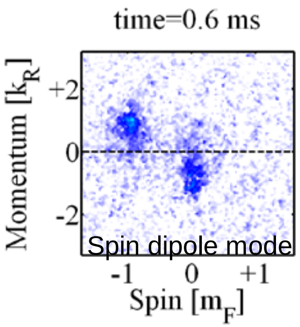
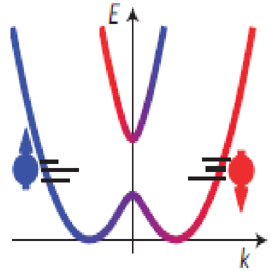
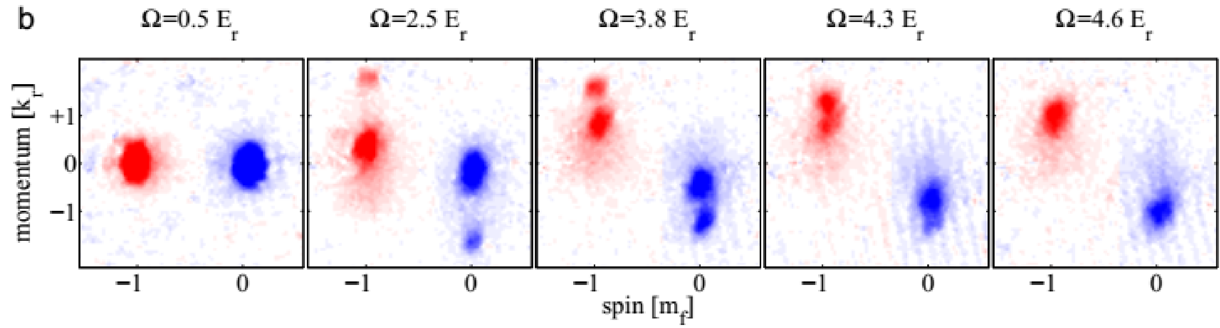
Workshop on Probing and Understanding Exotic Superconductors and Superfluids, ICTP-Trieste, Oct. 28, 2014







Dynamics & Transport in Spin-orbit Coupled Bose-Einstein Condensates (SOBEC)

Robert Niffenegger, *Abraham Olson,* Chuan-Hsun Li, David Blasing,

Yong P. Chen*, Dept. of Physics, Purdue Univ.

PURDUE UNIVERSITY

(Quantum Matter and Devices Laboratory @ Purdue: www.physics.purdue.edu/quantum)

(*on leave at SNS-NEST, Pisa, Itay in Fall 2014)

Simulation/Theoretical/Discussions: Su-Ju Wang/Chris Greene, Yuli Lyanda-Geller (Purdue)

Chunlei Qu/Chuan-wei Zhang (UTD)

Hui Zhai (Tsinghua)

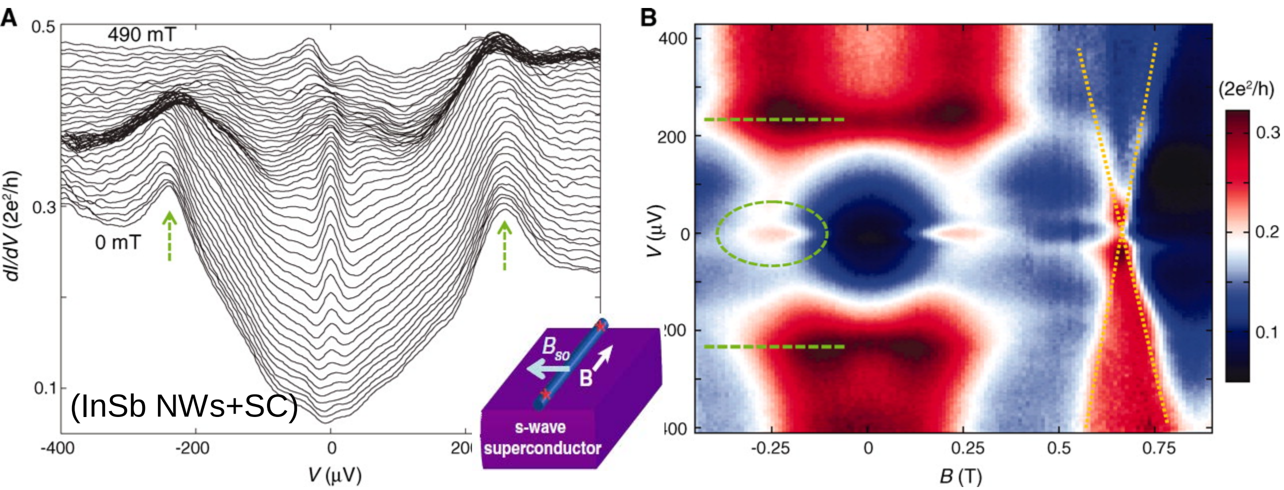
Acknowledge Support: DURIP-ARO Grant W911NF-08-1-0265

William F. Miller Family Endowment, Purdue OVPR Incentive program

NSF GRFP

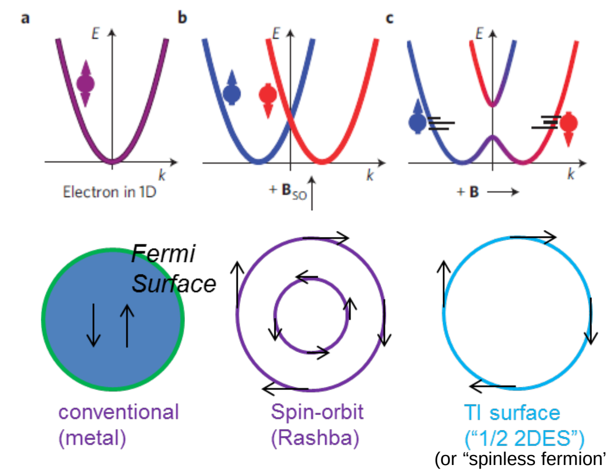
SOC+Superconductivity → Topological (Nonconventional) SC

(w/t eg. majorana excitations)

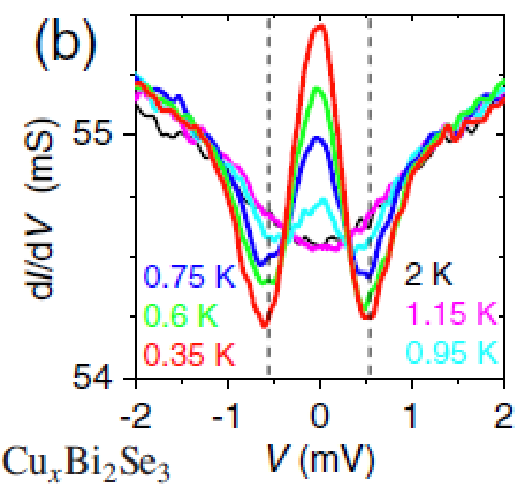


V.Mourik [L.Kouwenhoven] et al. Science'12

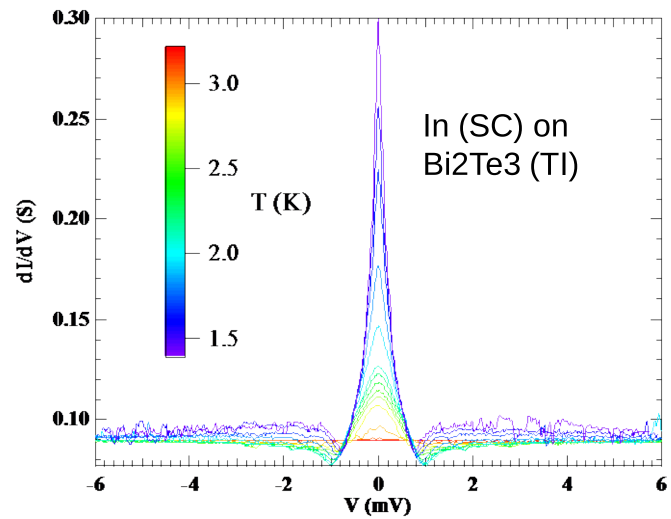
*Electronic SOC: B_{SO}~vxE→σ*p*



However, such "zero-bias anomaly" can be ambiguous

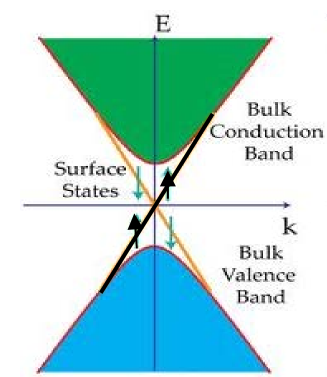


S.Sasaki [Y.Ando] et al. PRL'12



Y. Xu et al (unpublished)

$$2\ \uparrow_k\downarrow_{-k} = (\uparrow_k\downarrow_{-k}+\uparrow_{-k}\downarrow_k)+(\uparrow_k\downarrow_{-k}-\uparrow_{-k}\downarrow_k)$$



Topological insulator (TI)

REVIEW

doi:10.1038/nature11841

Spin–orbit coupling in quantum gases

Victor Galitski[1,2] & Ian B. Spielman[1]

Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.

