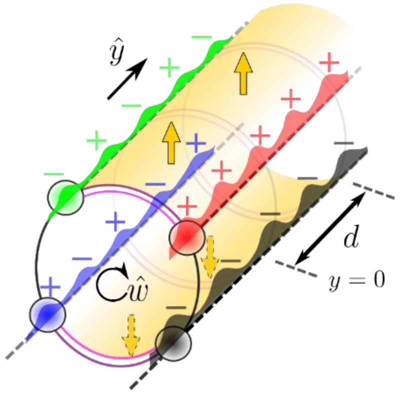


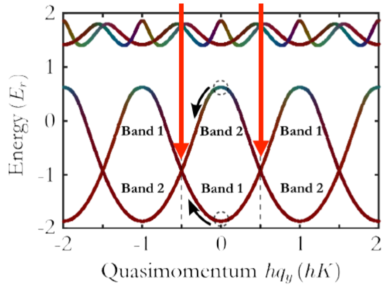
Outlook: Quantum science & technologies based on "Spin-helical" particles

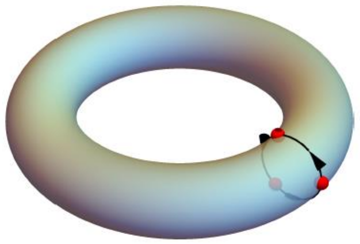


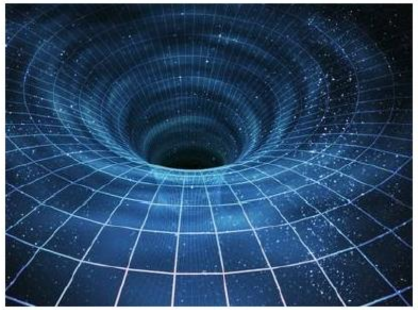
- Novel (Topological) Quantum Matter & Quantum simulation

(& in high dim/curved space)

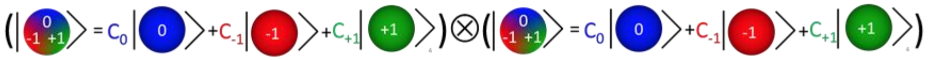


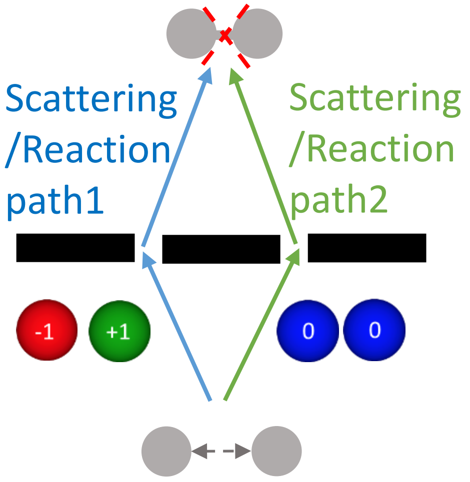






- (spin-based) quantum control/chemistry



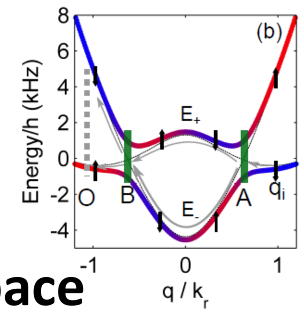


New playground/platforms/toolsets for:
"quantum transport/interferometry/measurement/manipulation (even chemistry)" of quantum condensed matter

“Spintronic” Quantum Transport, Chemistry and Interferometry in an atomic BEC

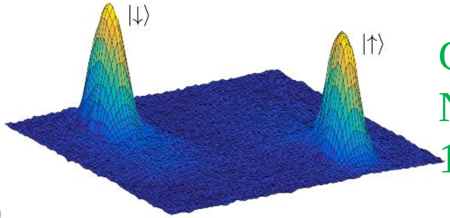
Summary

- Introduction to experimental platform: **“spin-orbit-coupled” (SOC) BEC**
- **Transport & Interferometry in energy-momentum (E-k) space**
  - Quantum Transport in synthetic (“dressed”) bandstructure
  - Landau-Zener transition: beam-splitter
  - Landau-Zener-Stuckelberg interferometer (via “Fluoquet” engineering)



