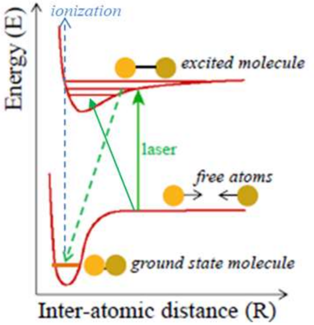
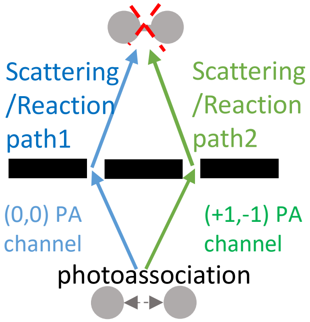
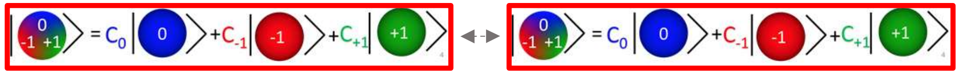
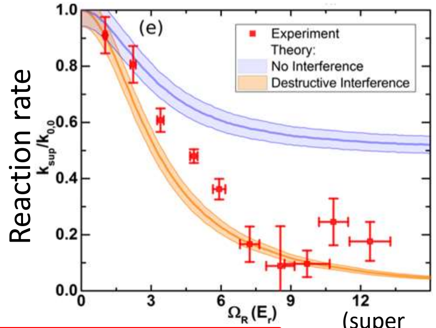
TAMIONS summer school, 5/21/2021

“Atomtronic Spintronics”: from Quantum Chemistry to Quantum Transport

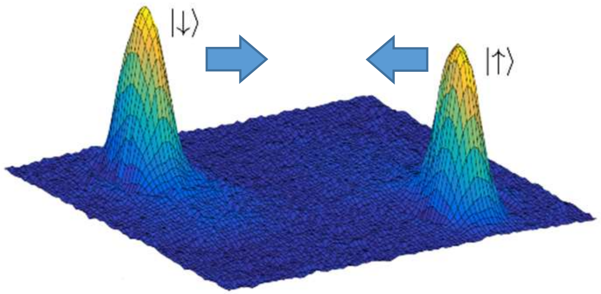


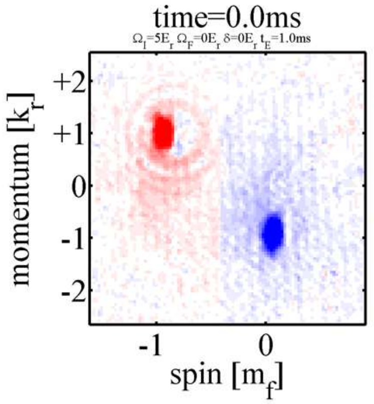




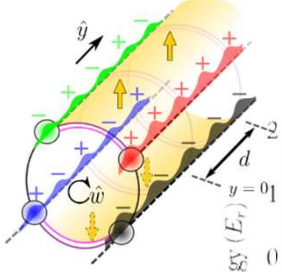


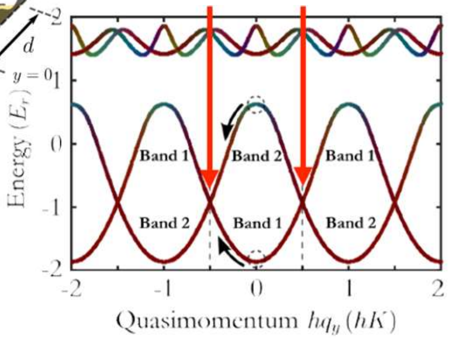
(super -position state)





Postdoc Opening





Yong P. Chen (yongchen@purdue.edu)

Dept. of Physics & Astronomy; School of Electrical & Computer Engineering;
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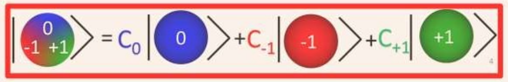
Purdue University, West Lafayette, IN 47907 USA
(**Quantum Matter and Devices Laboratory** : www.physics.purdue.edu/quantum)

“making and measuring interesting quantum matters”

Many thanks and best wishes to organizers and colleagues

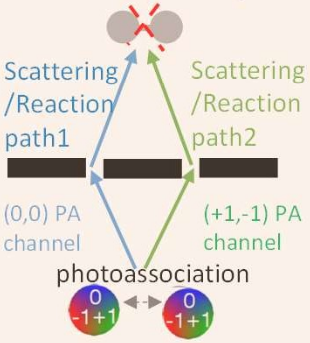
(my last trip to India [Jan 2016])

शुक्रिया



Idea 1: Putting **reactants** (atoms) in (spin) **quantum superposition states** ➔ controlling reaction via quantum interference!

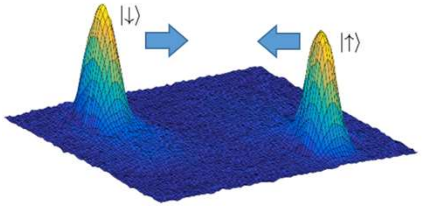
"Young's double slit in chemical/Hilbert space" (**quantum chemistry interferometer**) {2-body physics}



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

Idea 2: **"Synthetic"** (electric/magnetic) **fields** [for charge-*neutral* atoms] ➔ **atomtronic quantum transport**

[can be made spin-dependent] also realize "(spin) condensate collider"] {many-body physics}

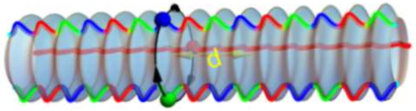


C. Li *et al*. Nature Comm. 10, 375 (2019)

(Bonus) Idea 3: **"Synthetic" dimension**/space ➔ realize novel "synthetic" geometry/topology

[not easy in solid materials] [e.g. "emergent" crystal w/o external lattice] {1-body physics}

C.Li et al., arXiv:1809.02122

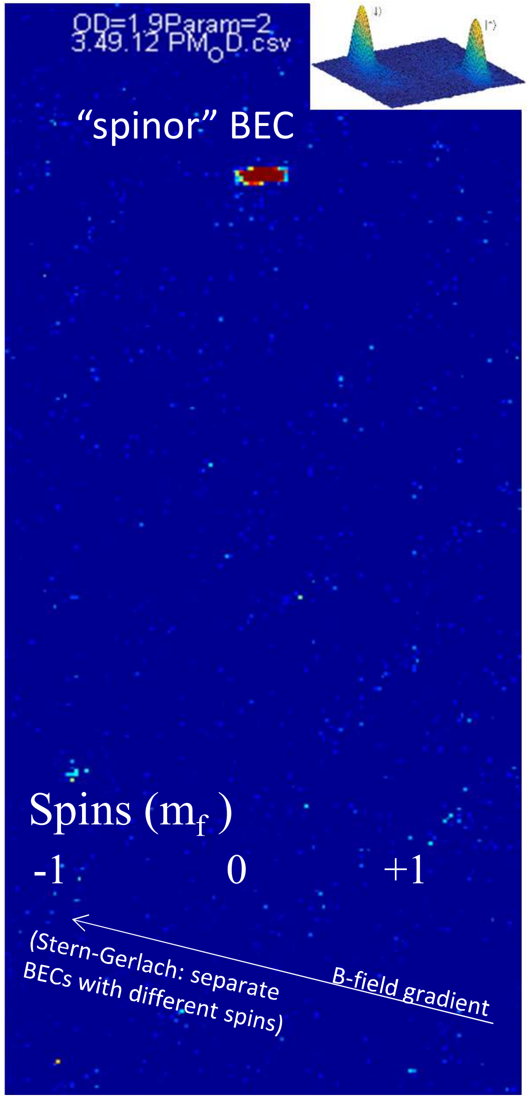


Postdoc
Opening

☞our platform to explore these (general) ideas: spinor/spin-orbit-coupled BEC

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

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



“spinor” BEC

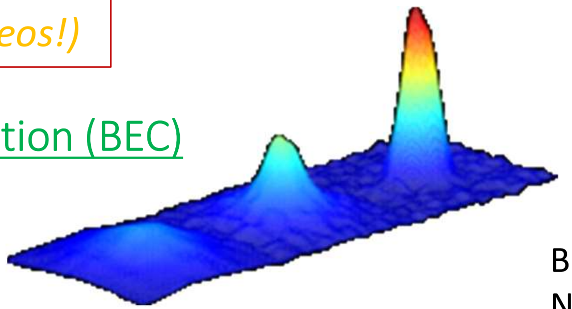
Spins (m_f)

-1 0 +1

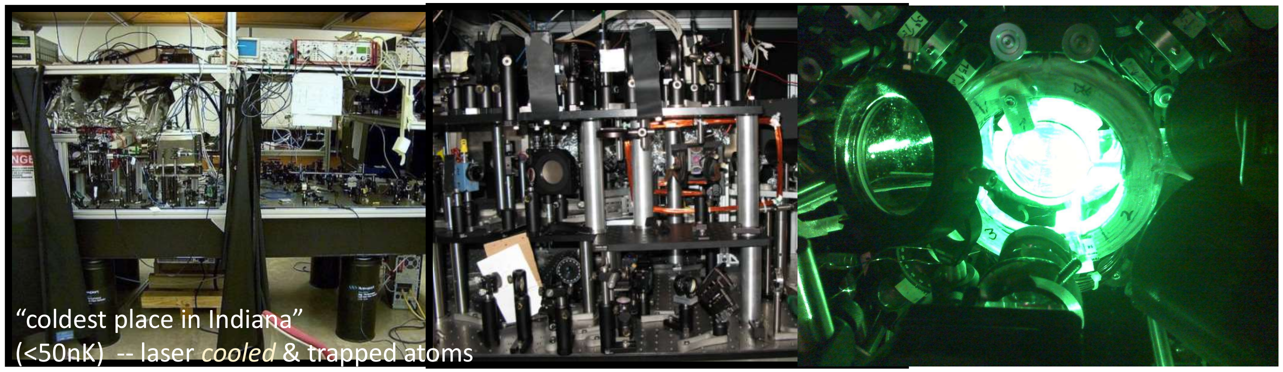
(Stern-Gerlach: separate BECs with different spins)

B-field gradient

Demo with our Bose-Einstein Condensation (BEC)



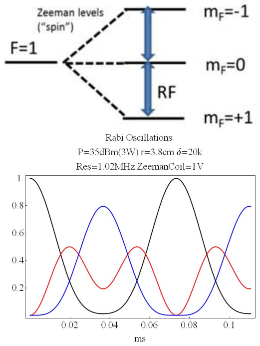
Purdue QMD’s “all-optical” Rb87 BEC apparatus with synthetic gauge fields and spin-orbit coupling

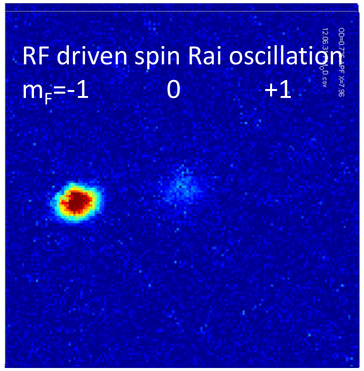


“coldest place in Indiana” (<50nK) -- laser *cooled* & trapped atoms

Based on several Nobel-prize technologies:

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

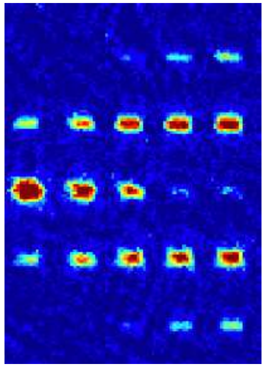




RF driven spin Rai oscillation

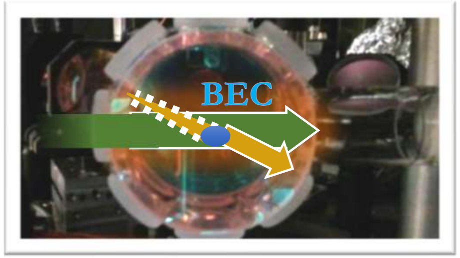
m_F=-1 0 +1

coherent oscillation of BEC between 3 spin states



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

”discrete spots” → ” synthetic dimension/lattice!

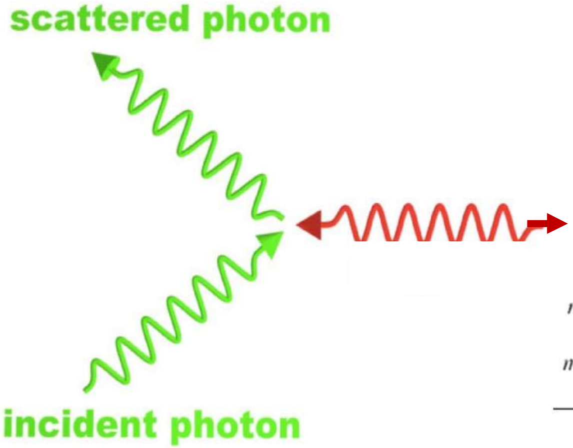


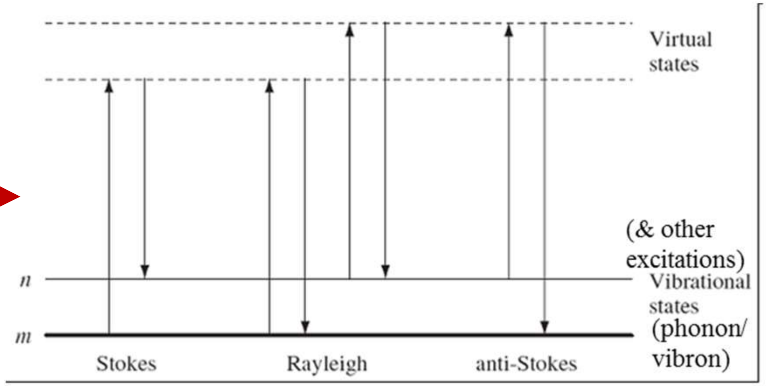
1550nm cross-beam optical trap (optical tweezer)

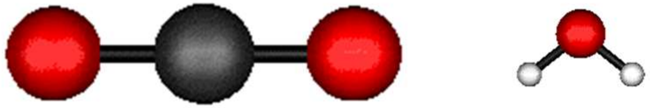
A.J. Olson *et al.*, PRA87, 053613 (2013) (exp. & modeling of efficient evaporative cooling in optical trap)

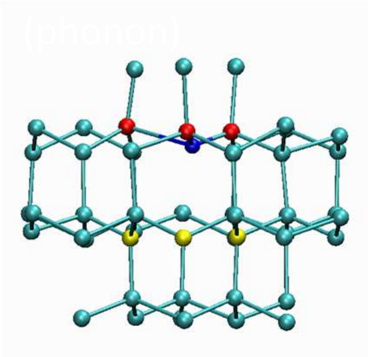
Digression: Raman Spectroscopy (Inelastic Light Scattering)

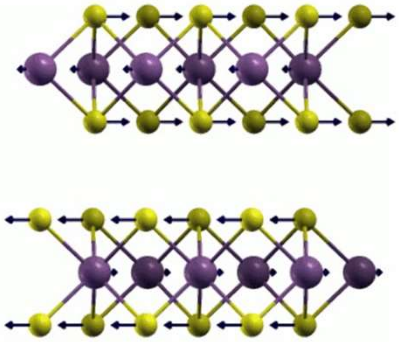
C.V.Raman 1928











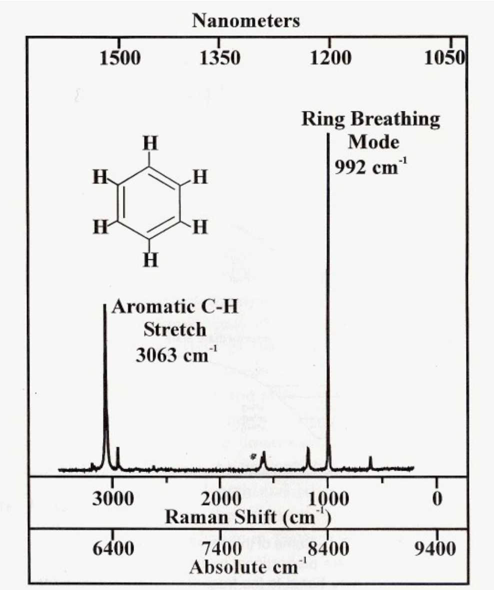
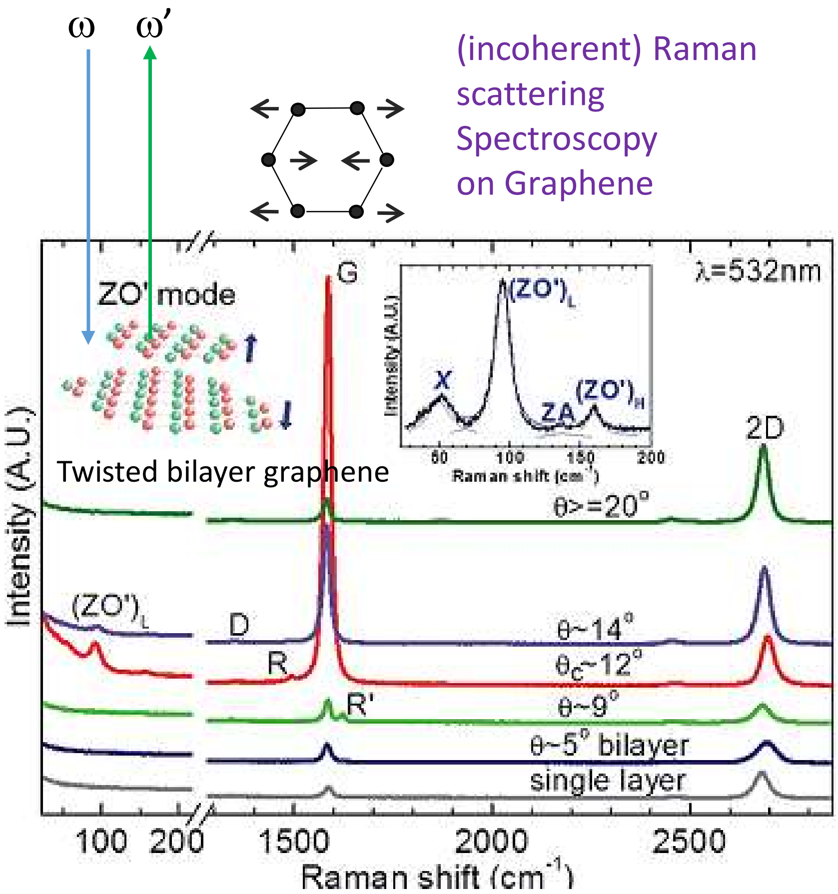


FIGURE 2 FT-Raman spectrum of neat benzene.