REVIEWS OF MODERN PHYSICS, VOLUME 83, OCTOBER–DECEMBER 20

Colloquium: Artificial gauge potentials for neutral atoms

Jean Dalibard* and Fabrice Gerbier†

Laboratoire Kastler Brossel, CNRS, UPMC, Ecole normale supérieure, 24 rue Lhomond, 75005, Paris, France

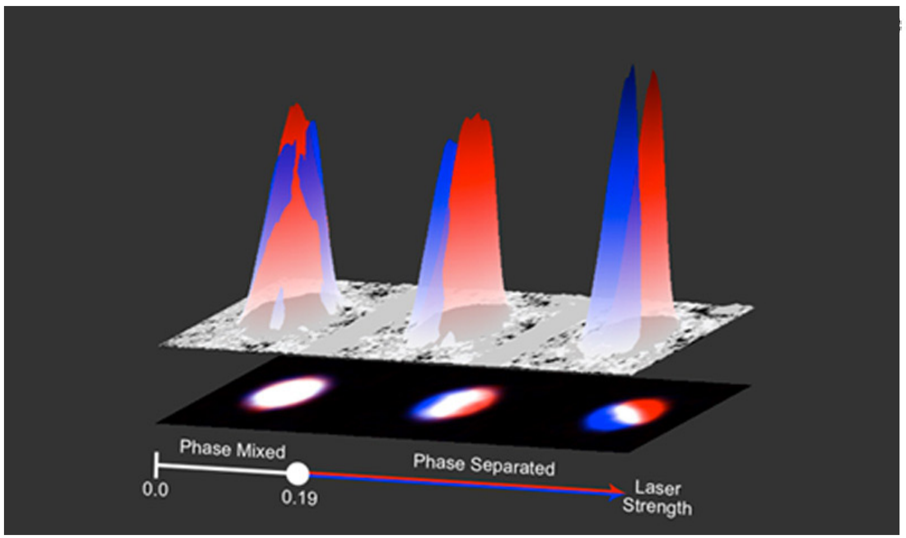
Gediminas Juzeliūnas‡

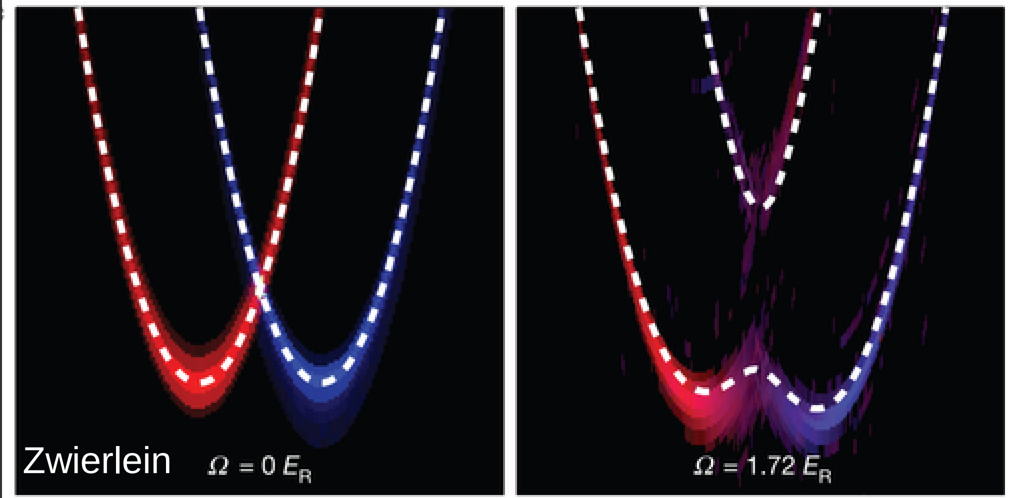
Institute of Theoretical Physics and Astronomy, Vilnius University, A. Goštauto 12, Vilnius 01108, Lithuania

Patrik Öhberg§

SUPA, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom

(published 30 November 2011)



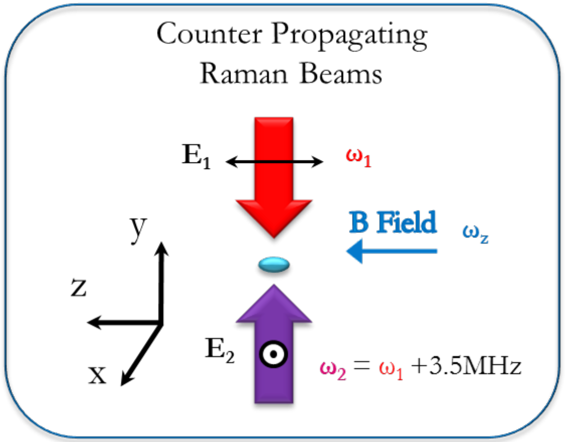


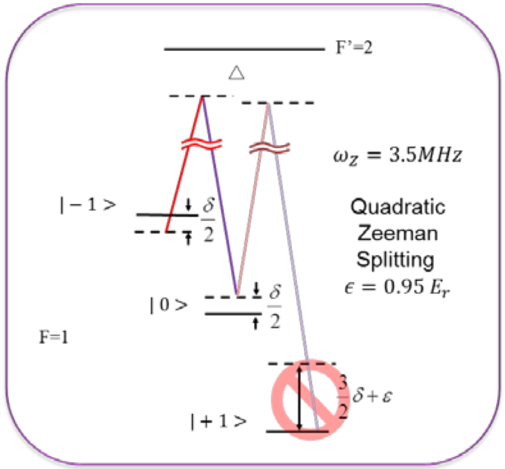
(**spin-orbit BEC – I.Spielman/NIST**)
[also USTC, SXU, WSU, Purdue, ..]

(**spin-orbit fermi gas**)
[MIT, SXU, NIST, ..]

See also reviews by: H. Zhai'11; Y. Li [Stringari] et al'14, J.Zhang'14 etc.

Synthetic Spin Orbit Coupling (SOC) by Raman

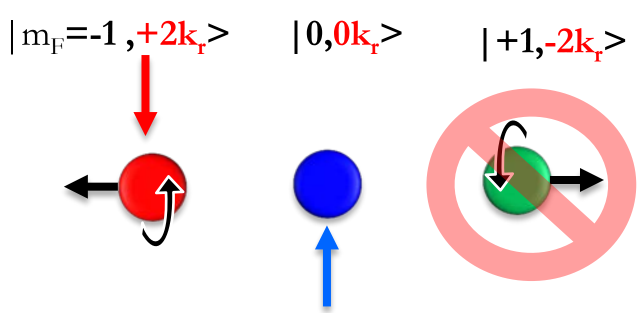




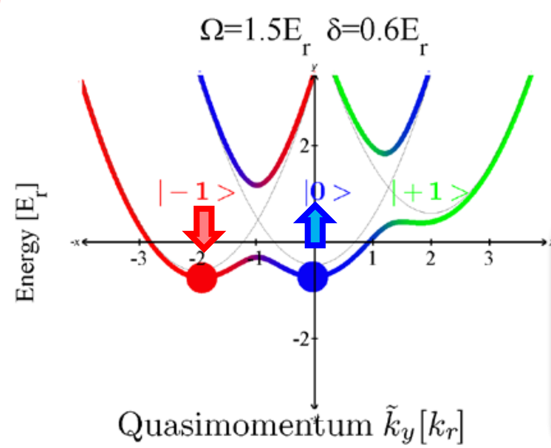
$$\hat{\mathcal{H}} = \begin{pmatrix} \frac{\hbar}{2m}(\hat{k}_y + k_r)^2 - \frac{\delta}{2} & \frac{\Omega_R}{2} \\ \frac{\Omega_R}{2} & \frac{\hbar}{2m}(\hat{k}_y - k_r)^2 + \frac{\delta}{2} \end{pmatrix}$$

$$\boxed{\hat{\tilde{k}}_y = \tilde{k}_y + k_r}$$

$$\delta_{SO} = E_{\min\downarrow} - E_{\min\uparrow}$$



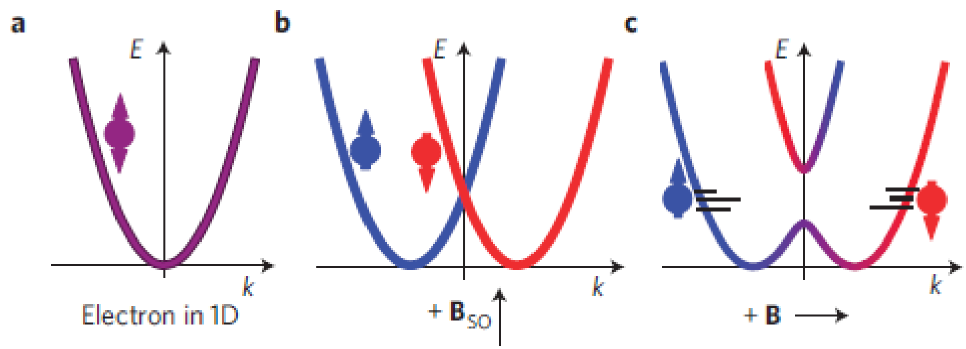
Y.-J. Lin [I.Spielman/NIST] et al, PRL (2009),
& Nature (2011)