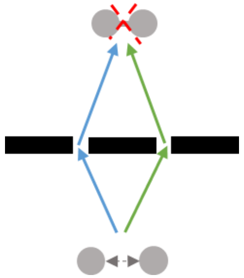
A.Olson *et al.*
PRA 90, 013616 (2014);
PRA 95, 043623 (2017)

- **Spinor BEC collider: (Spin) transport & interferometry in real-space**
  - Spin dipole mode (AC spin current) induce by *quantum quench* in spin-orbit-coupled BEC
  - How does such (spin) collective excitation decay?
  - How does spin-orbit-coupling affect spin transport (spin current relaxation)?
  - Interplay between SOC, interference, *interaction*



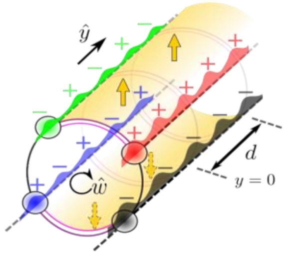
C. Li *et al.*,
Nature Comm. 10, 375 (2019)

- **Interferometry in quantum (photo)chemistry**
  - What happens when reactants are in quantum superposition states?
  - (spin-sensitive) photoassociation (PA): interference b/t 2 PA reaction pathways

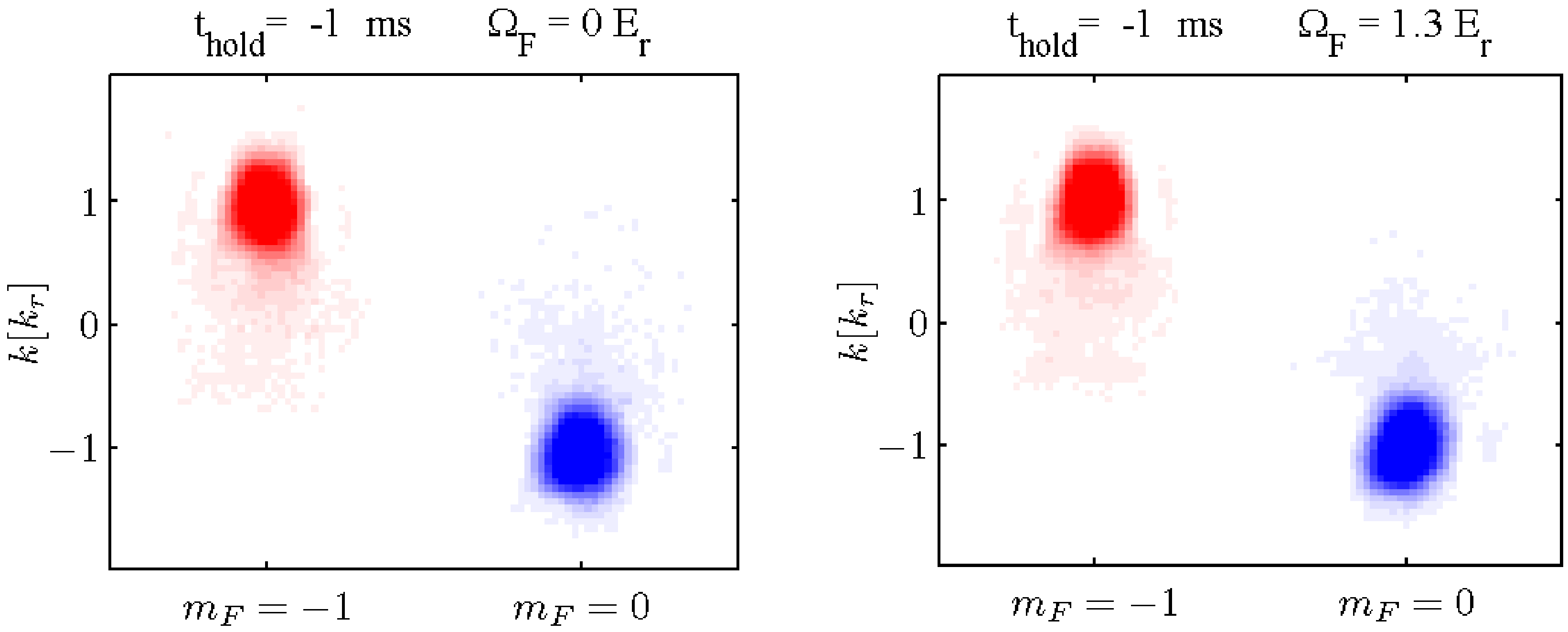


D.Blasing *et al.*
PRL 121, 073202 (2018)