Molecule “fingerprint”..

Also for nanomaterial & solids

Raman process as light-matter interaction
--- from optical scattering (incoherent) to optical dressing (coherent)

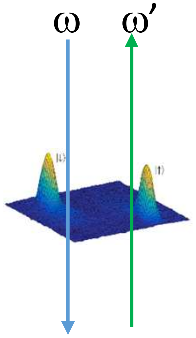


(incoherent) Raman scattering Spectroscopy on Graphene

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

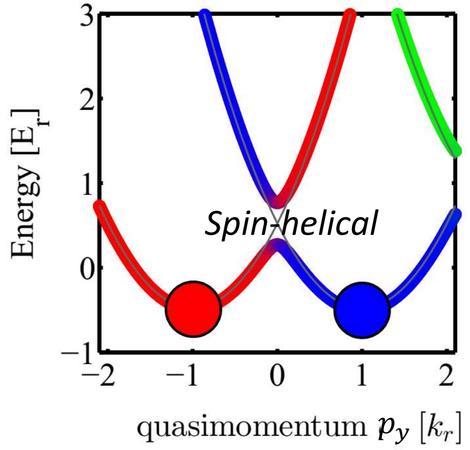
Can generalize to/realize 3x3, 4x4 .. NxN matrix Hamitonian…

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

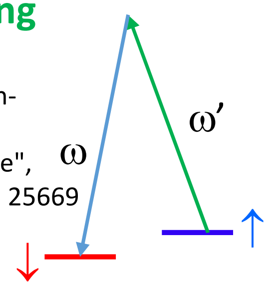


Raman (optical) dressing

→ Synthetic "bandstructure"/spin-orbit coupling



c.f.Ding/YPC/S.Kai et al. "Spin-momentum entanglement in a Bose-Einstein condensate", Phys. Chem. Chem. Phys. 22, 25669 (2020)



Spin-momentum superposition/entangled

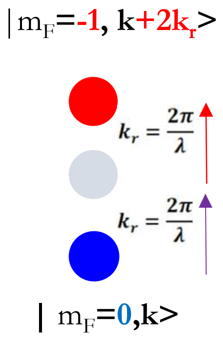
Eigenvalues E(Ω,p_y) and

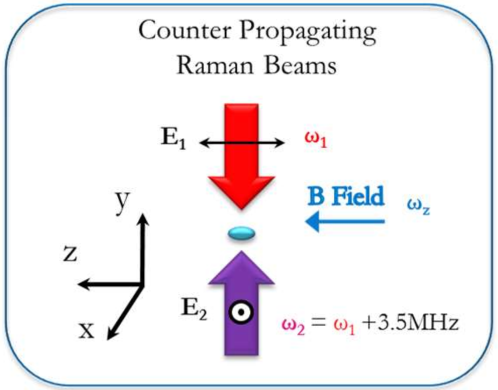
Eigenstate ("dressed state"):

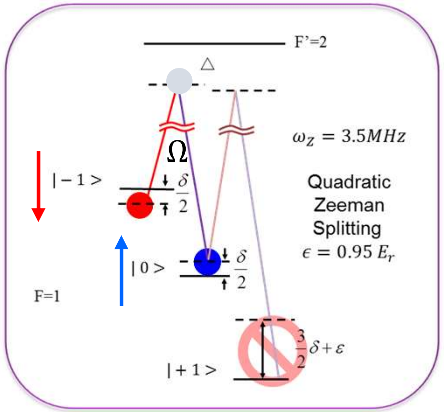
$\alpha(\Omega,p_y)|\downarrow,p_y+k_r>+\beta(\Omega,p_y)|\uparrow,p_y-k_r>$

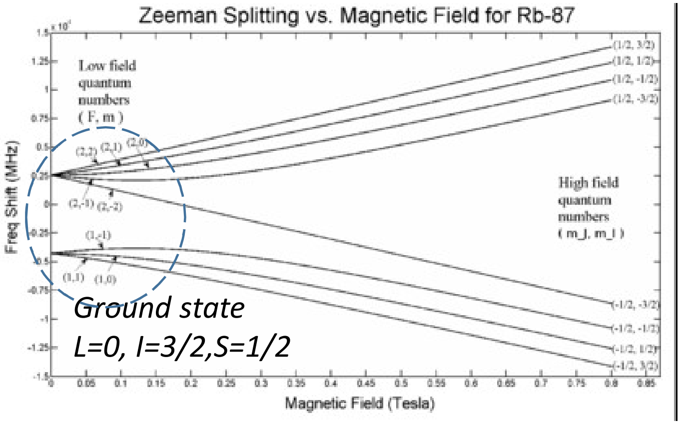
dep on parameters (p, Ω)

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







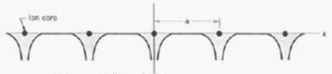


[similar to Spielman/NIST'2011]<also WSU, USTC,SXU,..>

Compare with bandstructure (due to coupling by periodic V)

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

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

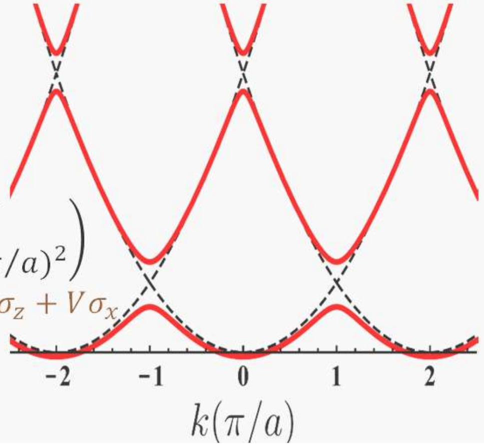


$G_n = n(2\pi/a)$

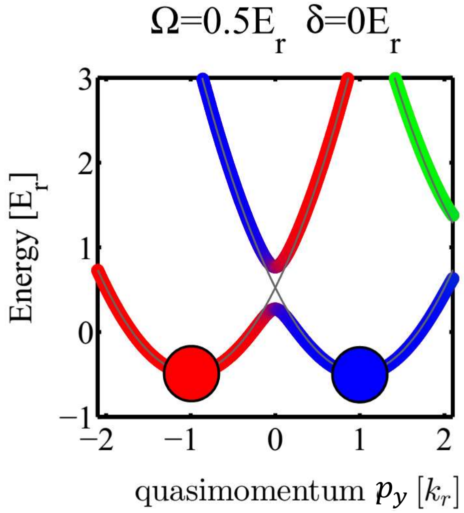
$\psi = e^{ikx}u(x) = e^{ikx}\left(\sum u_n e^{iG_n x}\right) = \sum u_n e^{i(k+G_n)x}$

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

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



Synthetic (Dressed) bandstructure/SOC



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

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

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

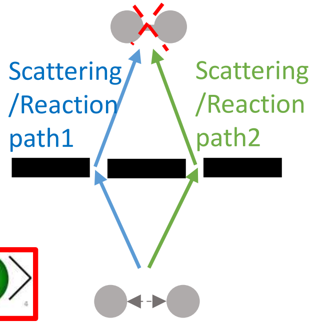
What happens in a chemical reaction when reactants are in quantum superposition states?

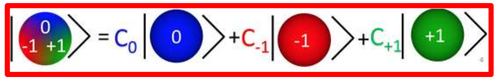
David Blasing
(→ Crane)

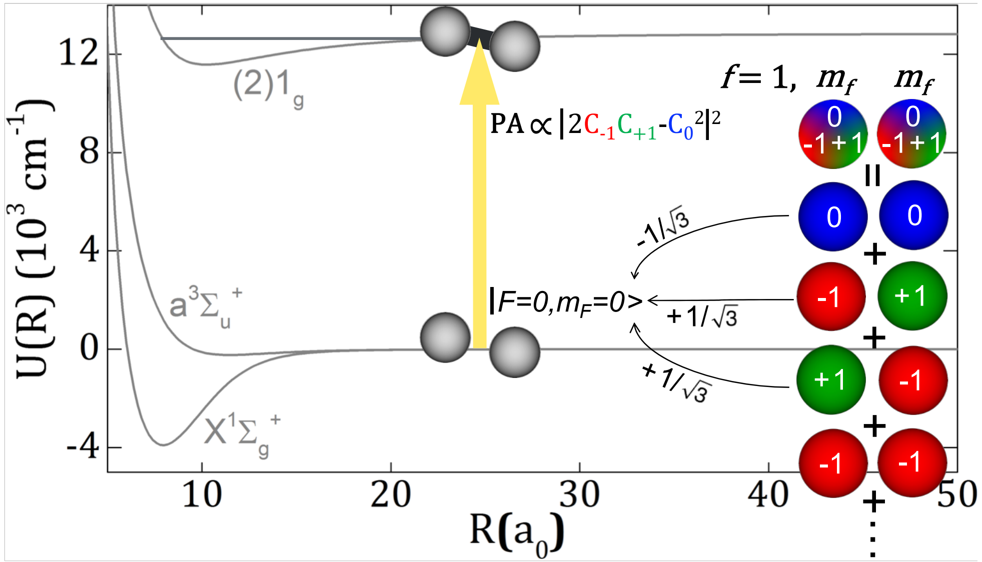
PHYSICAL REVIEW LETTERS **121,** 073202 (2018)

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,*]





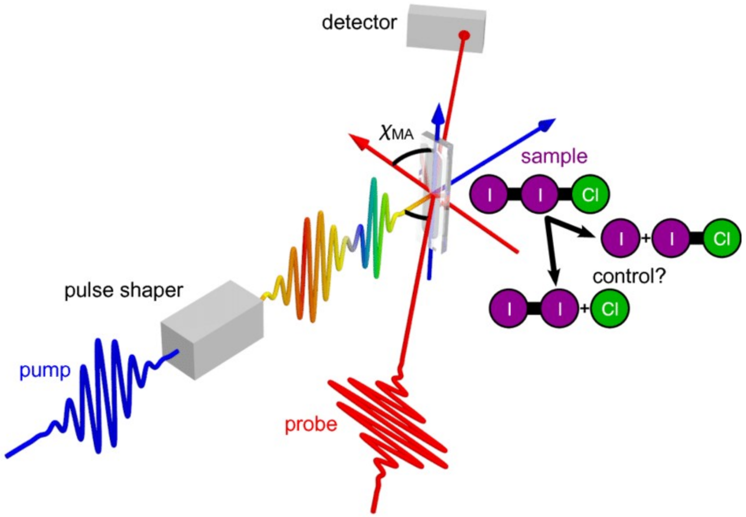


New approach for
“coherent photochemistry”
(not using pulsed/interfering lasers)

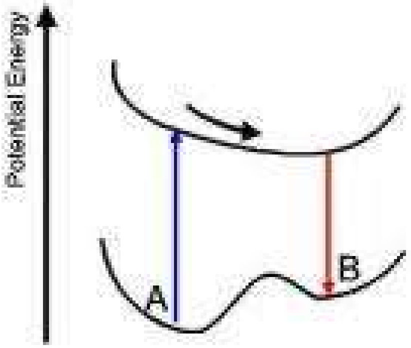
(we will also move onto 3x3 matrices..)

Long-standing dream in quantum chemistry: laser control of chemical reaction

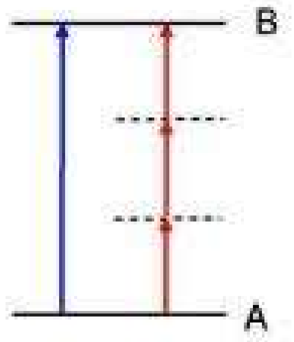
"coherent photochemistry" (using pulsed/interfering lasers)

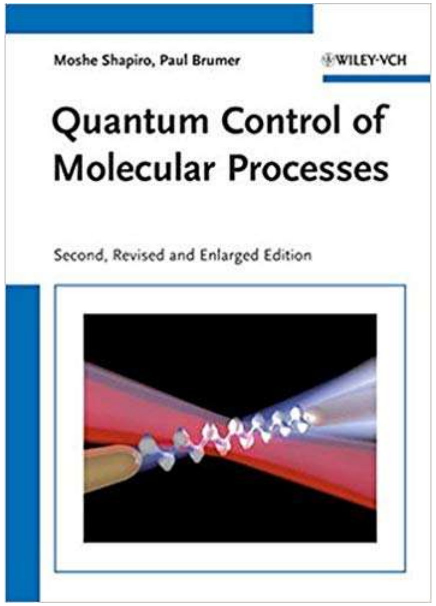


Tannor-Rice



Brumer-Shapiro





Moshe Shapiro, Paul Brumer

WILEY-VCH

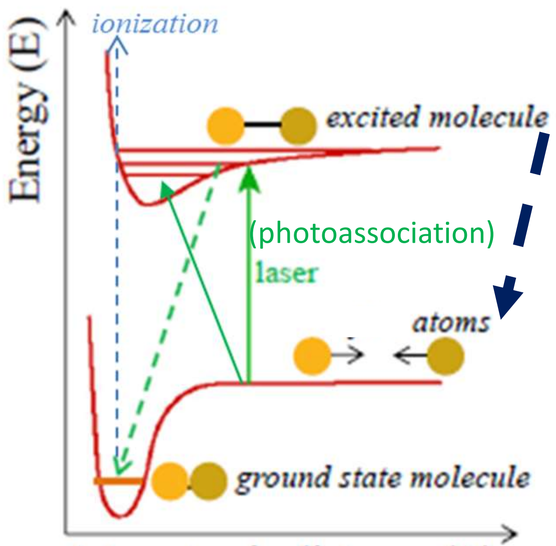
Quantum Control of Molecular Processes

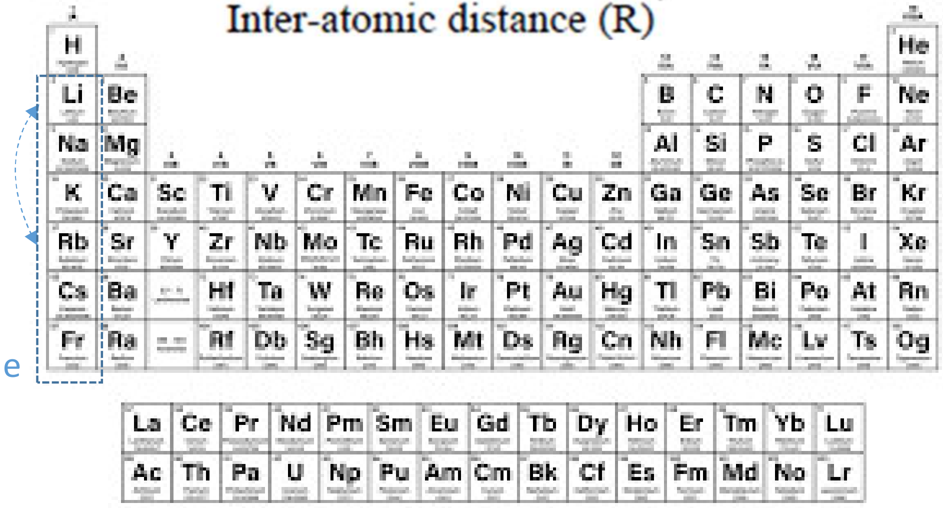
Second, Revised and Enlarged Edition

☞ Instead, our new approach focuses on controlling the ***reactants' quantum states***, rather than the laser fields

Photoassociation (PA)

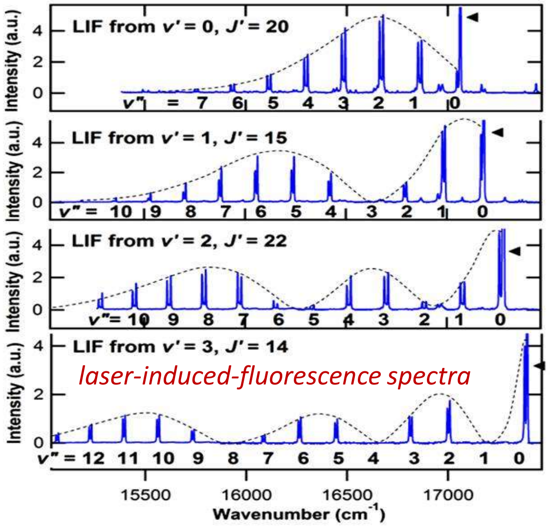
We will use this in BEC (Rb+Rb→Rb$_2$)





bi-alkali molecule (“XY” or X$_2$)

also: **LiRb Molecules**



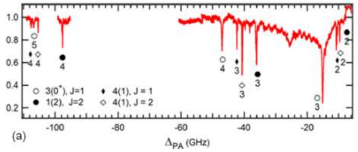
laser-induced-fluorescence spectra

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

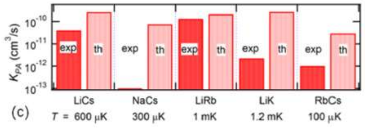
Joint experiment with Dan Elliott (Purdue)