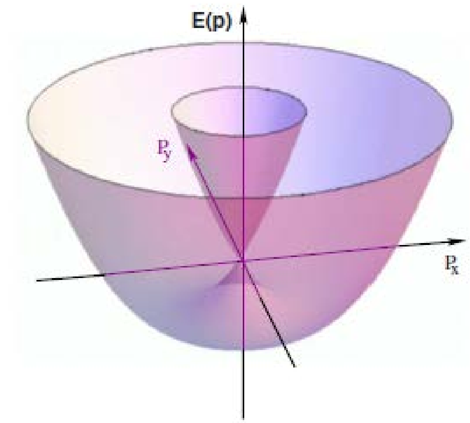


$$H = \frac{\hbar}{2m}(\vec{p} - q\vec{A})^2 \Rightarrow \boxed{\tilde{k}_{y,\min} = \frac{q\vec{A}_y}{\hbar}}$$

$$\frac{\partial \vec{A}_y(t)}{\partial t} = \vec{E}_y \qquad \frac{\partial \vec{A}_y(x)}{\partial x} = \vec{B}_z$$

Some cautions & contrast with electronic SOC



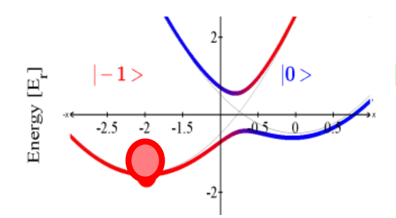


$$\hat{H} \sim \frac{\vec{p}^2}{2m} + \alpha p_{x,y} \cdot \sigma_{x,y} + B_z \cdot \sigma_z$$

Synthetic SOC for atoms:

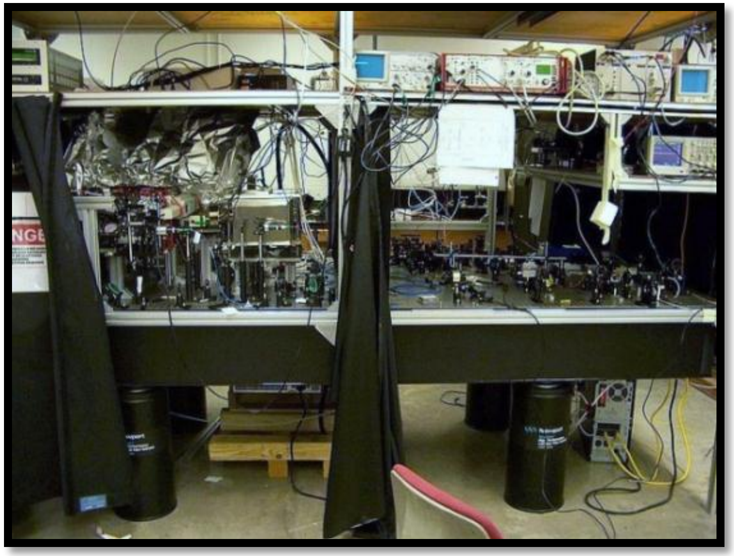
$$\hat{H} \sim \frac{\vec{p}^2}{2m} + (k_r p_x) \cdot \sigma_x + \Omega \cdot \sigma_z$$

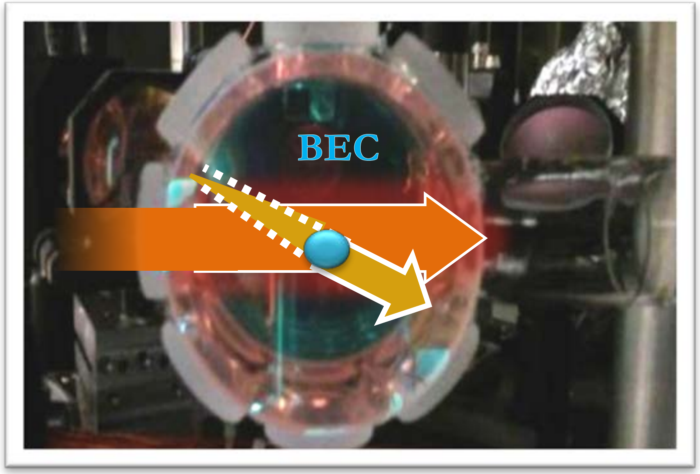
- 1D SOC only (so far)
- “p” in SOC is quasi-momentum
- SOC only for $|\Omega|>0$ – often Ω referred as “SOC” strength, whereas in Rashba α is SOC (here fixed by k_r)
- Can work for bosons as well as fermions



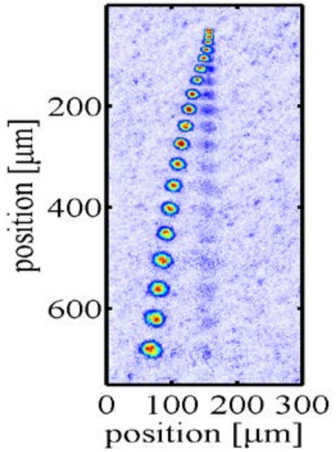
$$\hat{\mathcal{H}} = \begin{pmatrix} \frac{\hbar}{2m}(\hat{k}_y + k_r)^2 - \frac{\delta}{2} & \frac{\Omega_R}{2} \\ \frac{\Omega_R}{2} & \frac{\hbar}{2m}(\hat{k}_y - k_r)^2 + \frac{\delta}{2} \end{pmatrix}$$

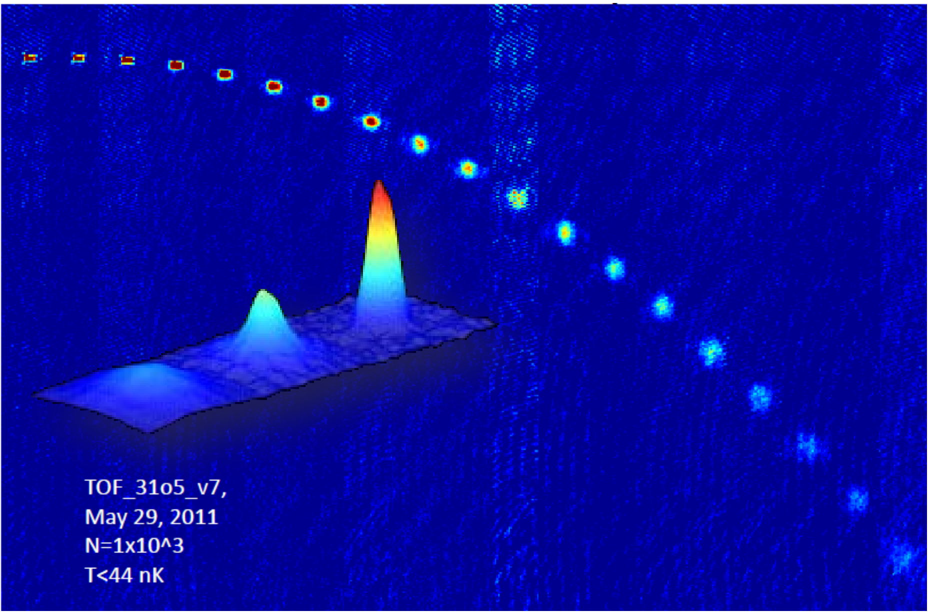
Production of ^{87}Rb BEC in λ=155nm optical trap (optimized evaporative cooling, γ~4)