- **BEC on a synthetic “Hall” cylinder** (a symmetry-protected bosonic topological state)
  - (circular) synthetic “dimension” → “emergent” crystalline order
  - Quantum transport on a Mobius strip (E-k space)
  - Topological band-crossing (protected by nonsymmorphic symmetry)
  - Breaking symmetry/unzipping cylinder → topological transition

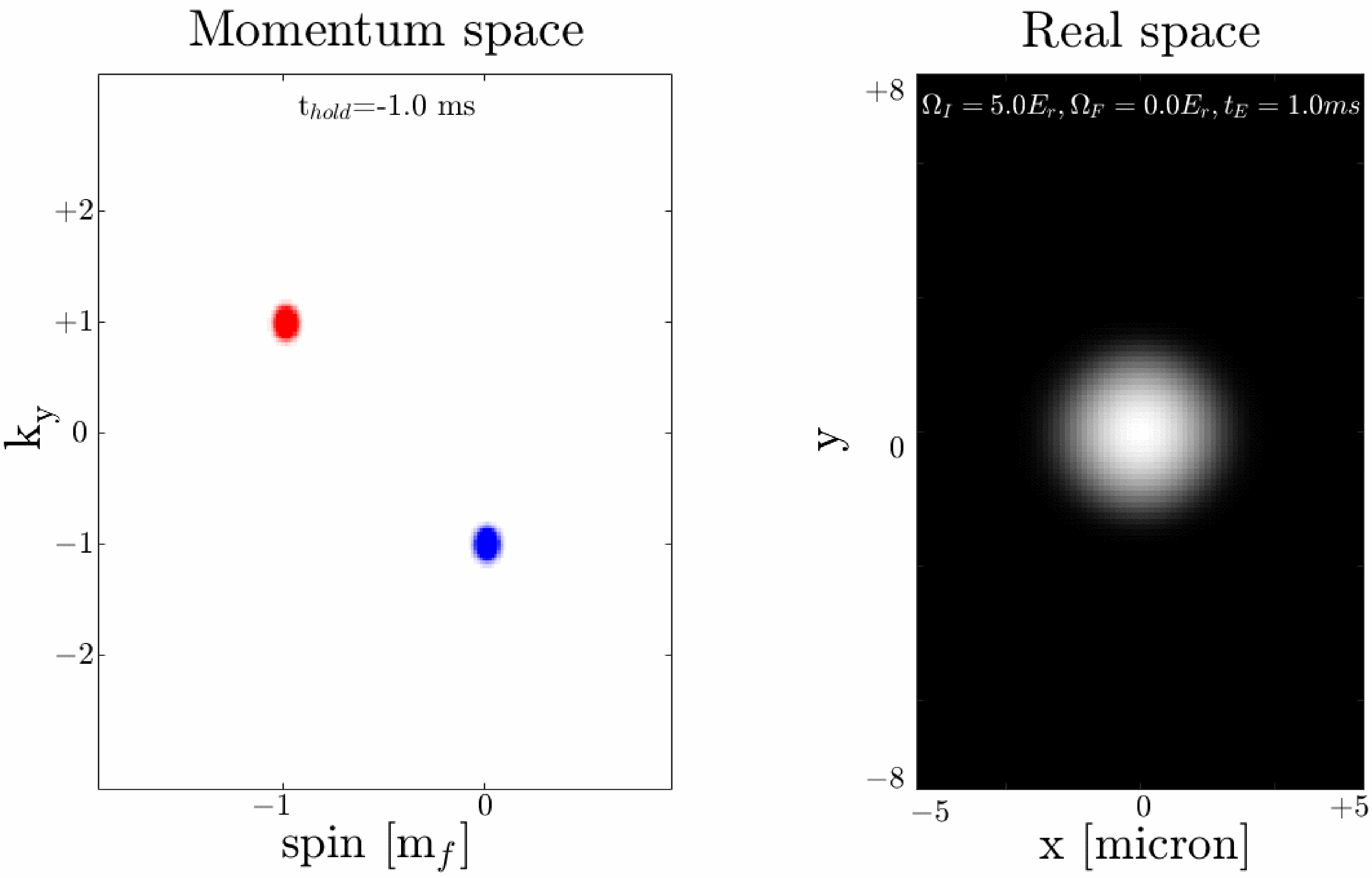


C. Li *et al.*,
arXiv: 1809.02122



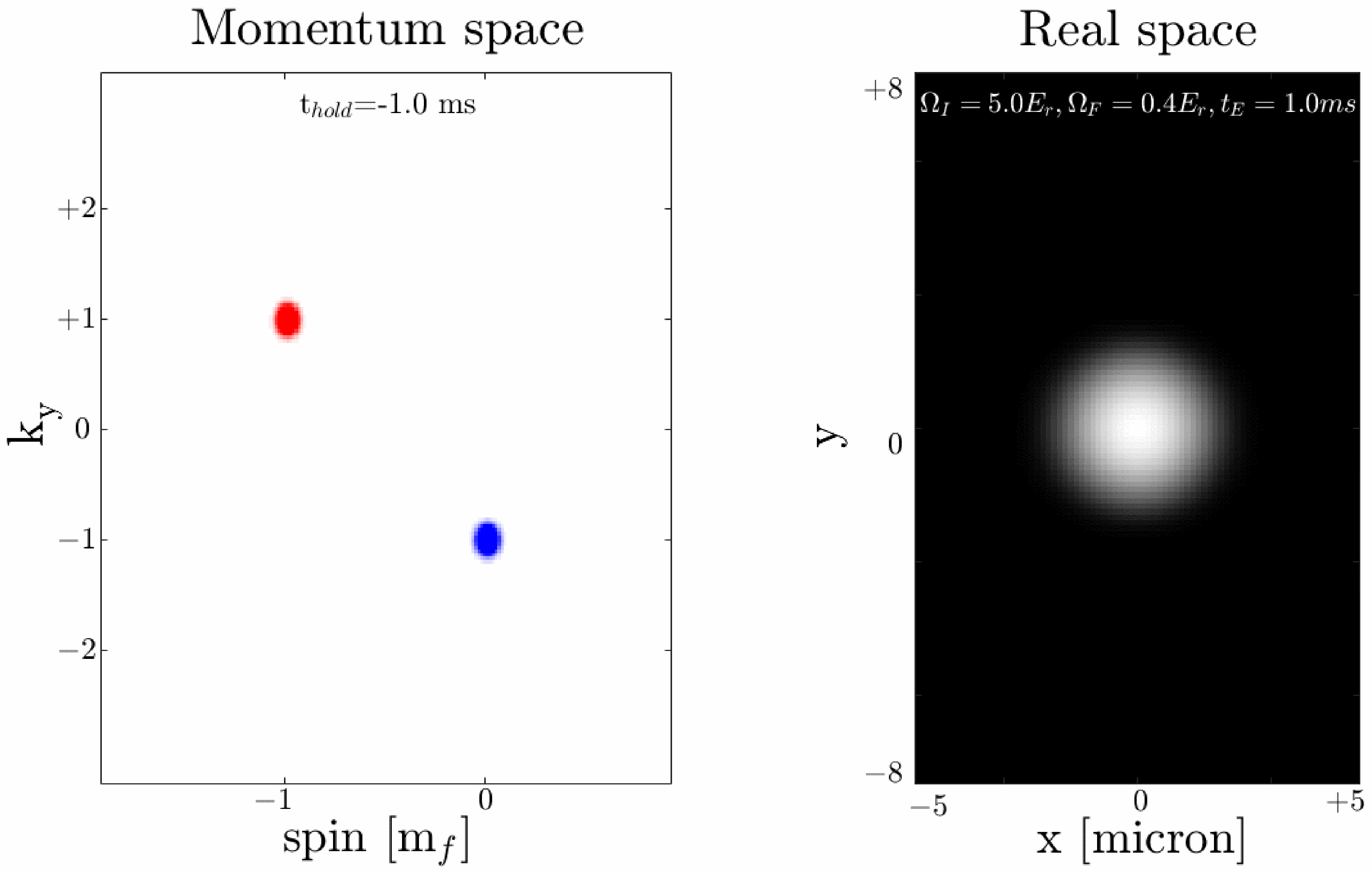
t_{hold}= -1 ms
Ω_F = 0 E_r
$k[k_r]$
1
0
−1
$m_F = -1$
$m_F = 0$
t_{hold}= -1 ms
Ω_F = 1.3 E_r
$k[k_r]$
1
0
−1
$m_F = -1$
$m_F = 0$