Photoassociation

*First **LiRb cold molecules***



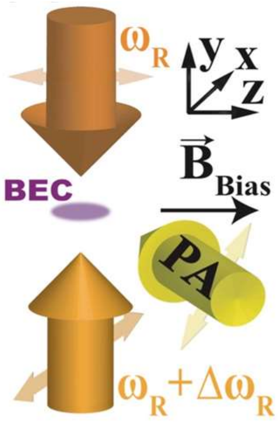
Highest PA rate among bi-alkalis! – unitarity

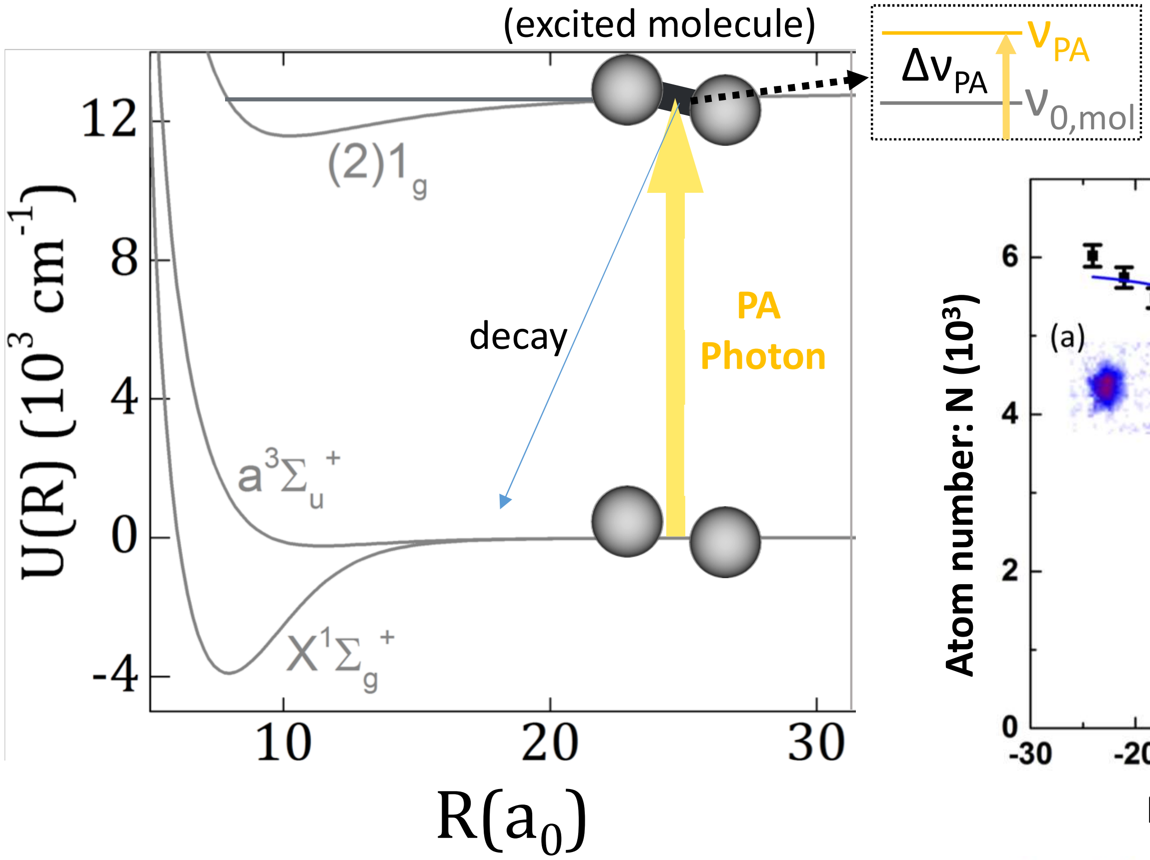


S. Dutta et al. EPL 104, 63001(2013); PRA 89,020702(2014)
D. Blasing et al. PRA 94, 062504 (2016) [short-range PA]
http://www.physics.purdue.edu/quantum/mol.php

c.f. reviews: K. Jones et al., Rev. Mod. Phys. 2006; Koch/Shapiro & Ulmanis et al. , Chem. Rev. 2012;

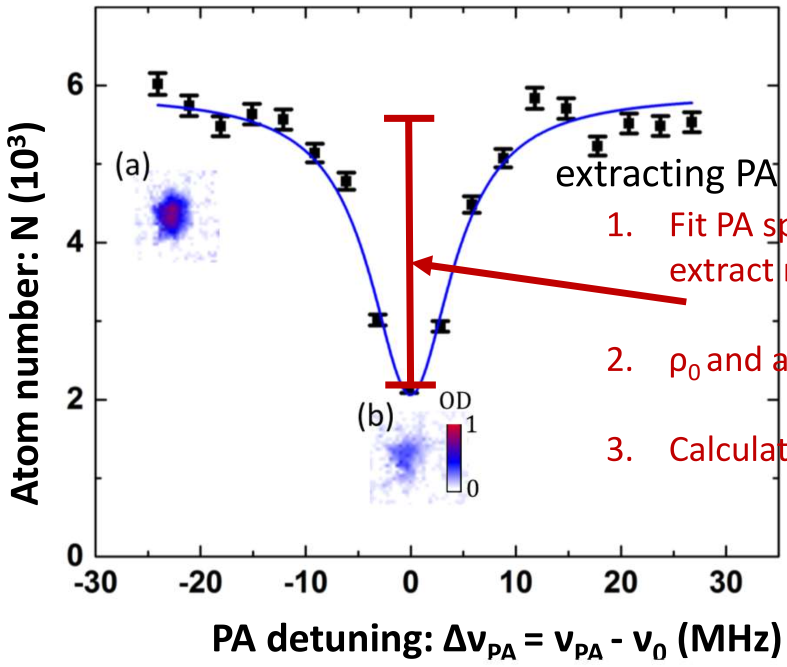
Photoassociation (PA) – loss of atoms from trap





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

Note: PA can measure “Tan’s contact”



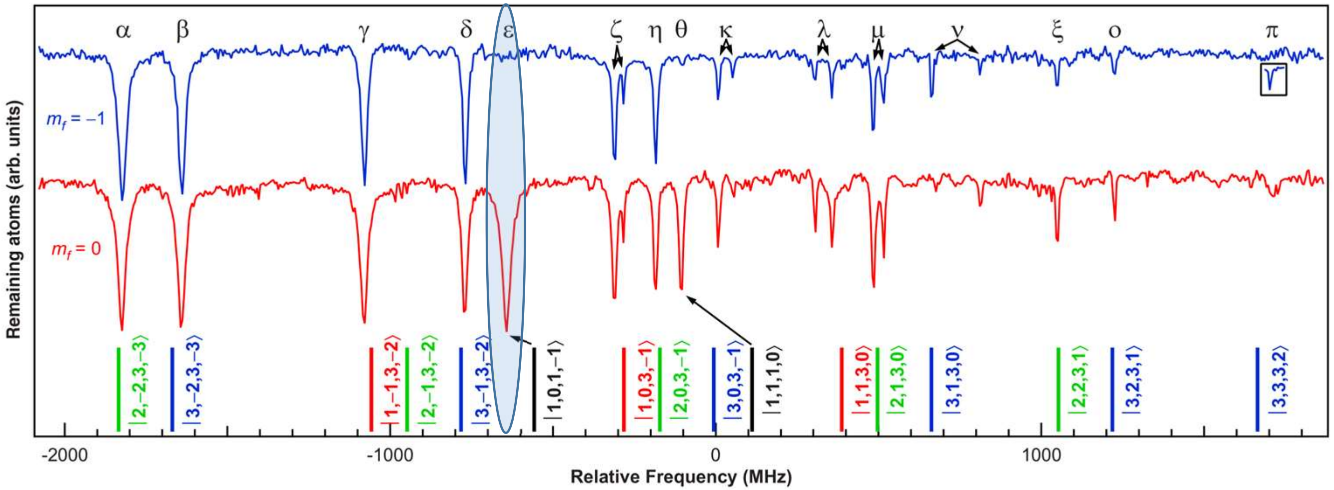
extracting PA rate k_{PA}

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

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

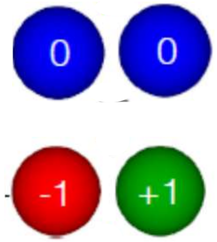
C. McKenzie et al., Phys. Rev. Lett. **88**, 120403 (2002).

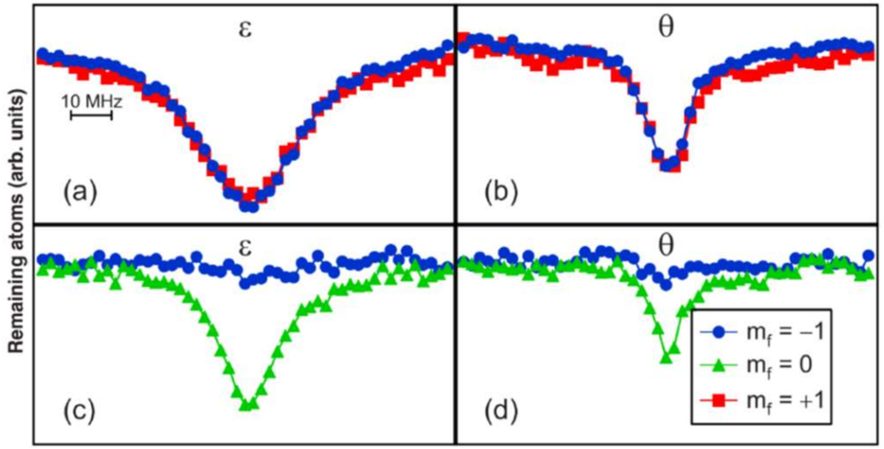
Photoassociation can be spin-dependent



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

$|f=1,m_f>$ pairs:

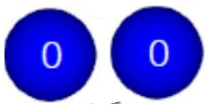


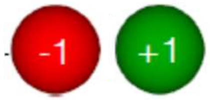


C. Hamley [M.Chapman], et al., Phys. Rev. A **79**, 23401 (2009).

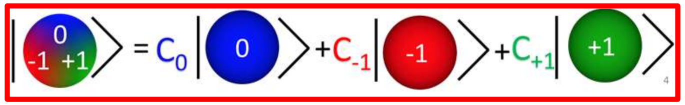
“spin-dependent” Photoassociation

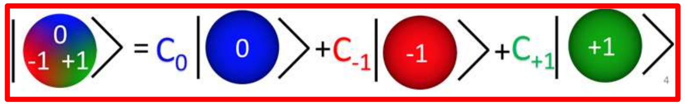
Key point: for our PA line, colliding atoms must have $m_{f,1} + m_{f,2} = 0$





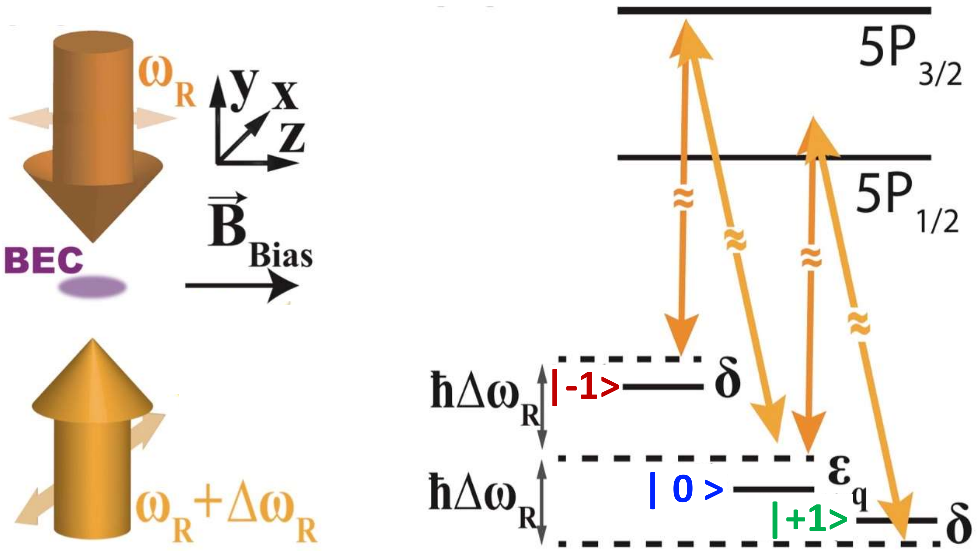
Question: atoms in spin superpositions simultaneously access multiple spin-pathways, what is PA process like?





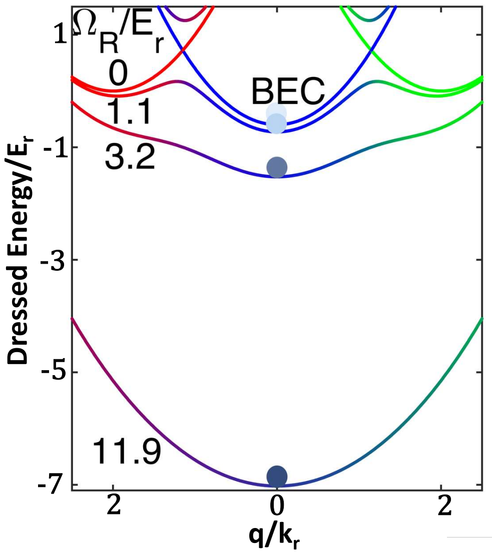
D. Blasing *et al*., “Observation of Quantum Interference and Coherent Control in a Photo-Chemical Reaction”, Phys. Rev. Lett. 121, 073202 (2018)

Spin(-momentum) superposition states



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

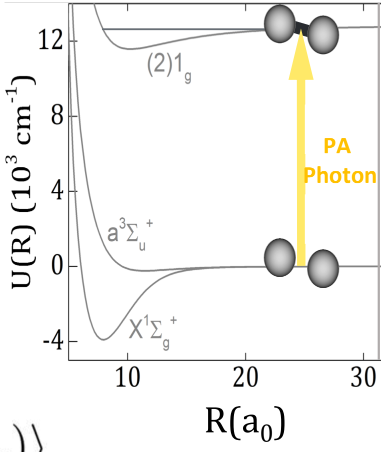
Rep. bandstructures at δ=0



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

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 :

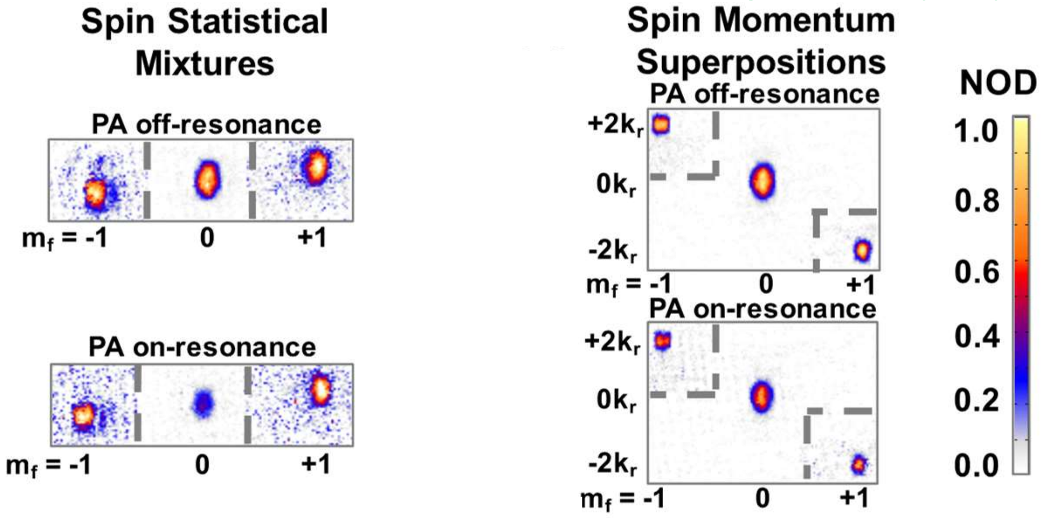
$$\sum_{i=1}^{3} C_i\,|m_f,p\rangle_i = C_{-1}\,|-1,\hbar(q+2k_r)\rangle + C_0\,|0,\hbar q\rangle + C_{+1}\,|+1,\hbar(q-2k_r)\rangle$$

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

PA on spin(-momentum) superpositions

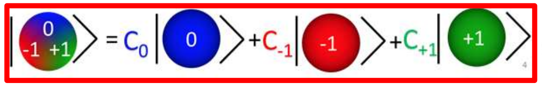
Evidence for superposition state (all components undergo PA together!)