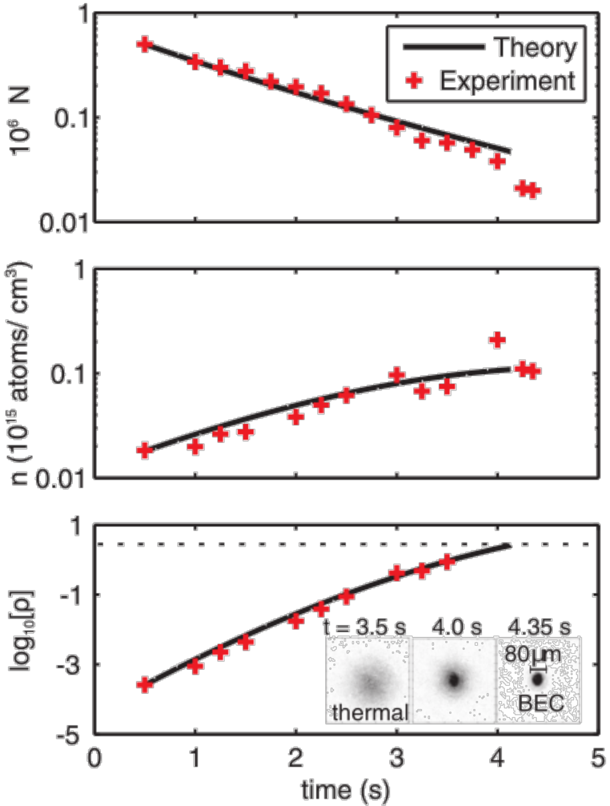




(Stern-Gerlach to separate/image spins)

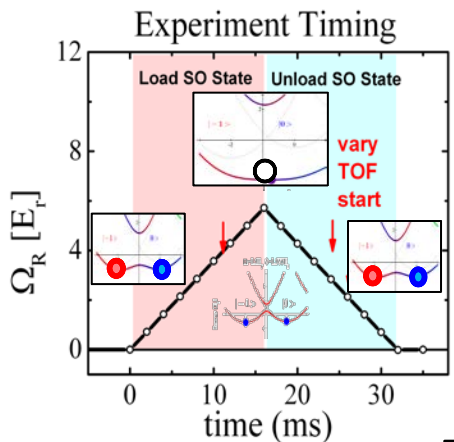


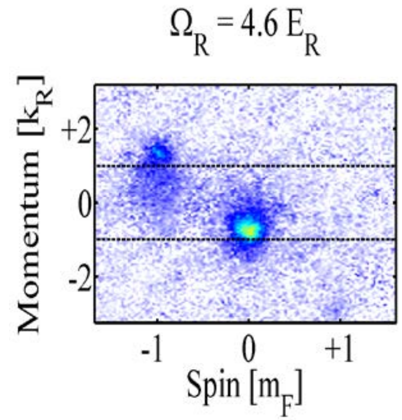


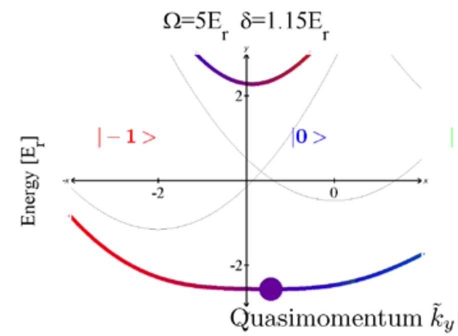


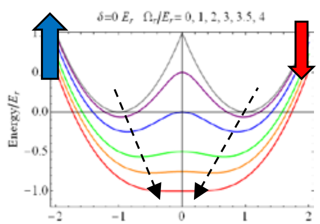
A.J. Olson *et al.*, Phys. Rev. A 87, 053613 (2013)

SOC BEC – Adiabatic Transition (Single to Double Minima)

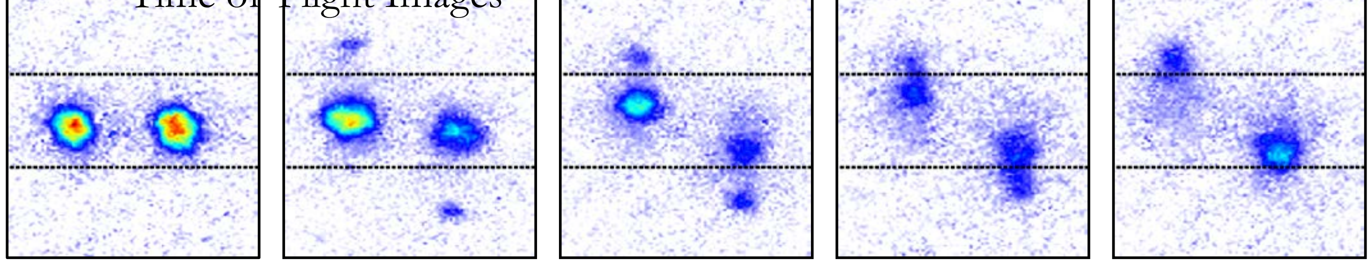






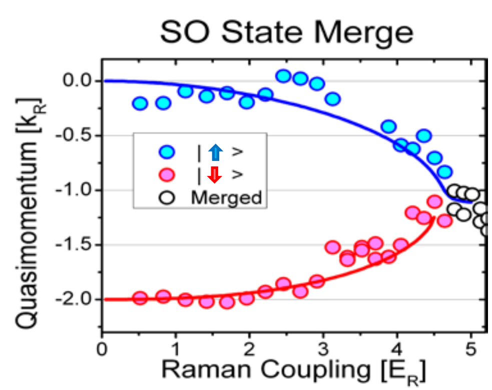


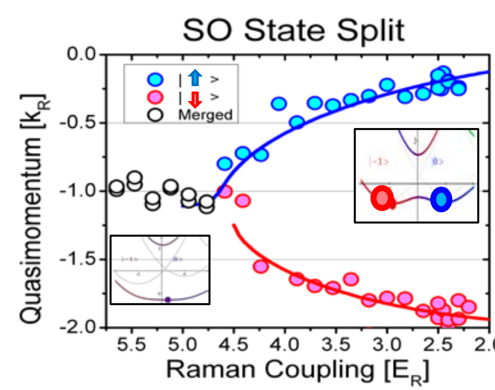
Time of Flight Images



Measured Quasimomenta vs Calculated Band Minima

Adiabatic Loading



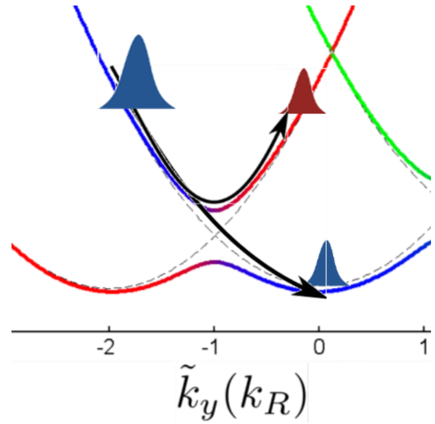


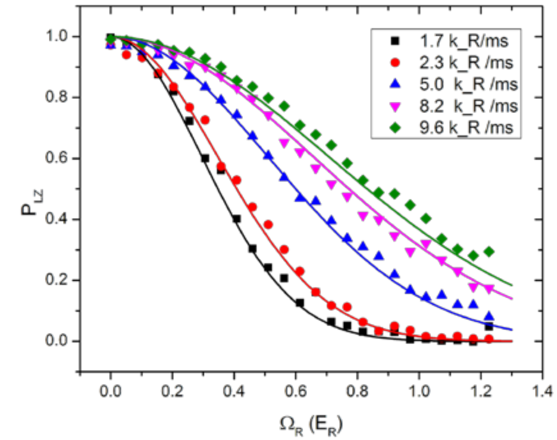
Similar to previous work by: Y.-J. Lin, K. Jiménez-García & I. B. Spielman, Nature 2011