Bare case

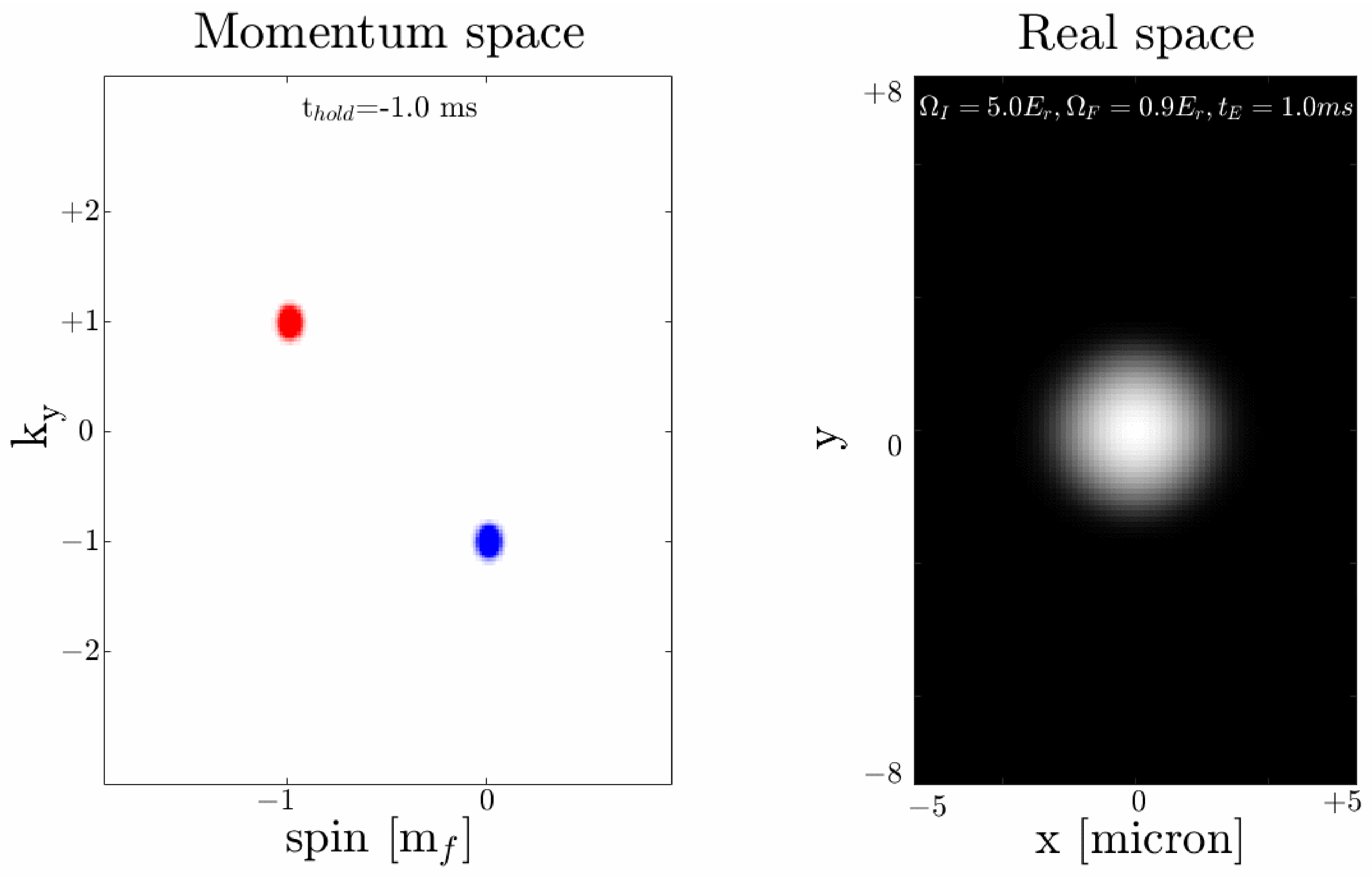


Momentum space
t_{hold}=-1.0 ms
k_y
+2
+1
0
−1
−2
−1
0
spin [m_f]
Real space
$\Omega_I = 5.0E_r, \Omega_F = 0.0E_r, t_E = 1.0ms$
y
+8
0
−8
−5
0
+5
x [micron]