"using chemistry to probe quantum matter"



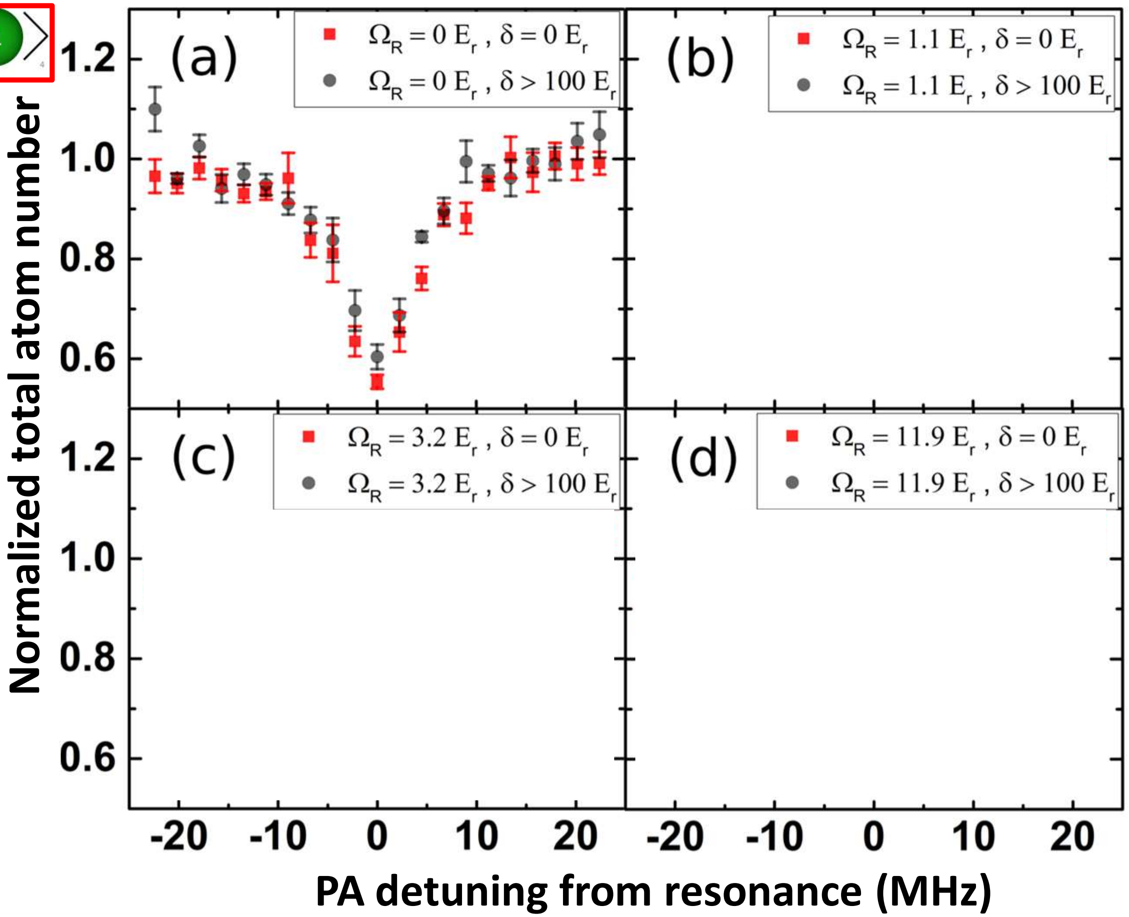
D. Blasing *et al.*, "Observation of Quantum Interference and Coherent Control in a Photo-Chemical Reaction", Phys. Rev. Lett. 121, 073202 (2018)

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]



D. Blasing *et al*
Phys. Rev. Lett. 121, 073202 (2018)

→ ***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

$$\left(\left|{}^{\;0}_{-1\,+1}\right\rangle = C_0\left|0\right\rangle + C_{-1}\left|-1\right\rangle + C_{+1}\left|+1\right\rangle\right) \otimes \left(\left|{}^{\;0}_{-1\,+1}\right\rangle = C_0\left|0\right\rangle + C_{-1}\left|-1\right\rangle + C_{+1}\left|+1\right\rangle\right)$$

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

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

f, m_f

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

opposite CG coefficient!

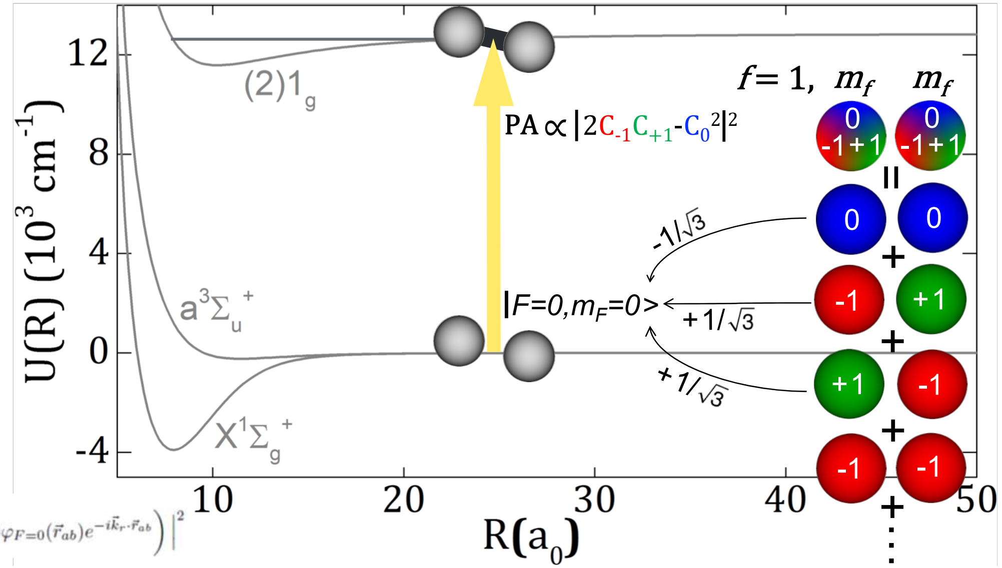
Total F, m_F

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

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

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

Prediction: PA rate for spin superpositions modified over bare rate

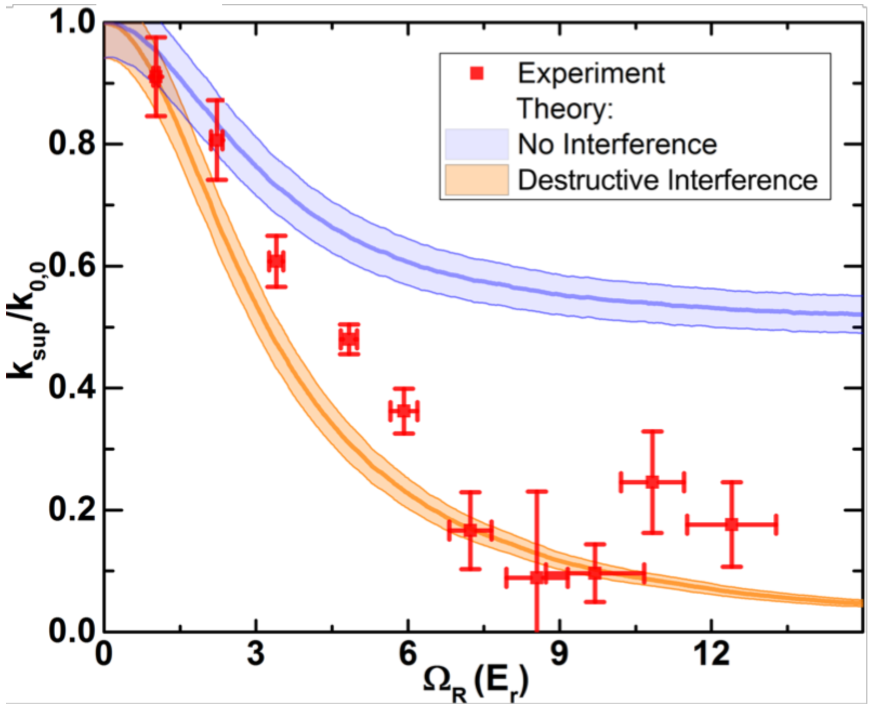


$$\Gamma_{sup} \propto \left|-\frac{C_0^2}{\sqrt{3}}\left(\int d\vec{r}_{ab}\varphi_m^*(\vec{r}_{ab})\varphi_{F=0}(\vec{r}_{ab})\right) + \frac{C_1C_{-1}}{\sqrt{3}}\left(\int d\vec{r}_{ab}\varphi_m^*(\vec{r}_{ab})\varphi_{F=0}(\vec{r}_{ab})e^{i\vec{k}_r\cdot\vec{r}_{ab}} + \int d\vec{r}_{ab}\varphi_m^*(\vec{r}_{ab})\varphi_{F=0}(\vec{r}_{ab})e^{-i\vec{k}_r\cdot\vec{r}_{ab}}\right)\right|^2$$

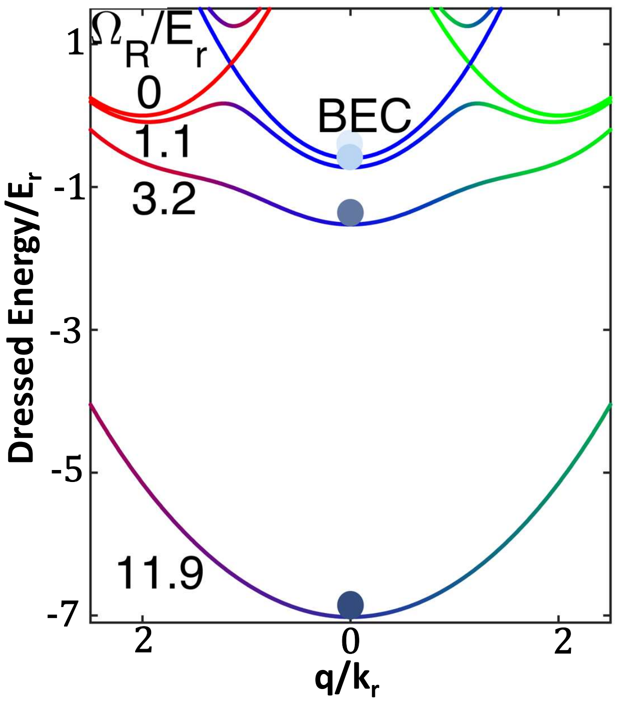
PA on spin(-momentum) superpositions

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

Various Ω_R at $\delta = 0$



Rep. bandstructures



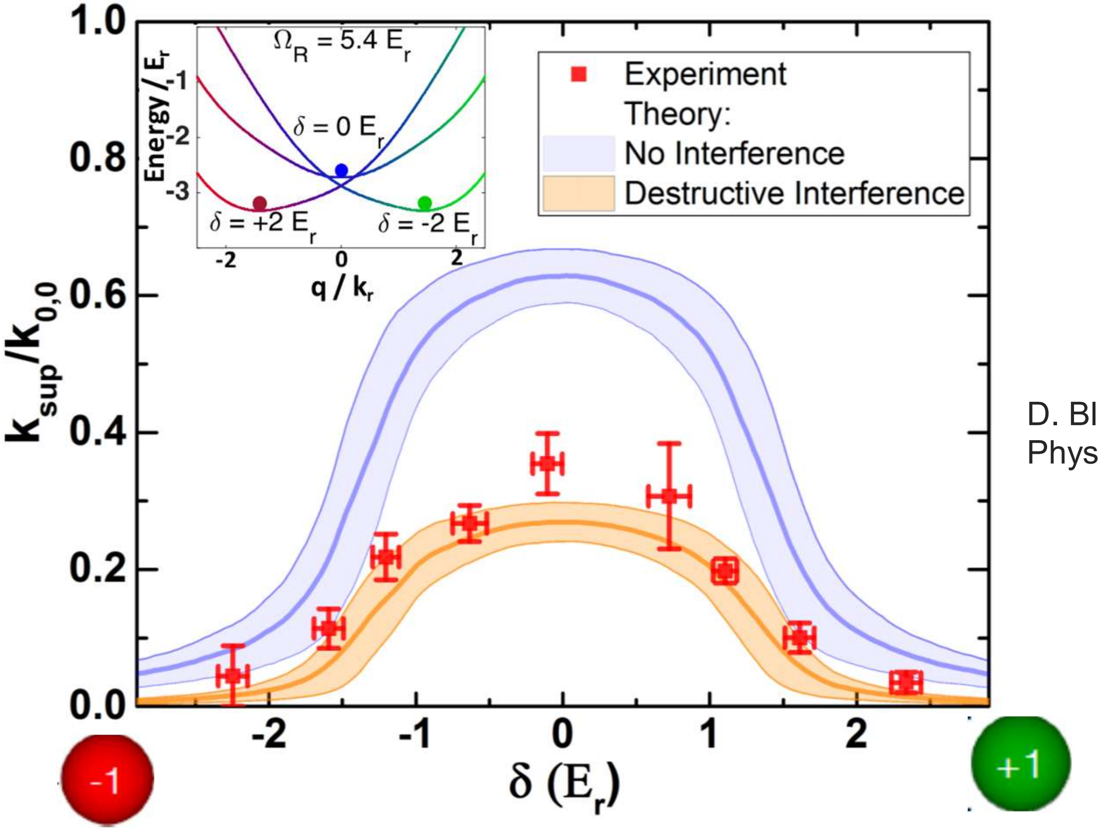
D. Blasing *et al.*,
Phys. Rev. Lett. 121, 073202 (2018)

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

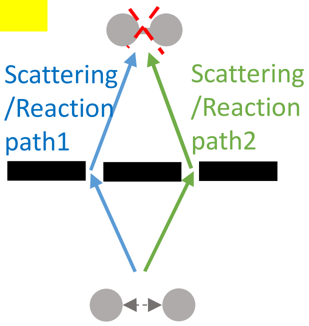
$$k_{sup} = k_{0,0}(|c_0^2|^2 + 4|c_{-1}c_{+1}|^2 - 4\Re(c_0^2 c_{-1}^* c_{+1}^*))$$

Various δ = 0 at Ω_R = 5.4 E_r



D. Blasing *et al.*,
Phys. Rev. Lett. 121, 073202 (2018)

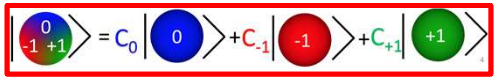
Can this (superposition) to generalized to control other beam/collision/reaction “A+B”?

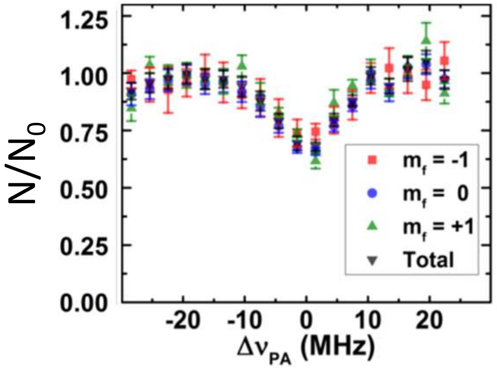


Two-pathway interference in Chemical space (reaction paths)

D. Blasing *et al.*,
Phys. Rev. Lett. 121, 073202 (2018)

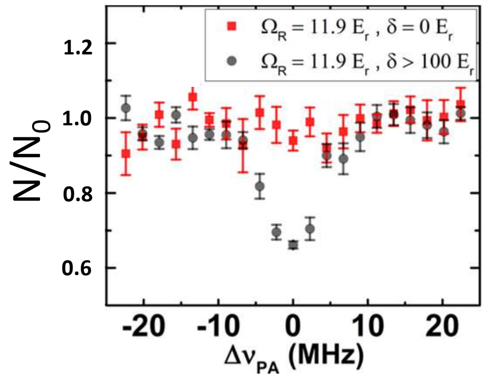
Novel “light-dressed” reactants
(in superposition state)





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

Observations indicate destructive interference



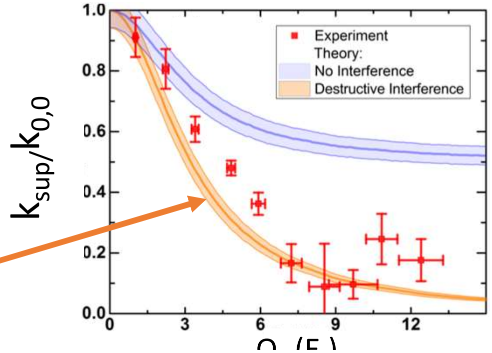
Lots of more to do:

- ***Constructive*** interference and *Full control*
- RF dressing
- F=2 (difference CG)
- Using spin-insensitive PA line

(could lead to big “superradiance-like” enhancement)

- Interplay PA with many-body/correlated effects [using PA/chemistry to probe few/many-body physics, “contact”, etc.]