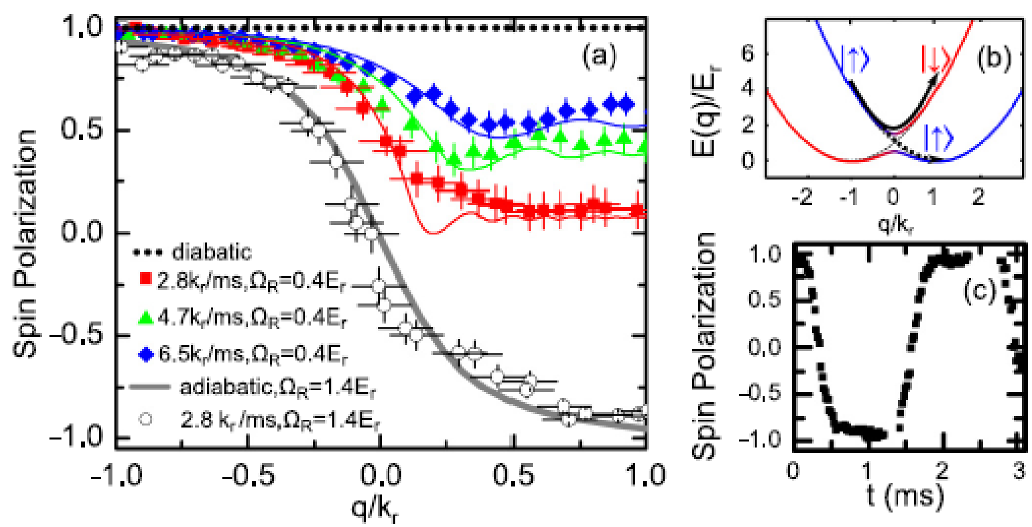
Tunable Landau-Zener Transition (between SOC dressed bands)

$$P_{LZ} = \exp\left[-2\pi \frac{(\Omega/2)^2}{\hbar v \beta}\right]$$

- Landau-Zener model
  Varied **all three parameters**
- acceleration in SO gauge fields by gravity or trapping potential
- Spin dependent "atomtronic" transistor
- Non-adiabatic breakdown of spin-momentum locking in SOC BEC

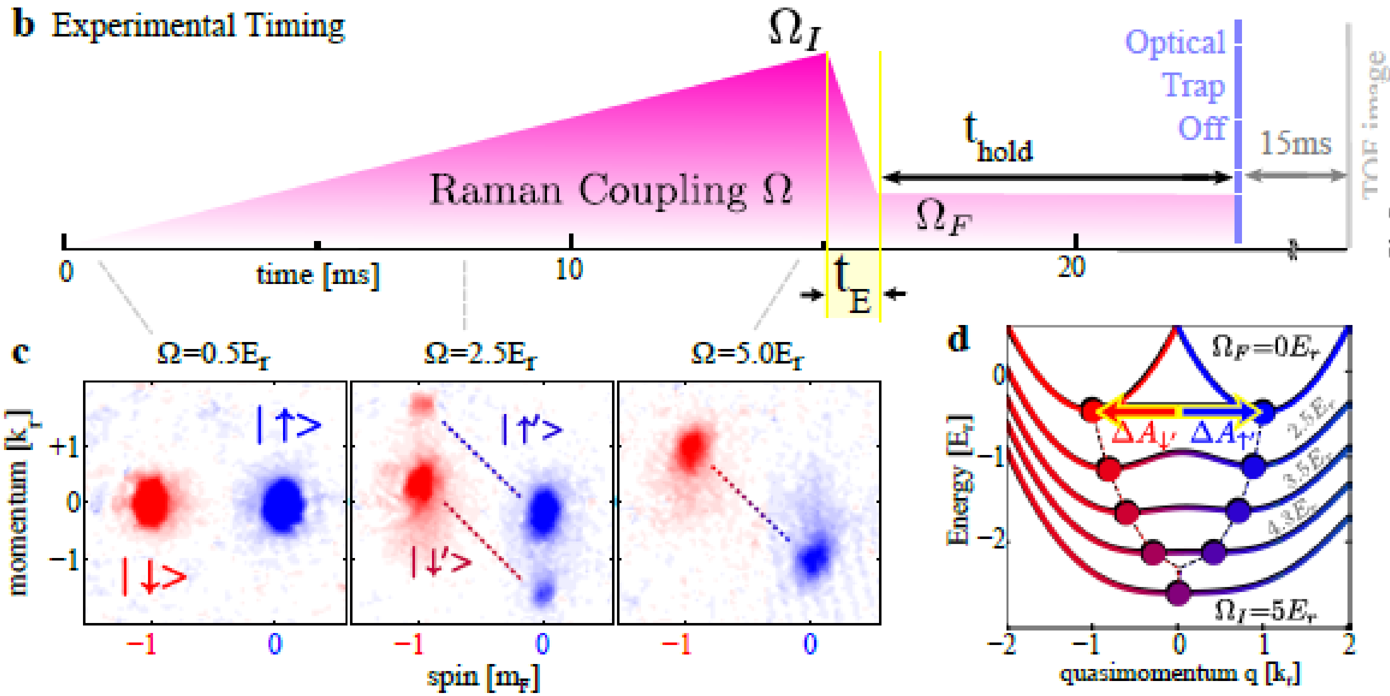






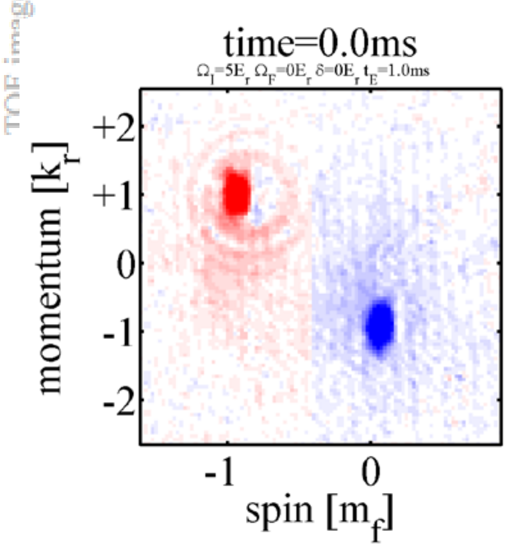
Abraham J. Olson, et al, Phys.Rev. A 90, 013616 (2014)

Using Spin-dependent Synthetic Electric Field to generate (AC) spin current and excite spin-dipole mode in trap



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

"Collide 2 spinor BECs in trap"