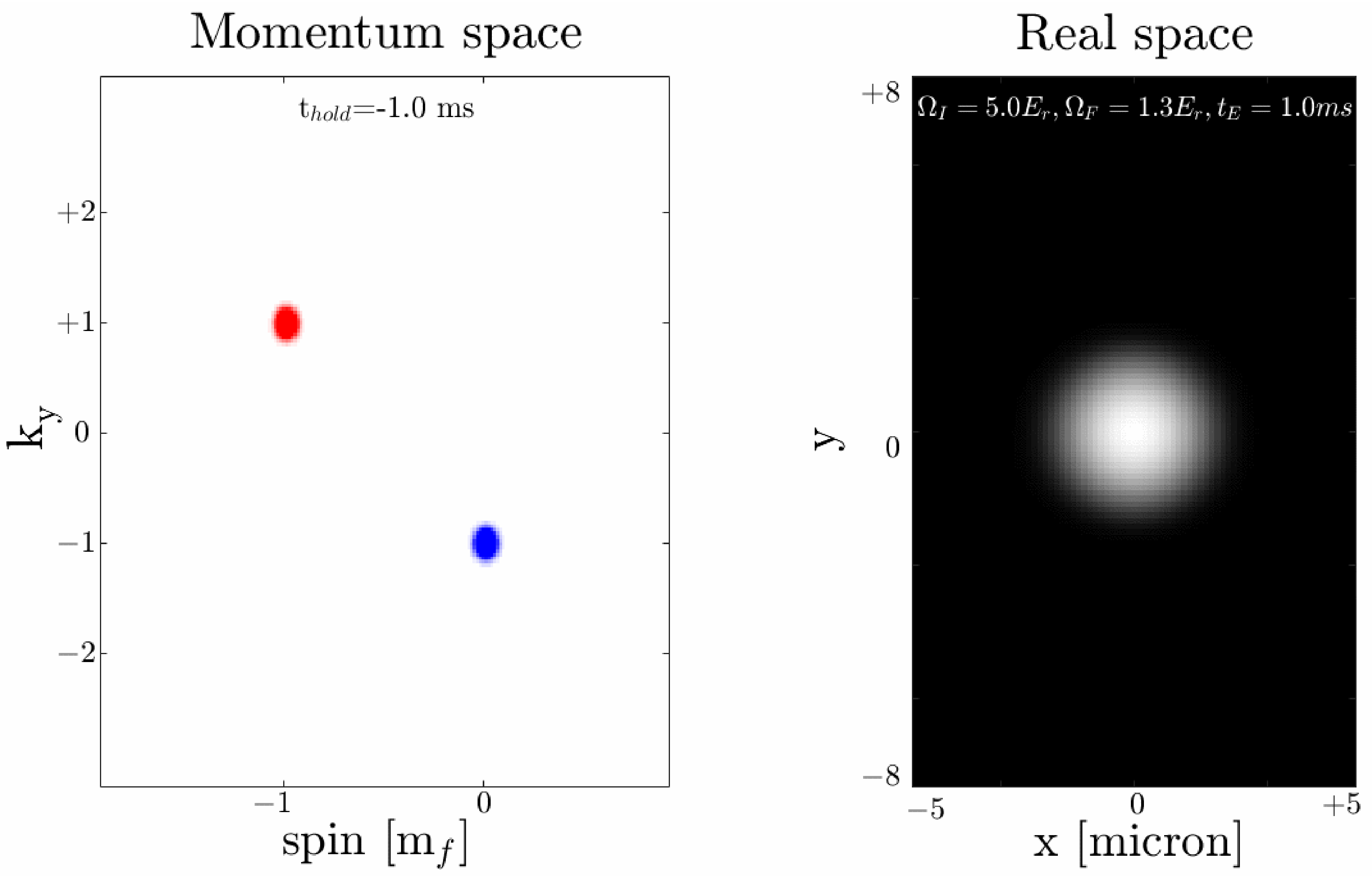
Dressed case



Dressed case



Dressed case



Dressed case