Agrees with theoretical model



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

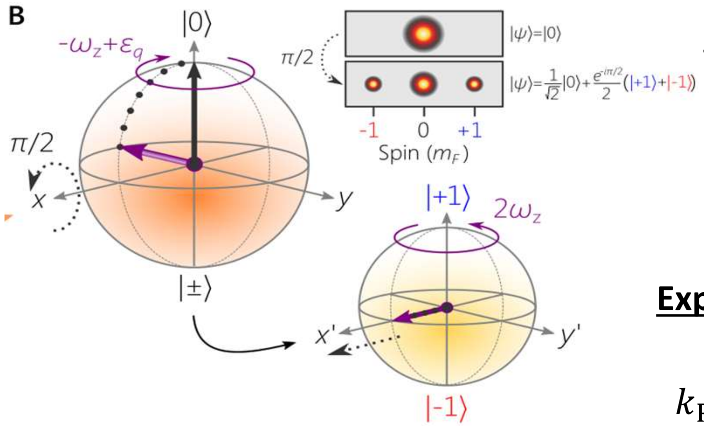
Recent Progress – new approach: **[RF + free evolution + PA] “Ramsey”**

State after $\pi/2$ RF pulse

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + e^{-i\pi/2}|\pm\rangle\right),$$

where $|\pm\rangle = \frac{1}{\sqrt{2}}\left(|-1\rangle + |+1\rangle\right)$

$$|\psi\rangle = \frac{e^{-i\pi/2}}{2}|-1\rangle + \frac{1}{\sqrt{2}}|0\rangle + \frac{e^{-i\pi/2}}{2}|+1\rangle$$

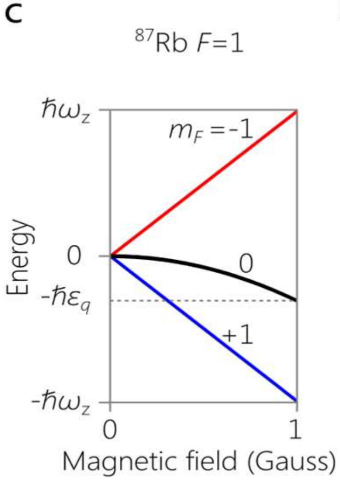


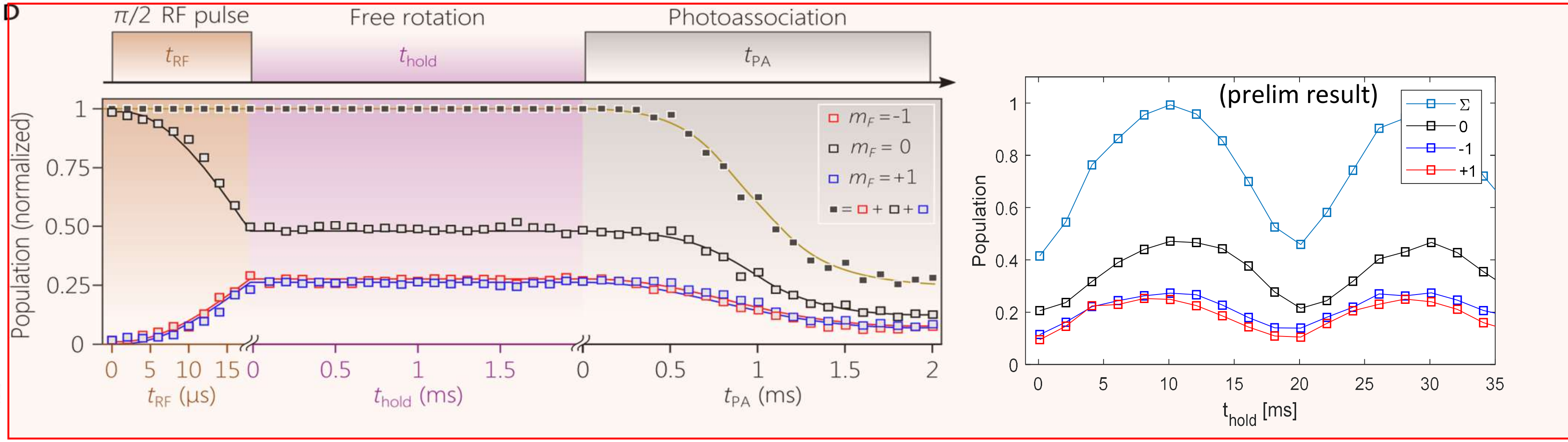
Free rotating state

$$|\psi\rangle = \underbrace{\frac{e^{i\omega_z t - i\pi/2}}{2}}_{C_{-1}}|-1\rangle + \underbrace{\frac{e^{-i\varepsilon_q t}}{\sqrt{2}}}_{C_0}|0\rangle + \underbrace{\frac{e^{-i\omega_z t - i\pi/2}}{2}}_{C_{+1}}|+1\rangle$$

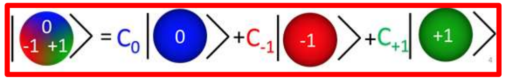
Expected PA rate during free rotation

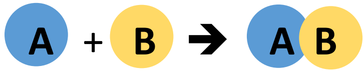
$$k_{\mathrm{PA}} = k_0\left|C_0^2 - 2C_{-1}C_{+1}\right|^2 = k_0\cos^2(\varepsilon_q t)$$





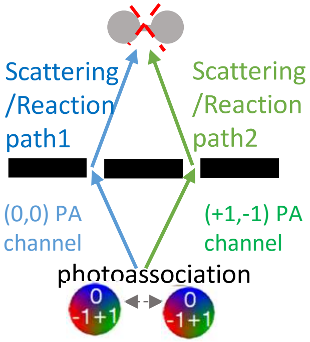
H. Esat Kondakci, et al. "Interferometric Control of Photo-Chemical Reactions in 87Rb Bose-Einstein Condensates", CLEO2020, FW4C.8 (2020)





Idea 1: Putting **reactants** (atoms) in (spin) **quantum superposition states** ➔ controlling reaction via quantum interference!

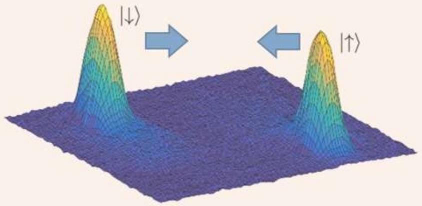
"Young's double slit in chemical/Hilbert space" (**quantum chemistry interferometer**) {2-body physics}



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

Idea 2: **"Synthetic"** (electric/magnetic) **fields** [for charge-*neutral* atoms] ➔ **atomtronic quantum transport**

[can be made spin-dependent] also realize "(spin) condensate collider"] {many-body physics}

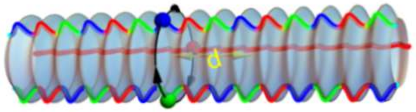


C. Li *et al*. Nature Comm. 10, 375 (2019)

(Bonus) Idea 3: **"Synthetic" dimension**/space ➔ realize novel "synthetic" geometry/topology

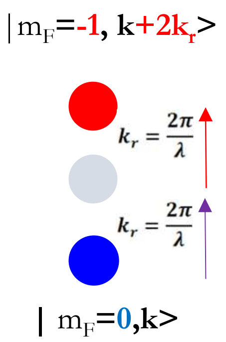
[not easy in solid materials] [e.g. "emergent" crystal w/o external lattice] {1-body physics}

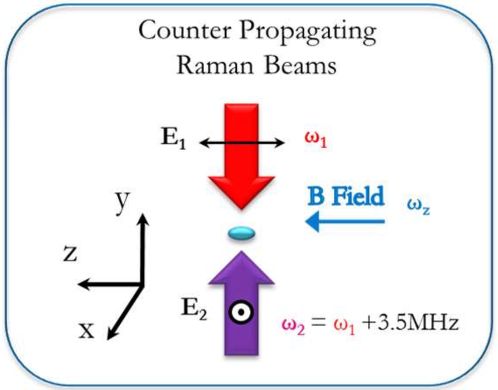
C.Li et al., arXiv:1809.02122

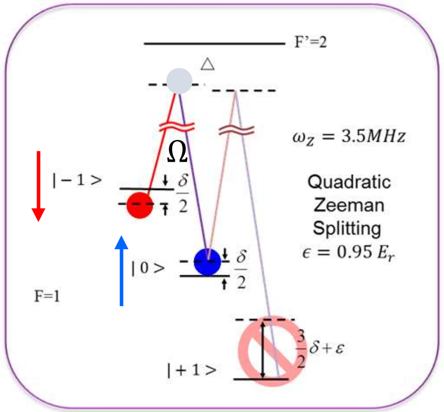


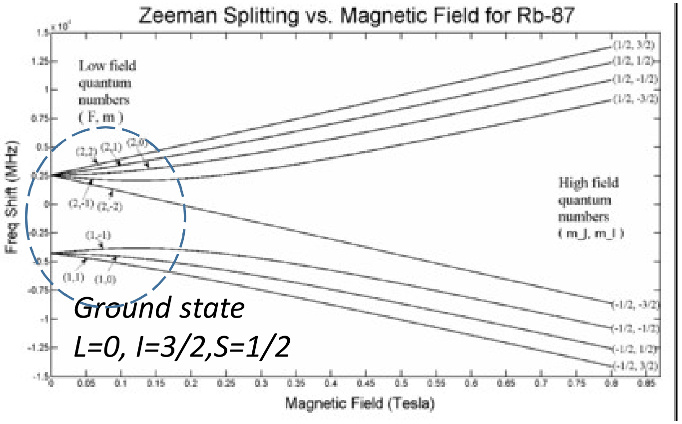
☞our platform to explore these (general) ideas: spinor/spin-orbit-coupled BEC

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







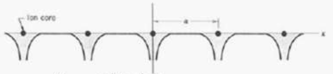


[similar to Spielman/NIST'2011]<also WSU, USTC,SXU,..>

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

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*

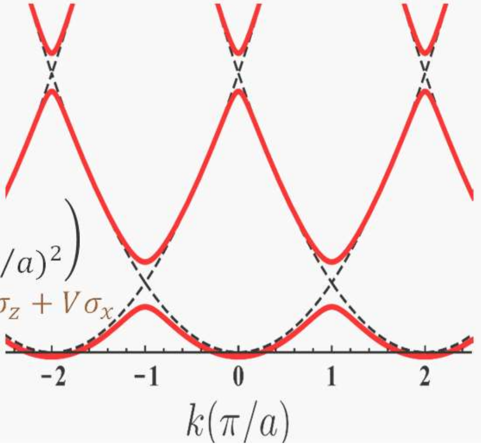


$G_n = n(2\pi/a)$

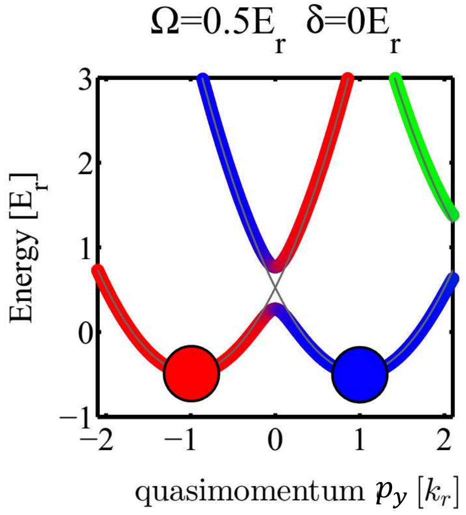
$\psi = e^{ikx}u(x) = e^{ikx}\left(\sum u_n e^{iG_n x}\right) = \sum u_n e^{i(k+G_n)x}$

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

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



Synthetic (Dressed) bandstructure/SOC



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

control knobs

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

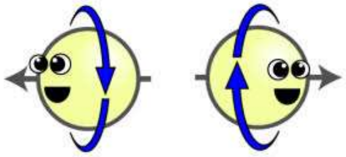
SOC "fictitious" B field

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

“Spin-helical” (“spin-less”) particles [electrons & atoms]

(Spin-momentum locking/coupling) $\vec{\sigma} \cdot \vec{p}$

(like neutrinos…)



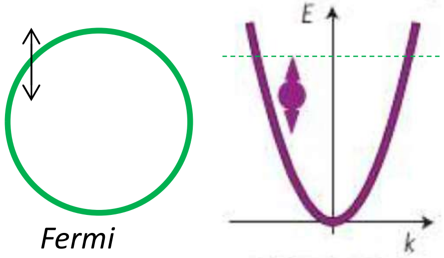
$\vec{p}$ $\vec{\sigma}$

- SOC (for electrons): a relativistic effect --- moving E-field acts as B-field: $\boxed{\vec{B}_{SO} \sim \left(\frac{h}{mc^2}\right) \vec{v} \times \vec{E}}$: act on spin!

Solid State/Electronic System → Spintronics & Topological Quantum Matter (TQM)

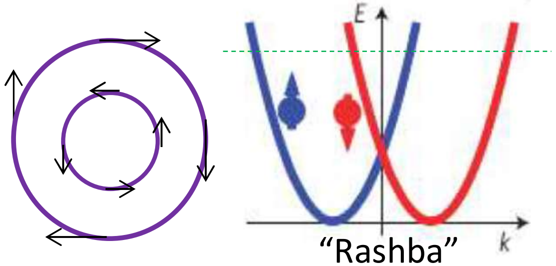
$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

$$\hat{H} = \frac{\vec{p}^2}{2m}$$



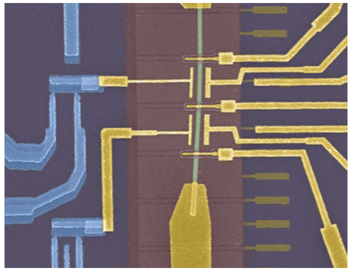
Fermi Surface (“spin-full”/2-fold degenerate)

$+\alpha p_{x,y} \cdot \sigma_{x,y}$



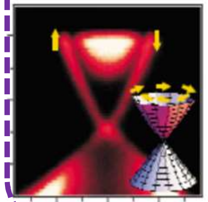
“Rashba”

Can we remove the spin deg.?
(2 →1) [get only “half” of full]

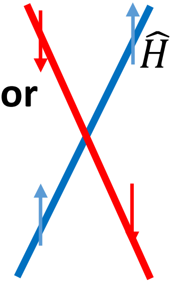


SOC Nanowires
(e.g. InSb)
[for “Majorana”]
[e.g. Microsoft]

$\alpha \to \infty$ $+B_z \cdot \sigma_z$



Topological insulator
(surface state
“spin-helical
Dirac fermion”)

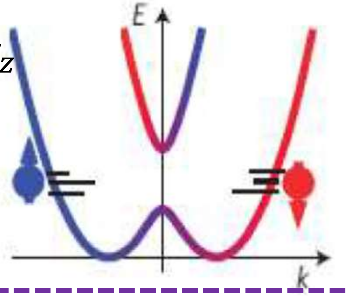


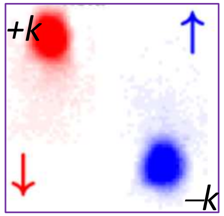
$$\hat{H} = \frac{\vec{p}^2}{2m} + \alpha p_{x,y} \cdot \sigma_{x,y} + B_z \cdot \sigma_z$$

“spin-helical” particles

- *make/measure/use them*
- *platforms for TQMs*

& spin-based quantum tech.

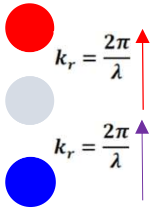




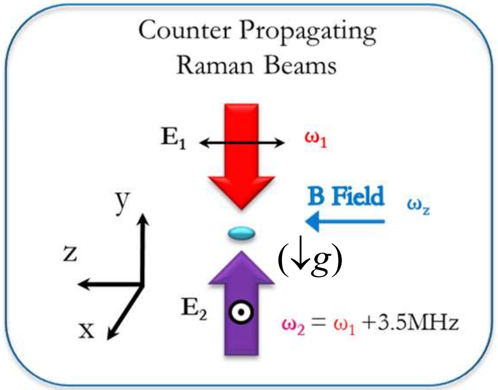
SOC Bose-Einstein condensate
(SOC-BEC) [with
“synthetic fields”]

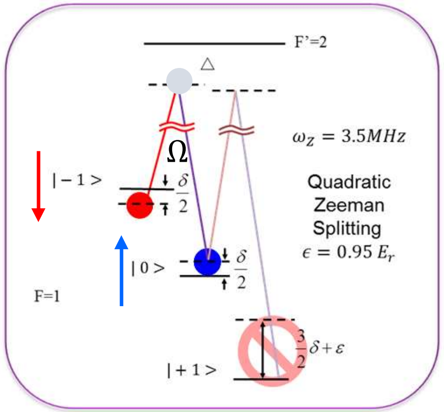
Synthetic Spin Orbit Coupling (SOC) by optical Raman coupling (spin-momentum)

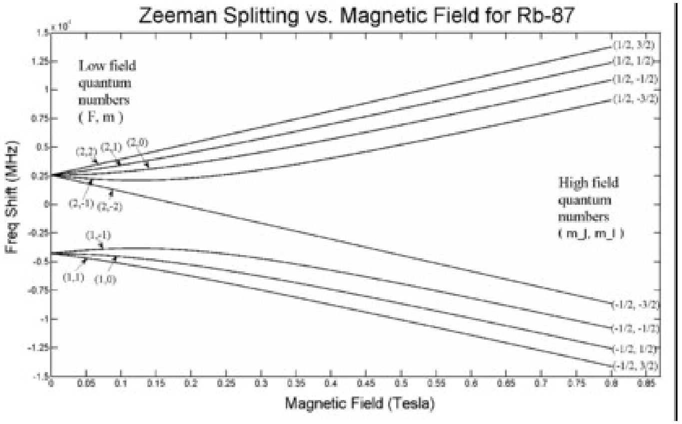
|m$_F$=-1, k+2k$_r$>

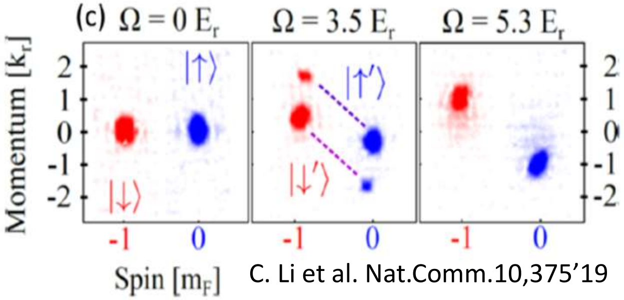


| m$_F$=0,k>



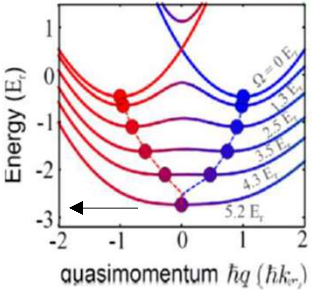






C. Li et al. Nat.Comm.10,375'19

Dressed bandstructure (Eigen-energies vs p$_v$)



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

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

Synthetic Gauge Fields

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

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

Eigenstate ("dressed state"): α(p$_y$)|↓,p$_y$+k$_r$>+β(p$_y$)|↑,p$_y$-k$_r$>

superposition of "bare state"