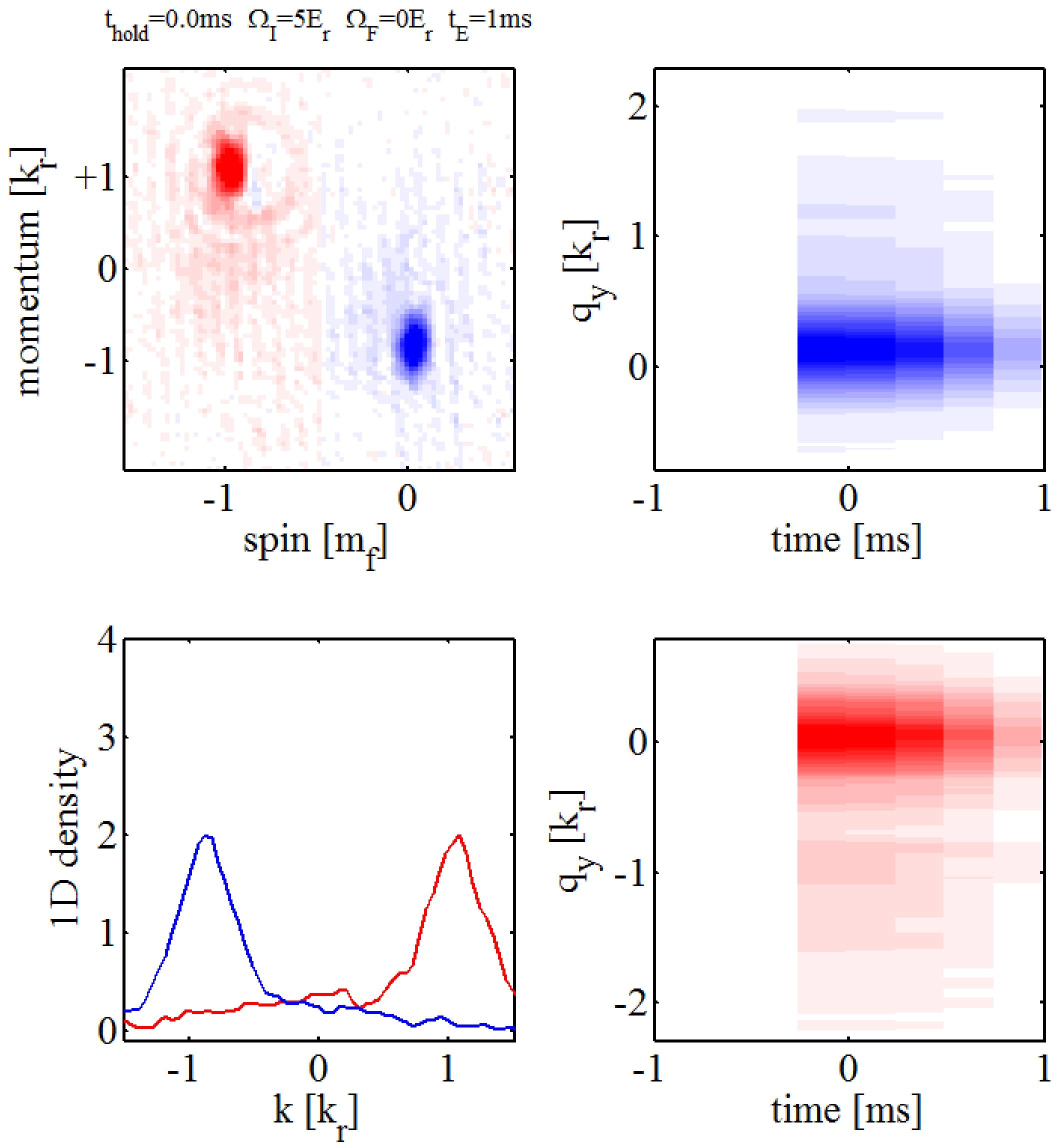


Spin Dipole Mode (SDM)
--- AC spin current

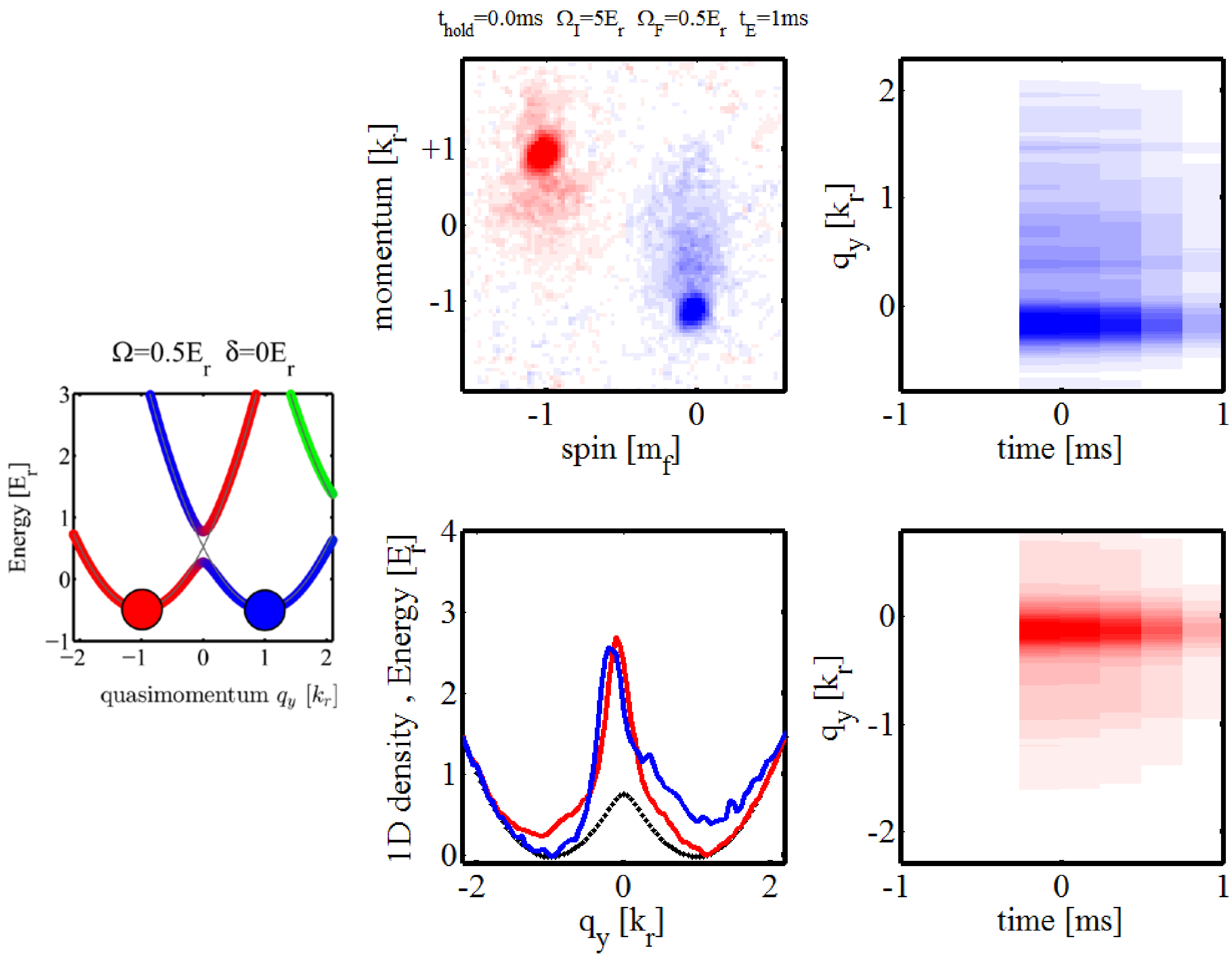
SDM previous studied in non SOC quantum gases,
eg. fermi gas: Sommer [Zwierlein] et al'11 by magnetic gradient
bosons: Koller et al'12; Maddaloni et al'00
theory (fermi gas): Stringari'99, etc.

What is the effect of SOC?

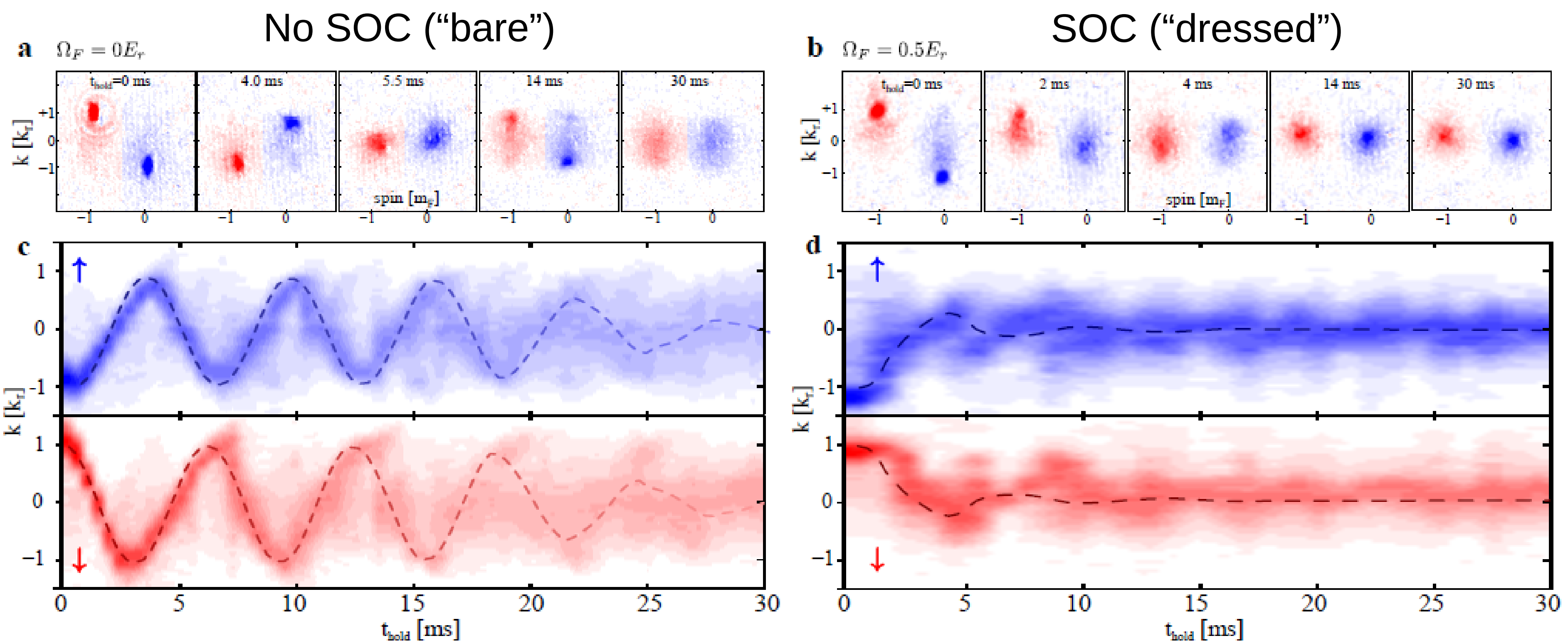
Spin Electric Field – Bare spin current $\Omega_F = 0E_r$



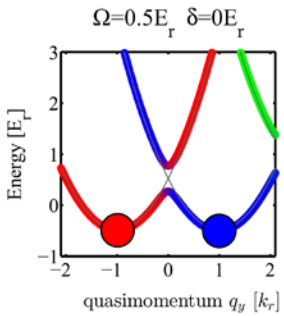
Dressed Spin Current ($\Omega_F = 0.5E_r$)



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

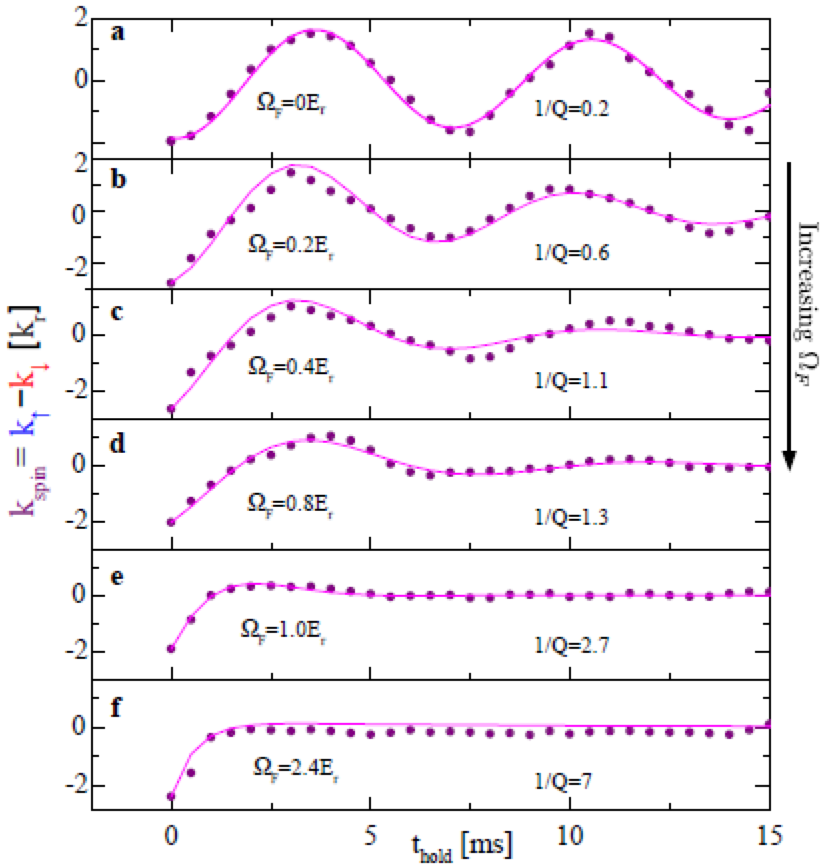


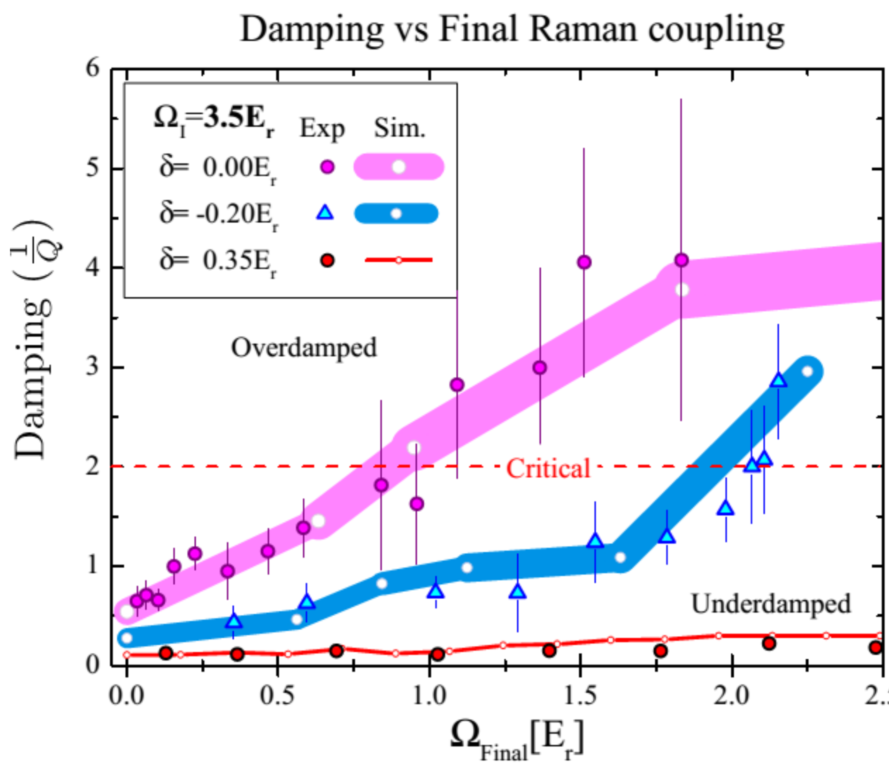
- Take longer time to damp
- ~full thermalization in the end



- SDM damp quickly (few oscillations)
- More BEC remains (less thermalization)

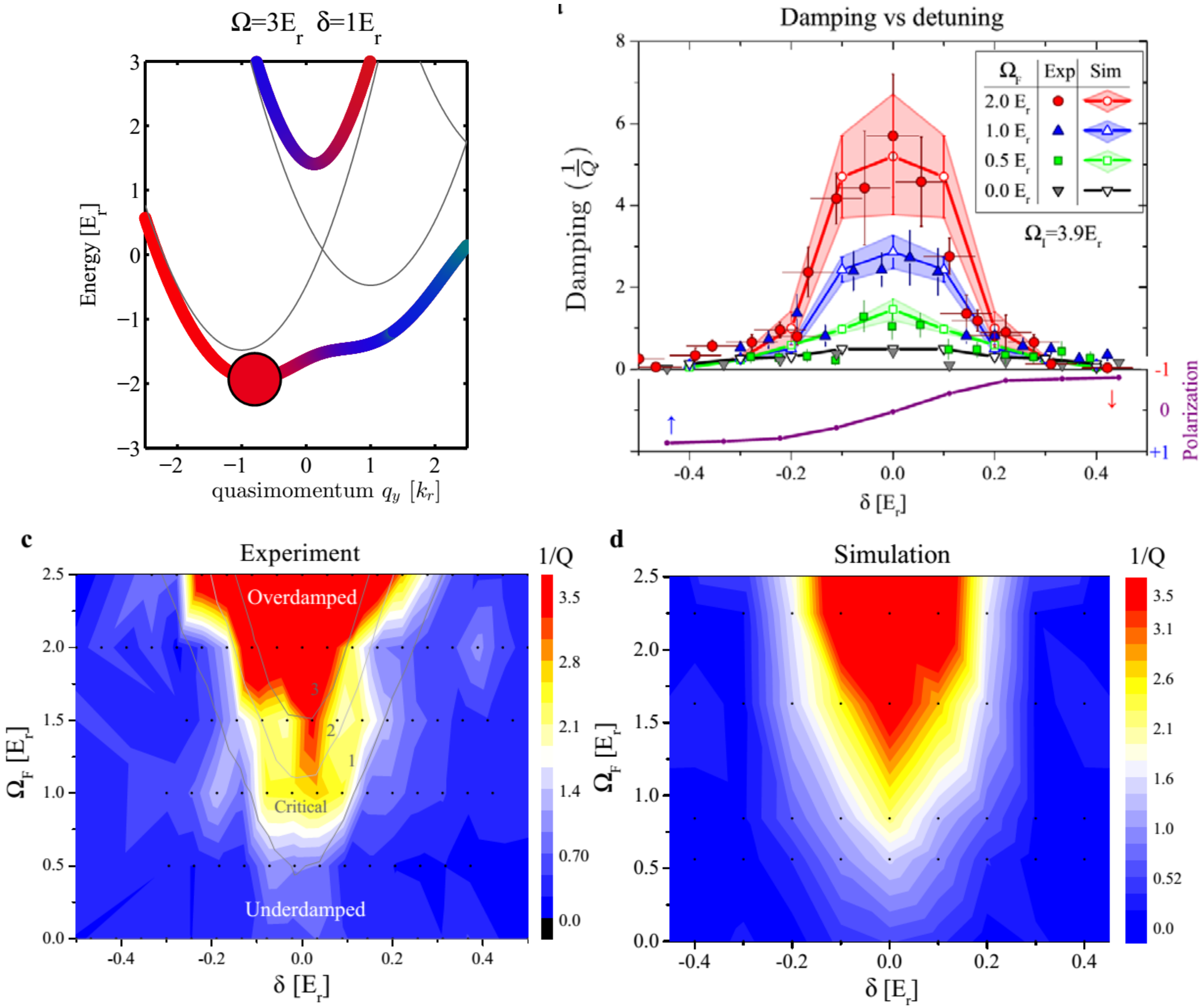
Damping vs Ω_F





GPE Simulations:
Chunlei Qu and Chuanwai Zhang
(University of Texas Dallas)