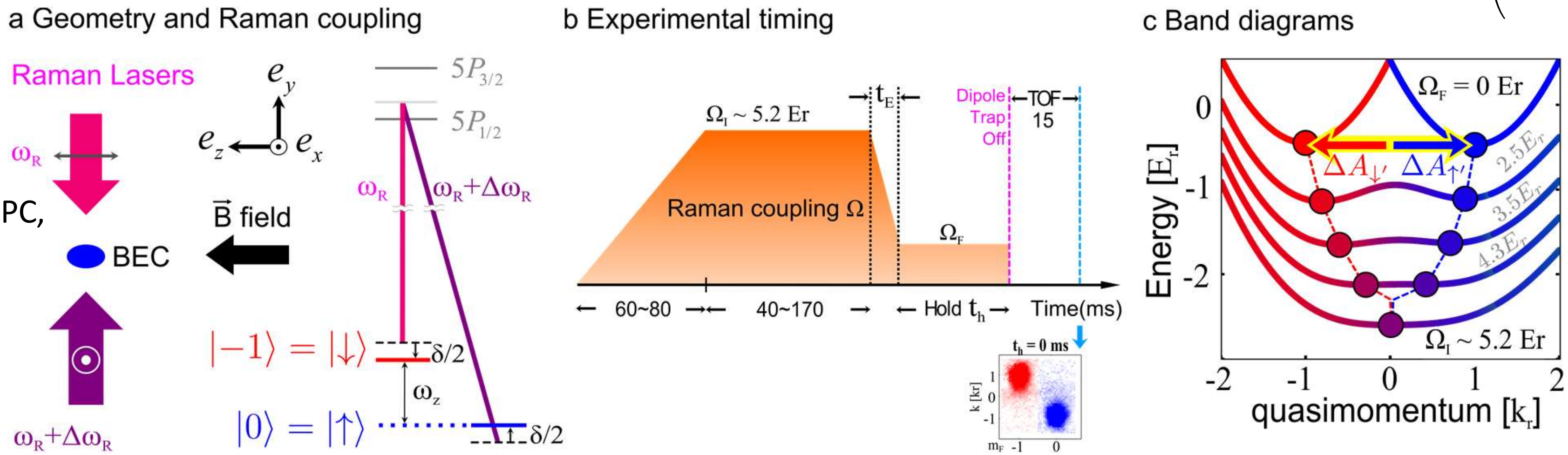
[c.f. review by Galitski/Spielman Nature'2013; Physics Today'2019;Hui Zhai, Int.J.Mod.Phys.B'2012;]

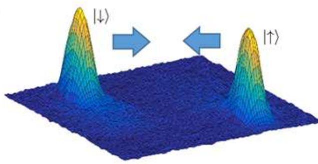
"Spinor BEC collider"

(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)



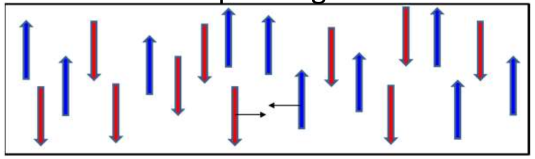


"Collide 2 spinor BECs in trap"

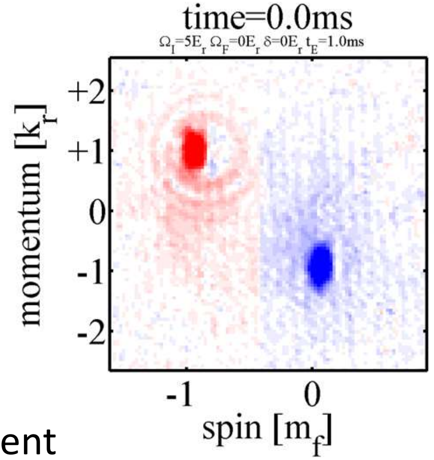
$$H = \frac{\hbar^2}{2m}p_y^2 I + \frac{\hbar^2 k_r}{m} p_y \sigma_z + \frac{\Omega}{2}\sigma_x$$

"quantum quench"

"spin drag"



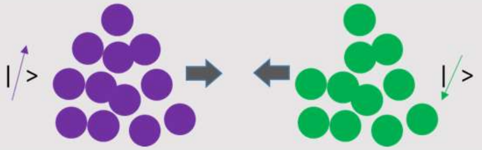
$$\boxed{E_\sigma = \frac{\delta A_\sigma}{\delta t} \approx \frac{\Delta A_\sigma}{t_E}}$$



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"]

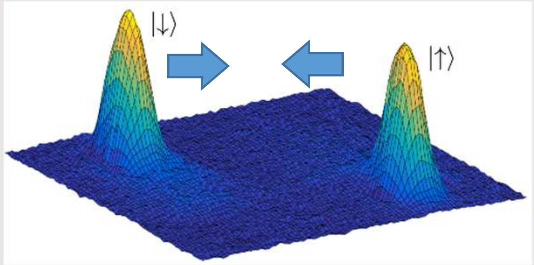
What is the effect of SOC?

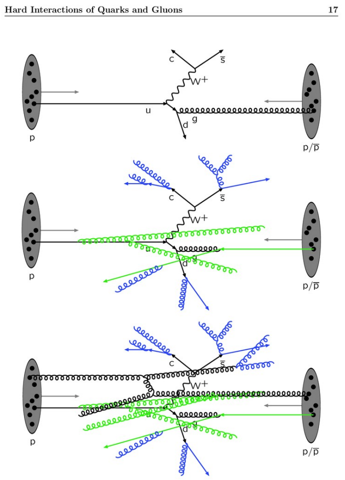
Spin Dipole Mode
(SDM) --- AC spin current

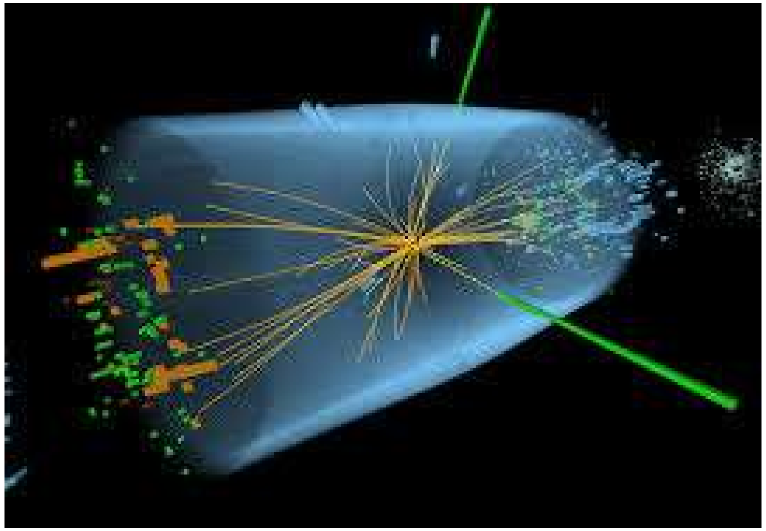


- **How do 2 (dressed) BECs collide?**
  [many-body]
- **How do “dressed” atoms collide?**
  [2-body]

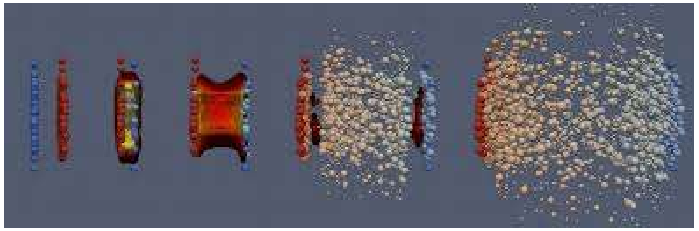
quantum gas collider

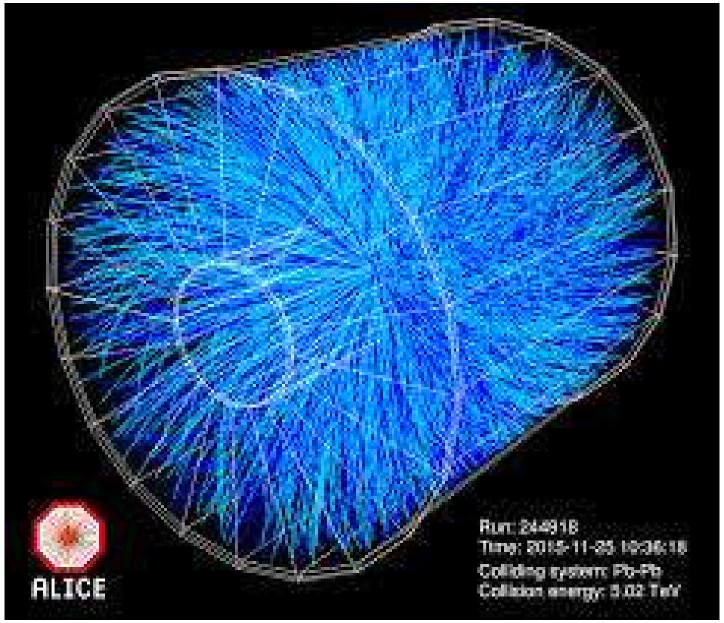



Hard Interactions of Quarks and Gluons 17



How do 2 protons collide





How do 2 (Pb) ions collide

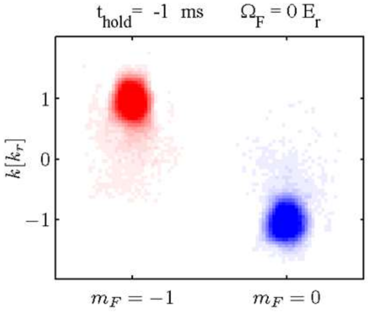
Courtesy LHC

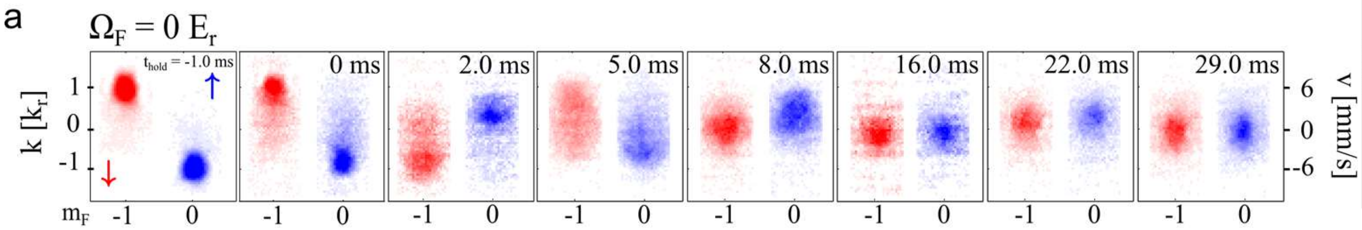
Spin Dipole Mode (AC Spin Current): no SOC vs SOC

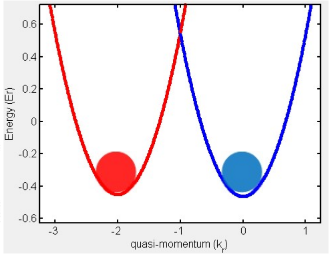
Mechanical momentum

Bare case

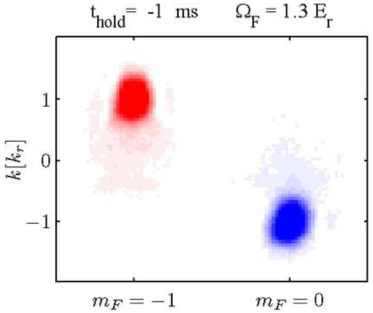
Stronger thermalization

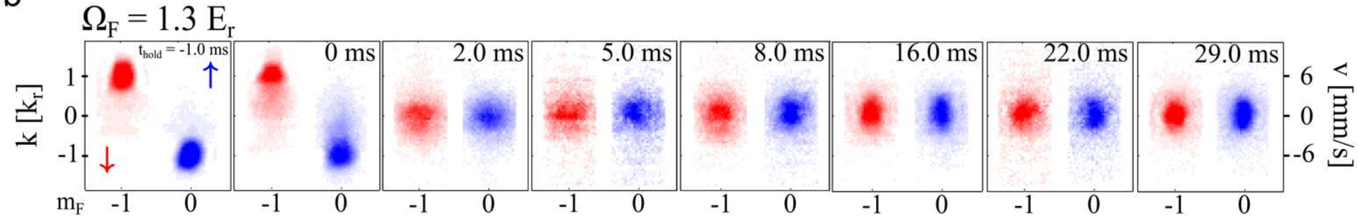


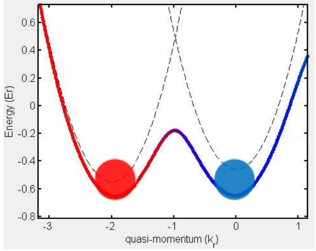




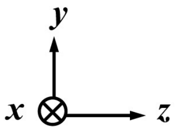
Dressed case







Stronger momentum damping, less thermalization

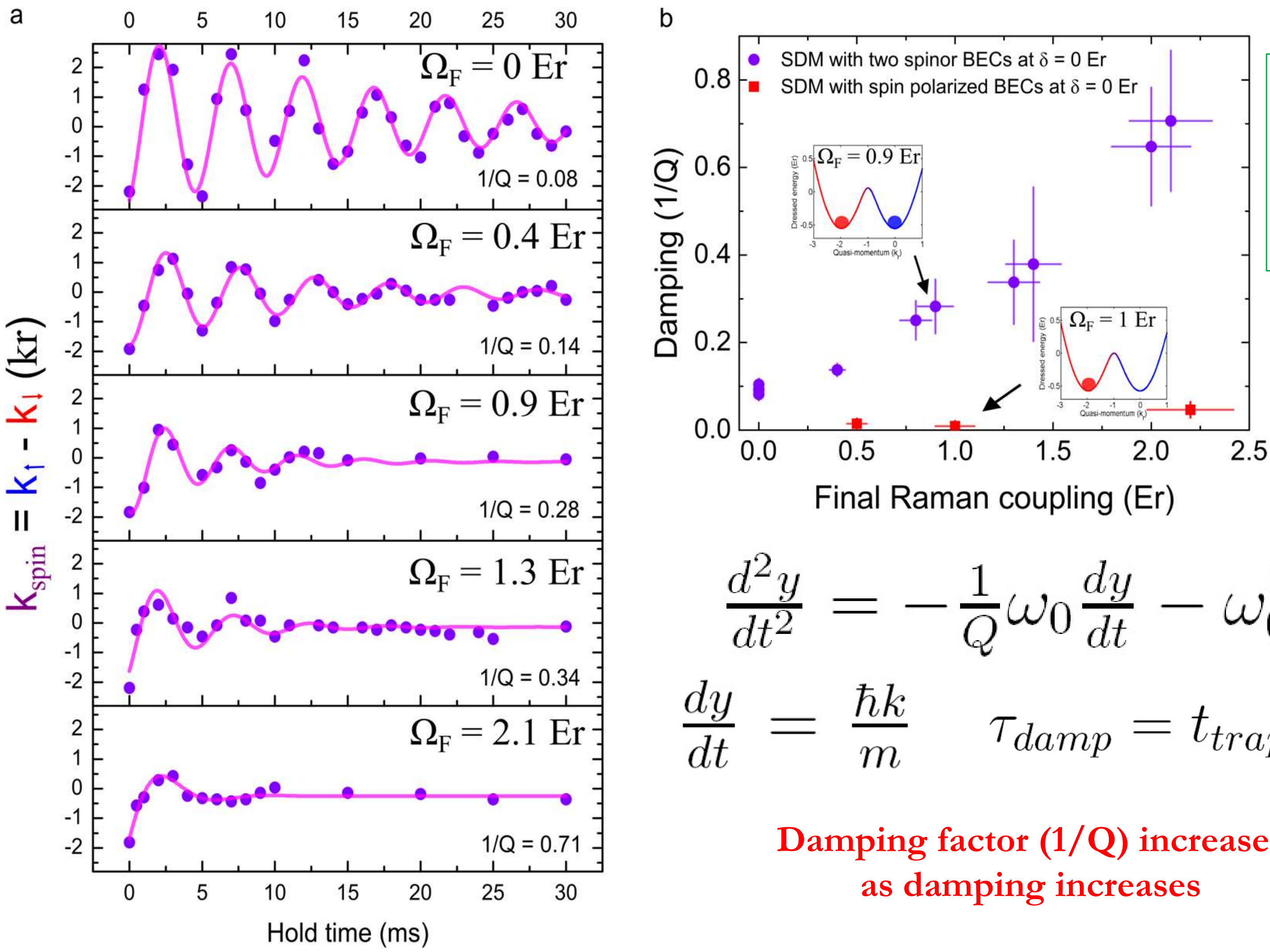


$$N_c \sim 1.3{-}1.6\times 10^4$$

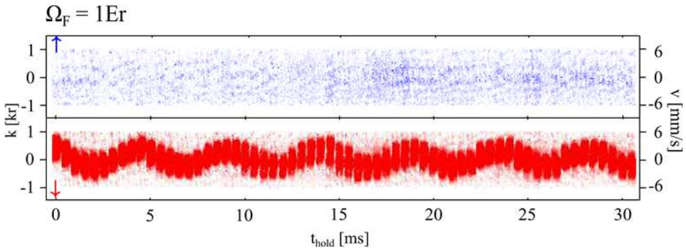
$$\omega_z \sim 2\pi\times(37\pm3)\ Hz$$

$$\omega_x \sim \omega_y \sim 2\pi\times(205\pm15)\ Hz$$

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)

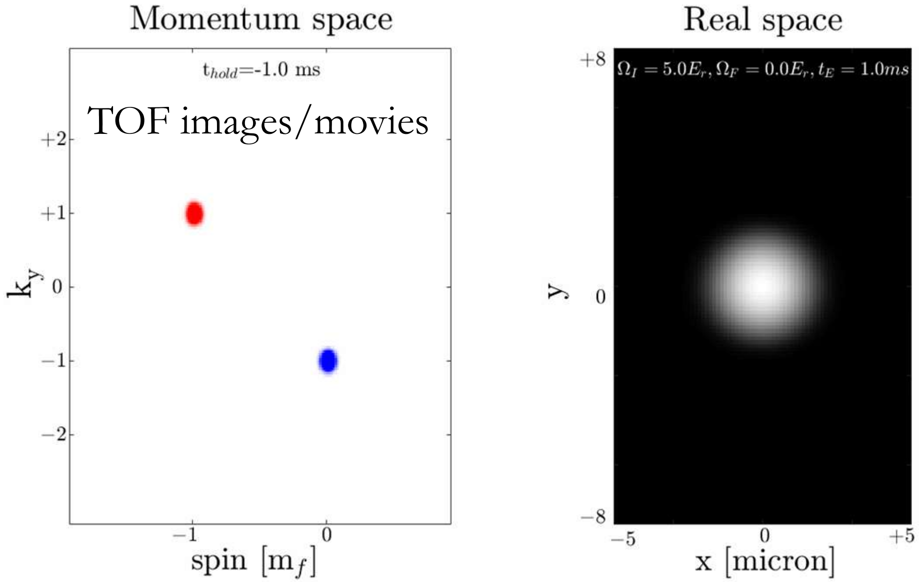


$$\frac{d^2y}{dt^2} = -\frac{1}{Q}\omega_0\frac{dy}{dt} - \omega_0^2 y$$

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

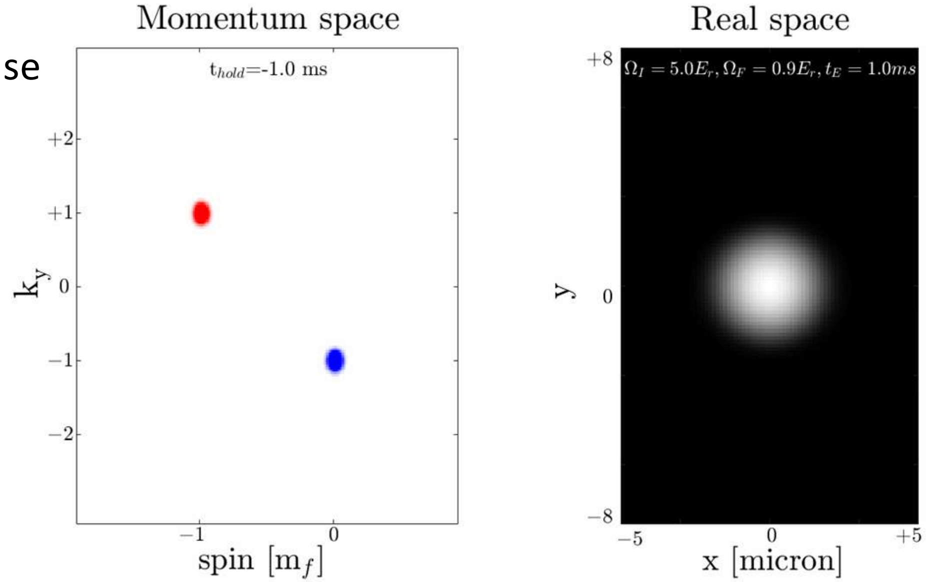
Damping factor (1/Q) increases as damping increases

Bare case



TOF images/movies

Dressed case



GPE Simulation of SDM:
In-situ images/movies

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

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

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

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

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

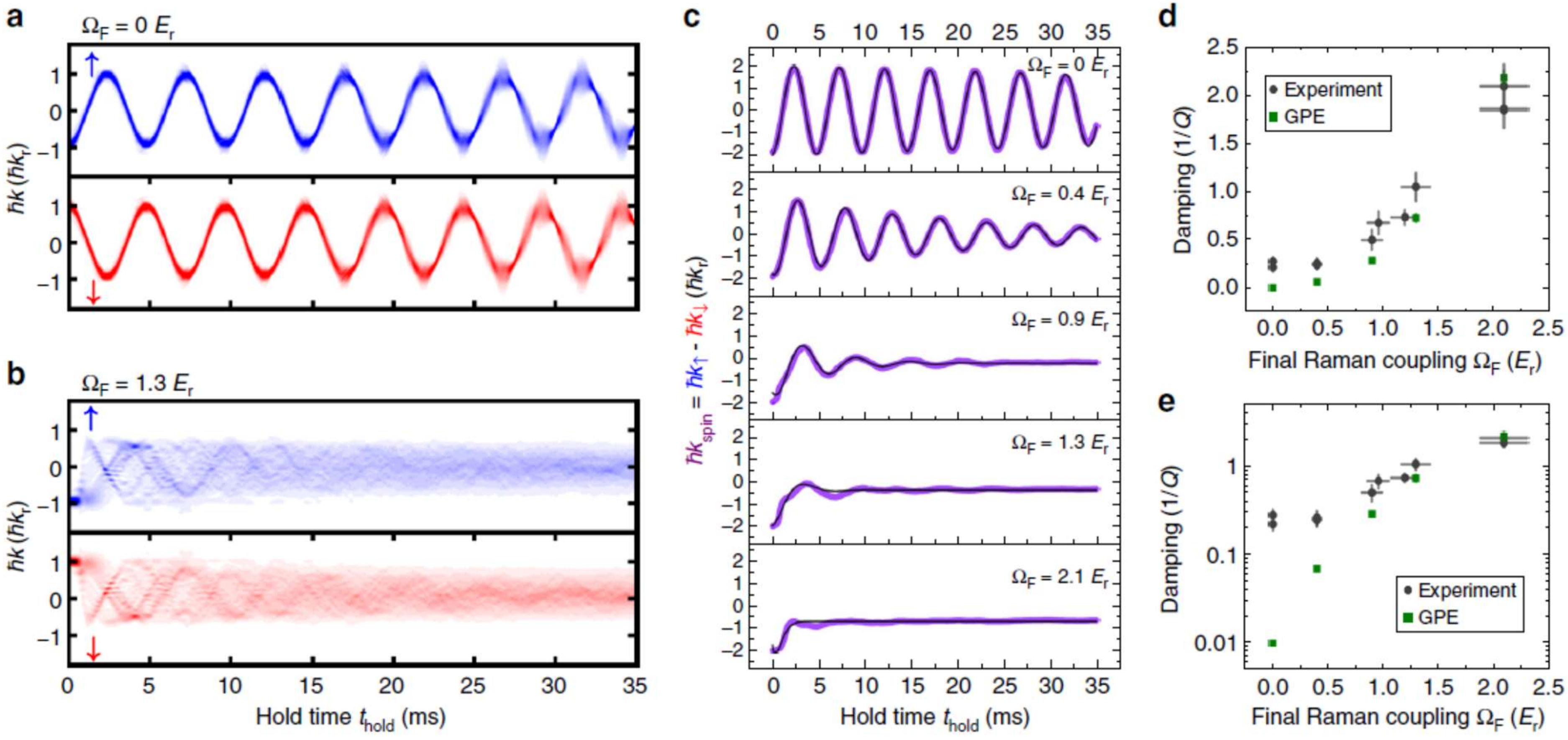
$$V_{\text{trap}} = \frac{1}{2}m\omega_x^2x^2 + \frac{1}{2}m\omega_y^2y^2 + \frac{1}{2}m\omega_z^2z^2$$

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

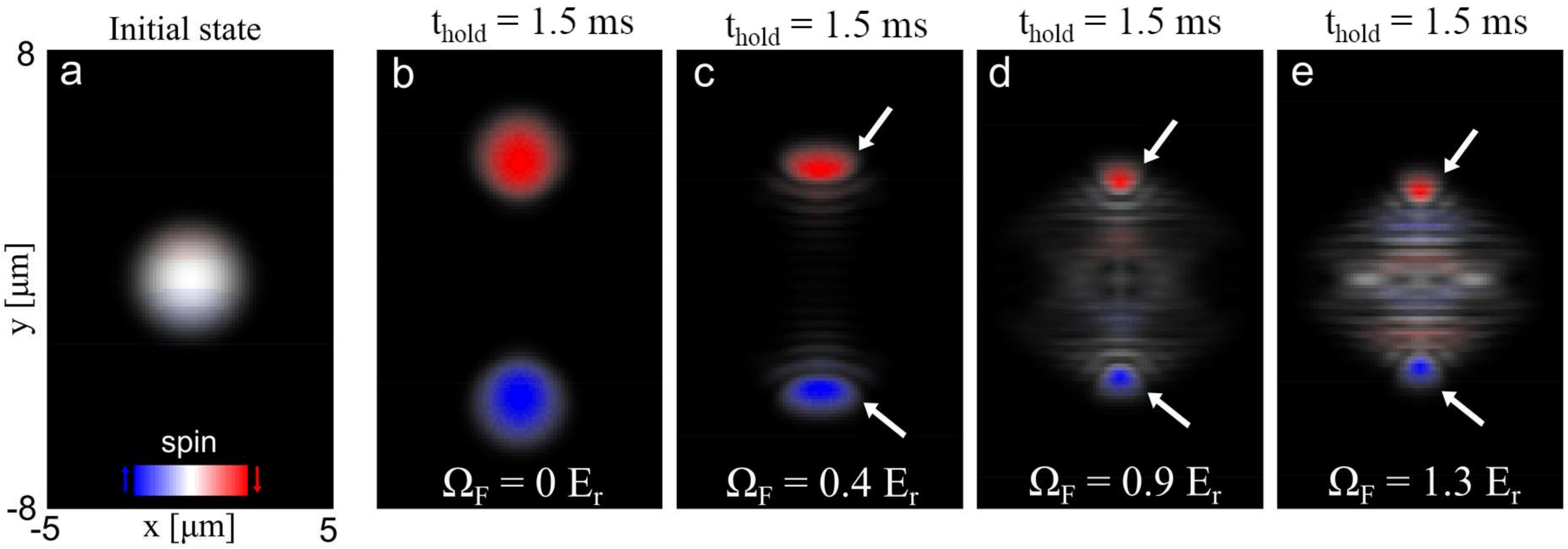
$$g_{\downarrow\downarrow} = g_{\downarrow\uparrow} = g_{\uparrow\downarrow} = \frac{4\pi\hbar^2(c_0 + c_2)}{m} \qquad c_2 = -0.46a_0$$

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

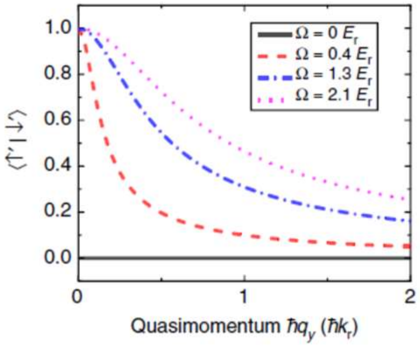
GPE simulation qualitatively explains damping



Understanding the SDM damping

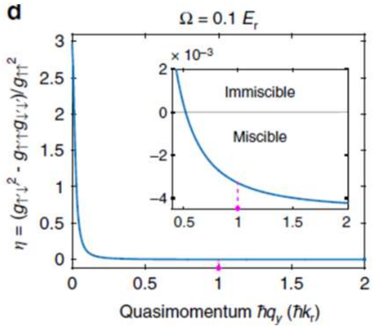


GPE Simulation of SDM:
In-situ images
GPE done by Chunlei Qu
& Chuanwei Zhang (UT Dallas)

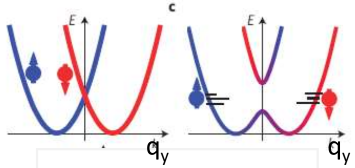


(M.He & Q.Zhou)

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



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



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

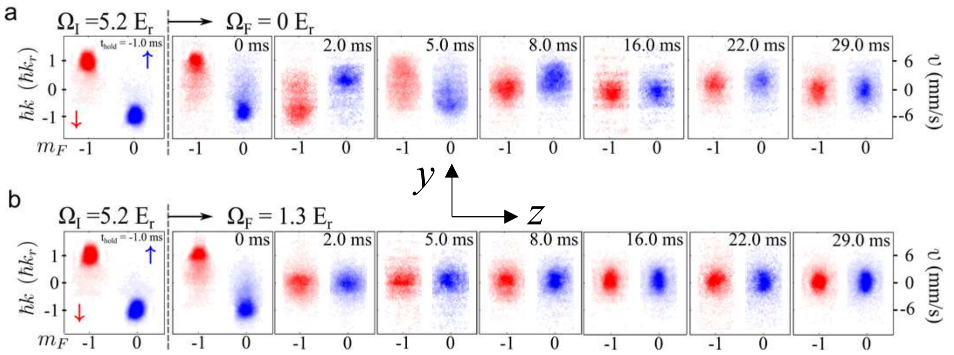
Acknowledge discussion with Hui Zhai et al.

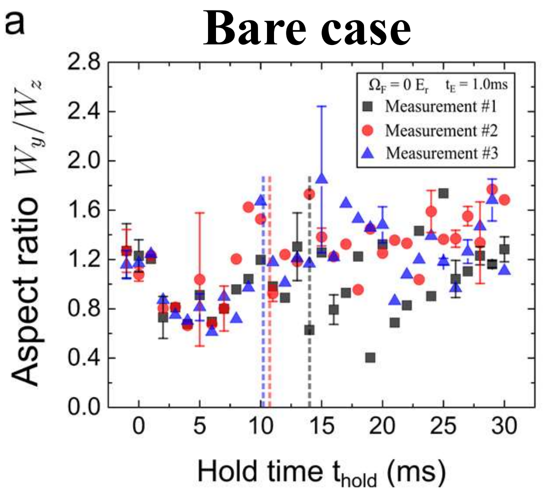
At Ω>0 (dressed), spin part no longer orthogonal, the wavefunction interference leads to enhanced interaction, which excites breathing mode (decay channel of SDM) and leads to strong damping of SDM; this strong damping gives less oscillation thus less heating

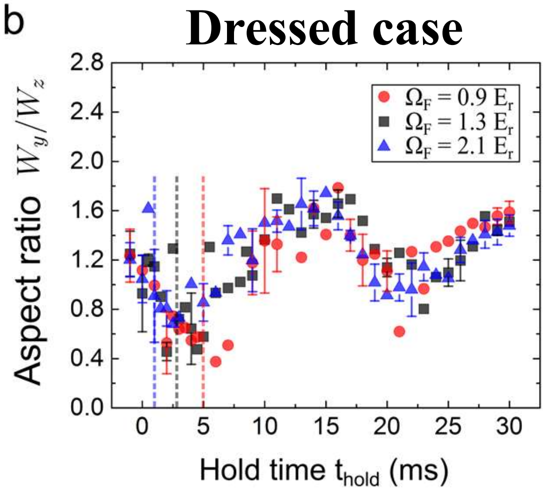
Other important factor: (enhanced) immiscibility of dressed BECs when moving (q →0)

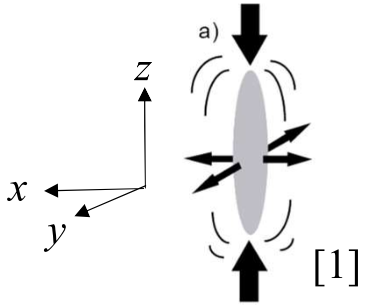
Where does the energy go? --- Observation of BEC Shape Oscillations (Quadrupole Modes)

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









$\omega_z \sim 2\pi\times(37\pm3)\ Hz$

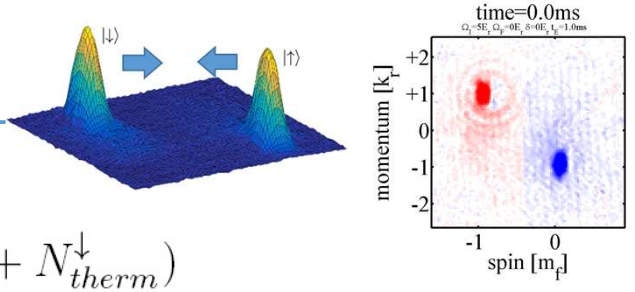
$\omega_x \sim \omega_y \sim 2\pi\times(205\pm15)\ Hz$

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

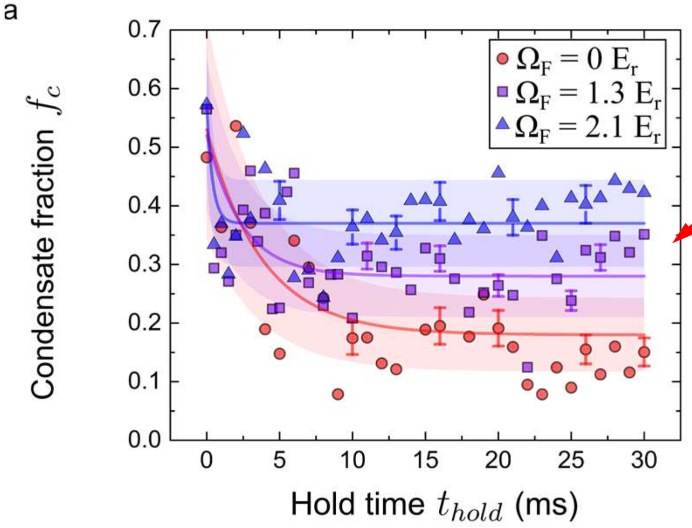
Oscillations have a well-defined average frequency of 58 Hz, consistent with the predicted frequency of the m=0 quadrupole mode: $f_{m=0} = \sqrt{2.5}\omega_z/(2\pi) \sim 59$ Hz for a cigar shape BEC.