Damping vs δ & Ω_F



Chunlei Qu and Chuanwai Zhang

What relaxes spin current?

$$J_s = N_c^{\uparrow} v_{\uparrow} - N_c^{\downarrow} v_{\downarrow}$$

$$\Gamma_s = \frac{1}{\tau_{\text{therm}}} + \frac{1}{\tau_{\text{damp}}}$$

- Collison induced thermalization

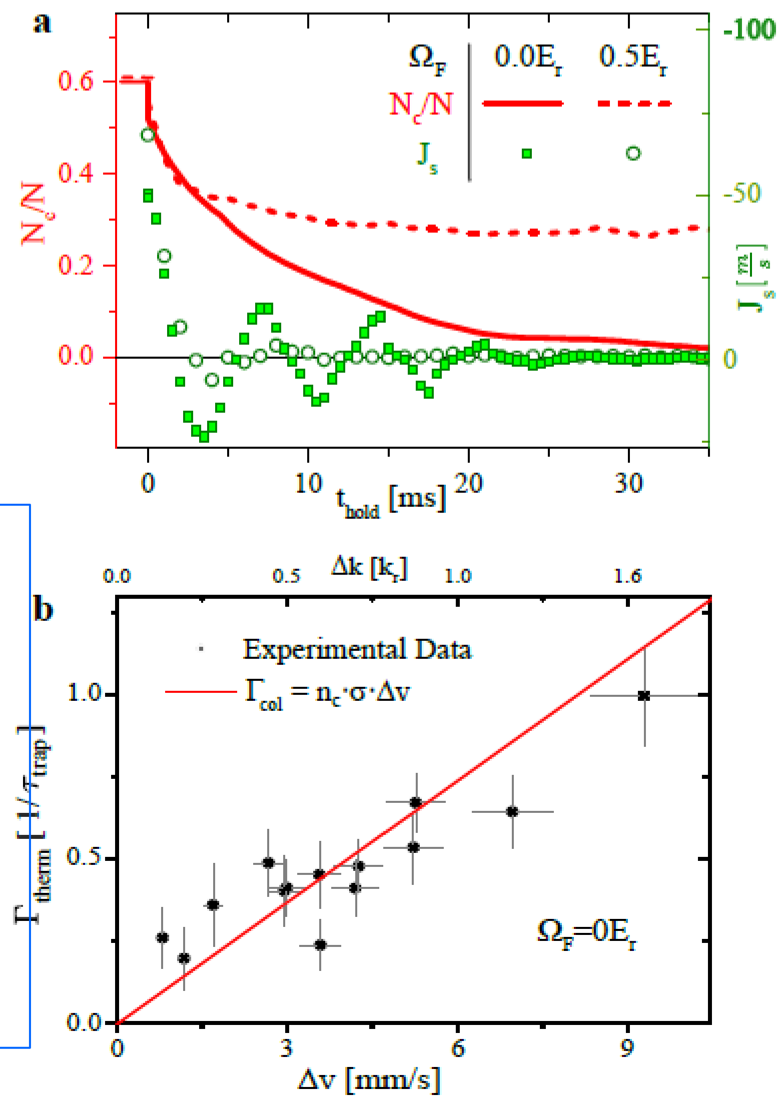
  --- (dominates for bare BEC)
- SDM momentum damping

  --- (dominates for SOC BEC)

- Less collision (SDM osc.)

  → less thermalization in SOCBEC

- What gives (enhanced) damping in SOCBEC?



SDM decays to: thermal particles in bare BEC, ?? in SOC BEC

Real Space Simulation: damping mechanism

Physics PURDUE

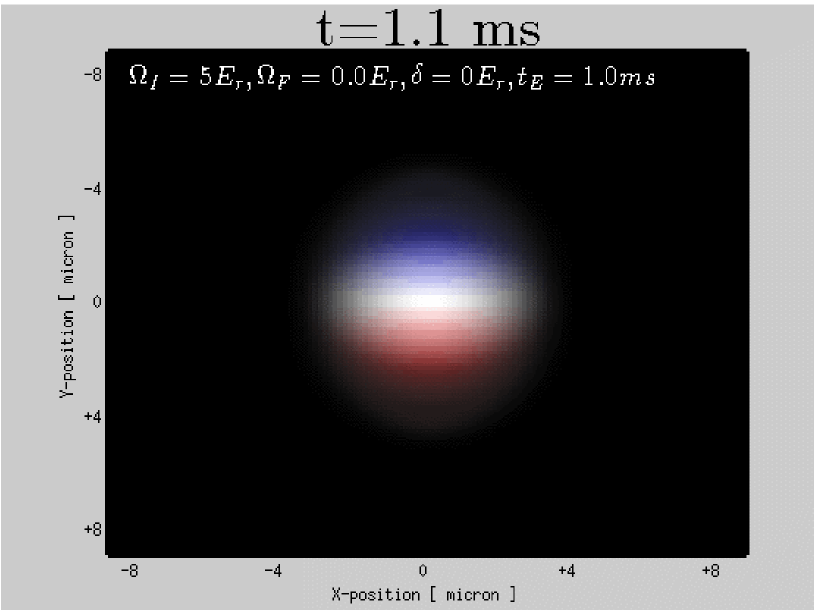
"colliding two *(bare or dressed)* spinor BECs in trap"

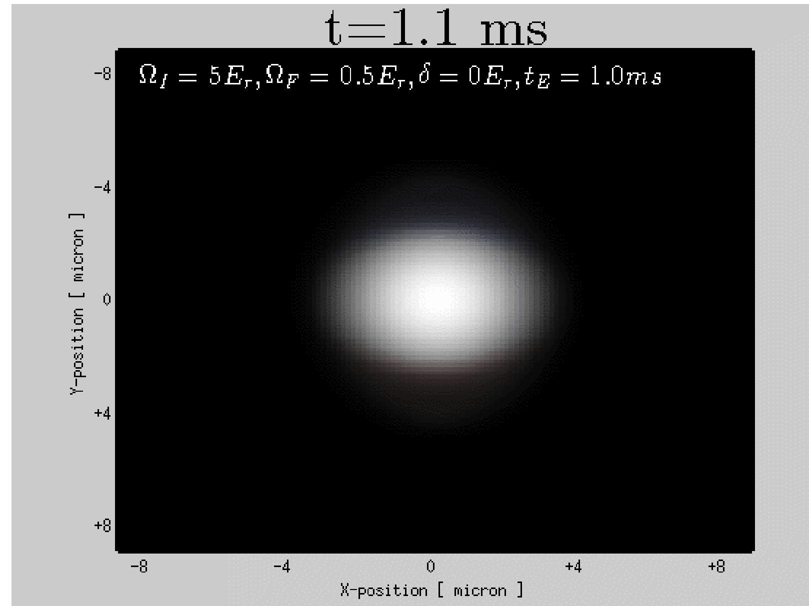
GPE (position)

No SOC

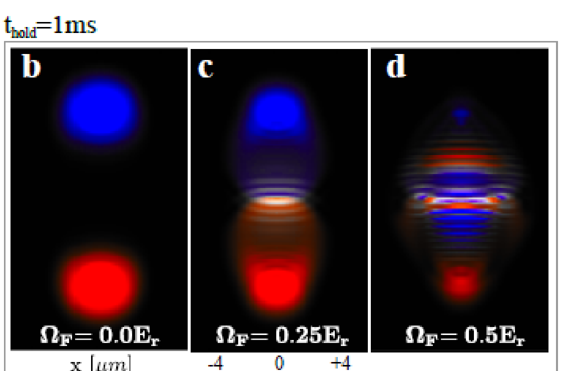
SOC

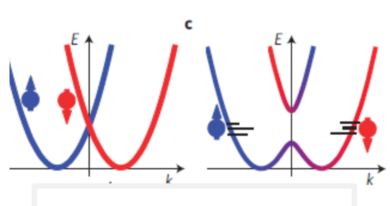
position





Chunlei Qu and Chuanwai Zhang (University of Texas Dallas)





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