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

Thermalization and Spin Current Relaxation



“Quantum Gas Collider”



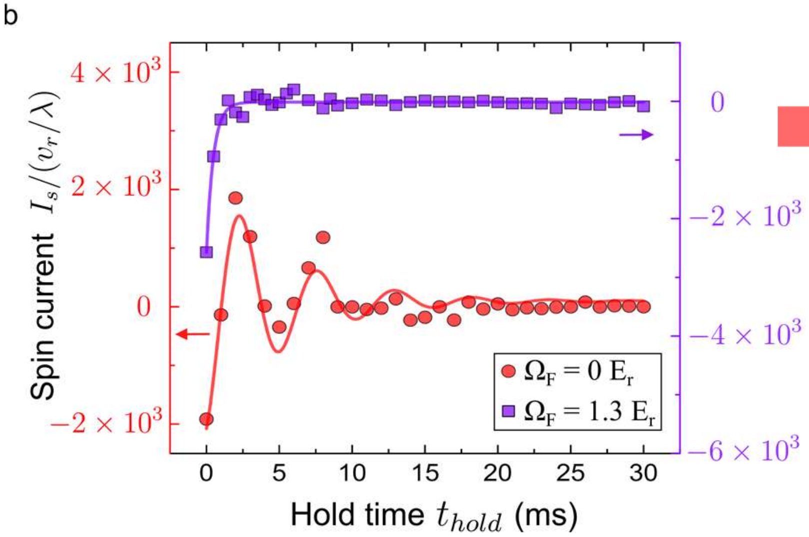
Condensate fraction:

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

Stronger momentum damping stops the collision between different spins earlier.

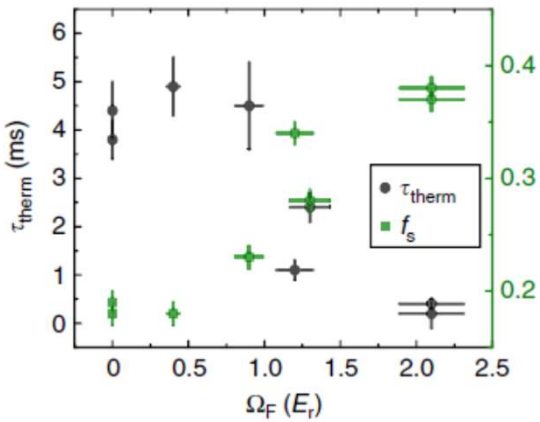
$$f_c(t_{hold}) = f_s + (f_i - f_s)\exp(-t_{hold}/\tau_{therm})$$

Thermalization Momentum damping



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

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

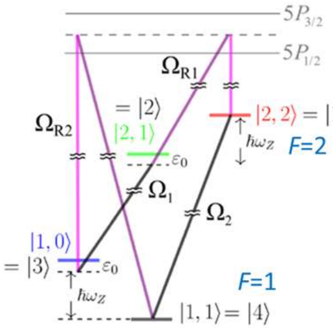


Effects of SOC on spin current relaxation:

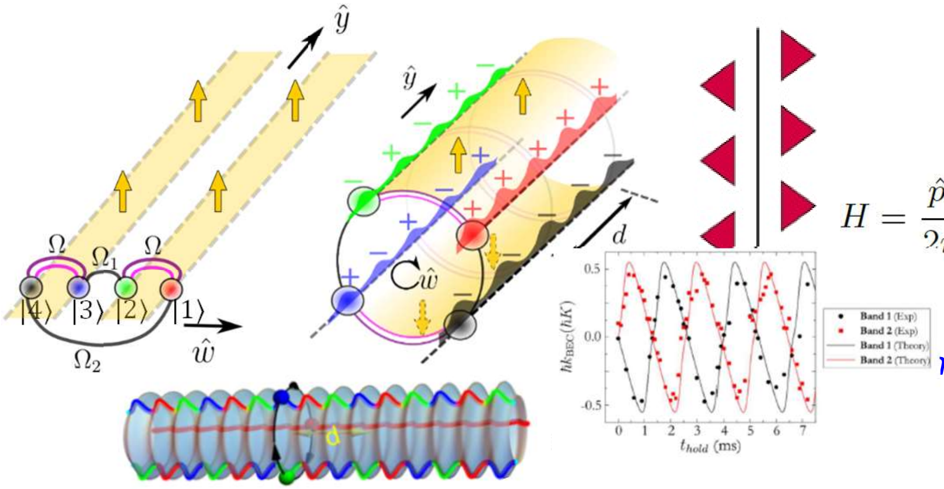
1. Stronger momentum damping
2. Less thermalization

Quantum simulation: topological matters

- **BEC on a synthetic Hall cylinder** --- a (nonsymmorphic**) symmetry-protected topological state** (band crossing), mimicking transport on a Mobius strip



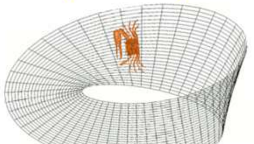
No external. op. lattice applied



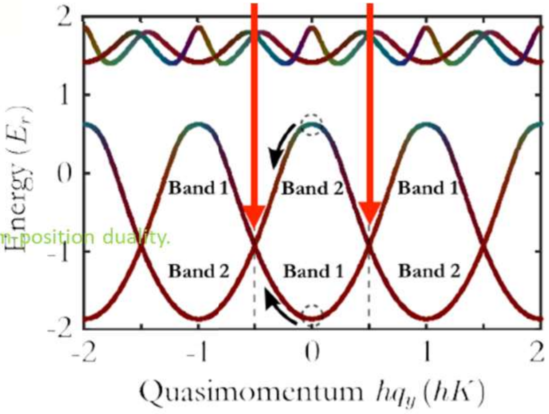
morphic symmetry

"4x4" matrix

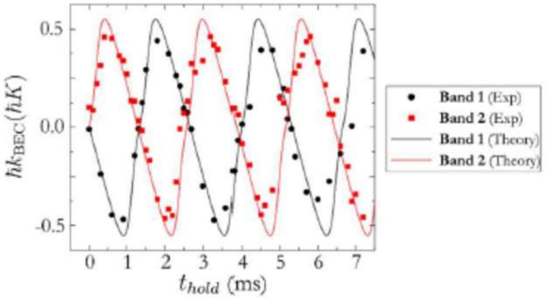
$$H = \frac{\hat{p}_y^2}{2m}\mathrm{I} + \begin{array}{ccccc} |1\rangle & |2\rangle & |3\rangle & |4\rangle & \\ 0 & \frac{\Omega_{\rm R1}}{2}e^{iKy} & 0 & \frac{\Omega_2}{2} & |1\rangle \\ \frac{\Omega_{\rm R1}^*}{2}e^{-iKy} & \varepsilon_0 & \frac{\Omega_1}{2} & 0 & |2\rangle \\ 0 & \frac{\Omega_1^*}{2} & \varepsilon_0 & \frac{\Omega_{\rm R2}}{2}e^{iKy} & |3\rangle \\ \frac{\Omega_2^*}{2} & 0 & \frac{\Omega_{\rm R2}^*}{2}e^{-iKy} & 0 & |4\rangle \end{array}$$



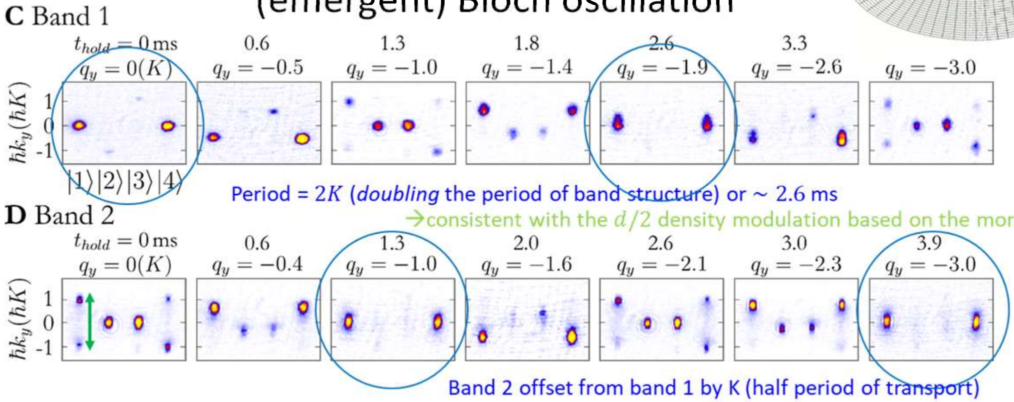
Topological bandcrossing ("Dirac")



Like "topological semimetal"



(emergent) Bloch oscillation



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

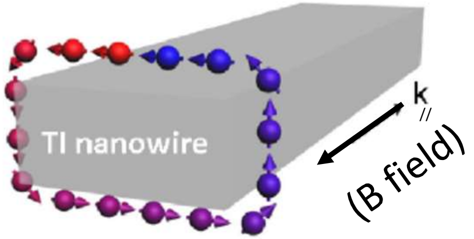
→consistent with the $d/2$ density modulation based on the momentum-position duality.

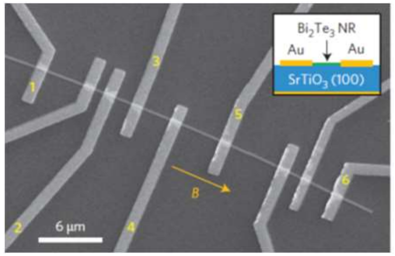
Band 2 offset from band 1 by K (half period of transport)

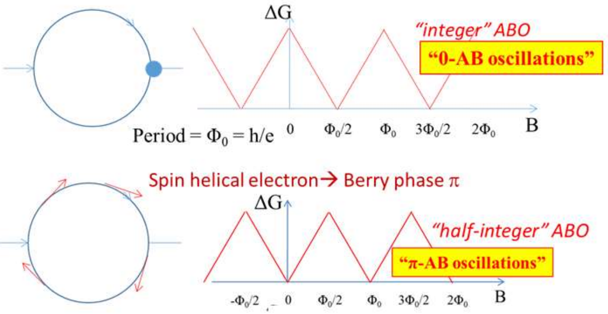
C.Li et al., arXiv:1809.02122; see also Qi Zhou/Y.Yang et al theory paper PRL'19

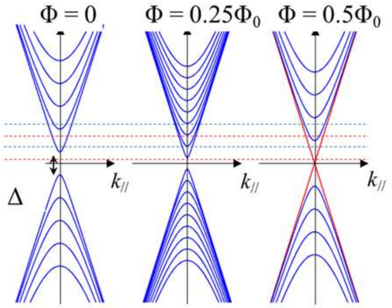
Topological Quantum Matter on a Cylinder

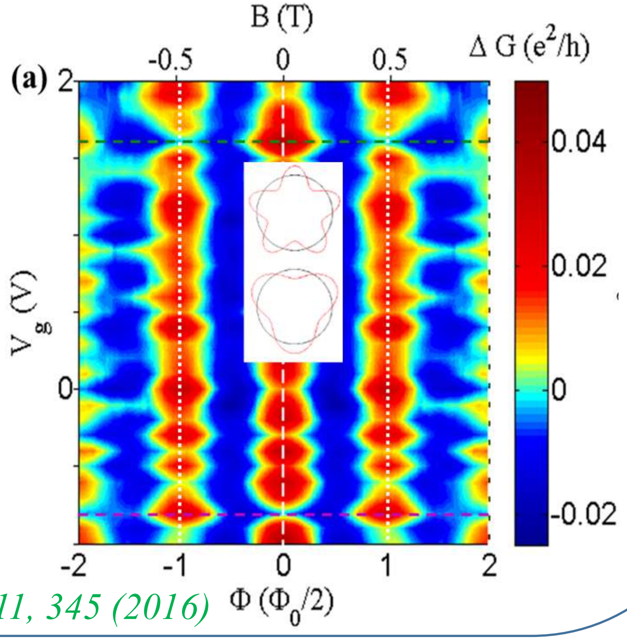
Spin-helical **electrons** on topological insulator (TI) surface











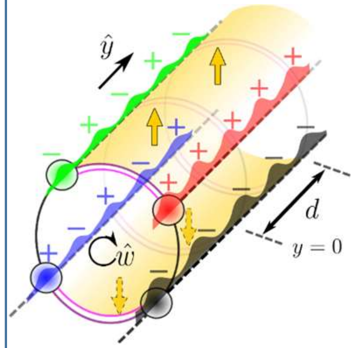
L.A.Jauregui, et al. Nature Nano 11, 345 (2016)

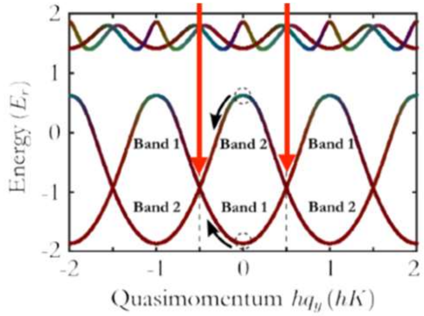
atomic **BEC** on synthetic "Hall" cylinder

<difficult in real/physical space>

"synthetic" space & (synthetic) flux (radial)

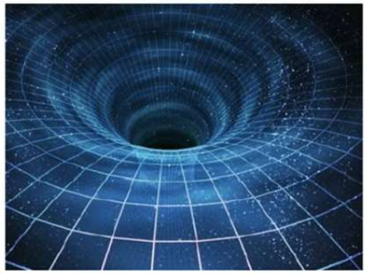
C. Li et al., arXiv: 1809.02122

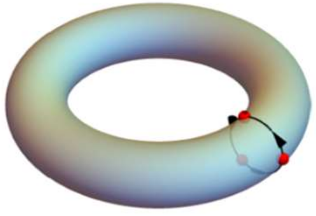




A (nonsymmorphic) Symmetry protected bosonic topological state

Future: quantum matter in curves spaces?





Q.Zhou et al PRL'19

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[now postdoc @ Lincoln Lab]
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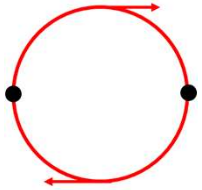
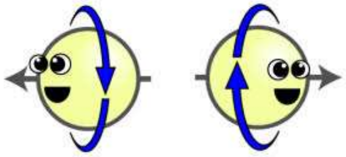
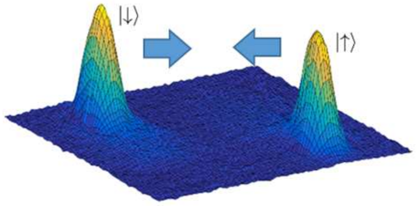


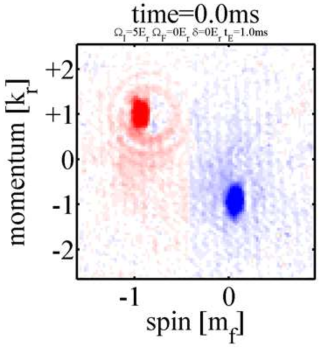
Quantum science & technologies based on "Spin-helical" particles

Postdoc Opening

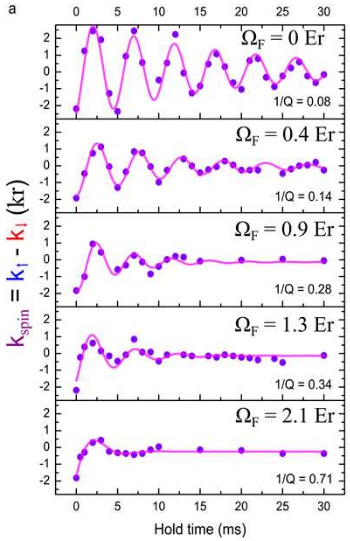


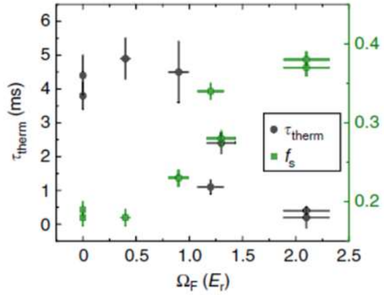
- Quantum simulation



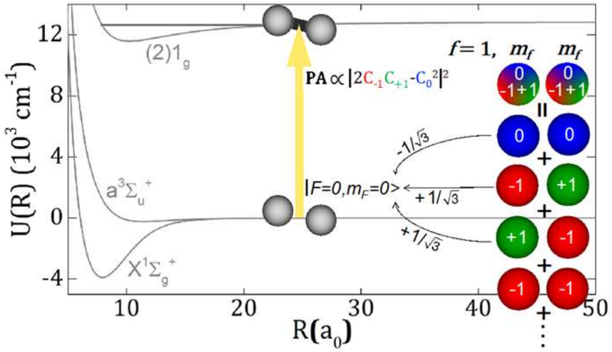


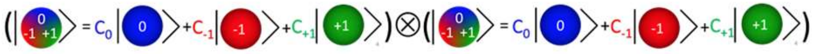
C. Li *et al.*, Nature Comm. 10, 375 (2019)



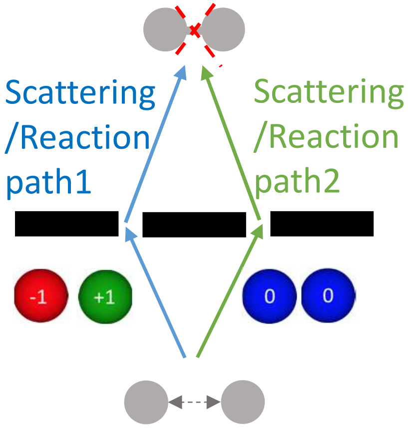


- (spin-based) quantum control/chemistry





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



Scattering /Reaction path1

Scattering /Reaction path2

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