

Spin-orbit Coupling (SOC)

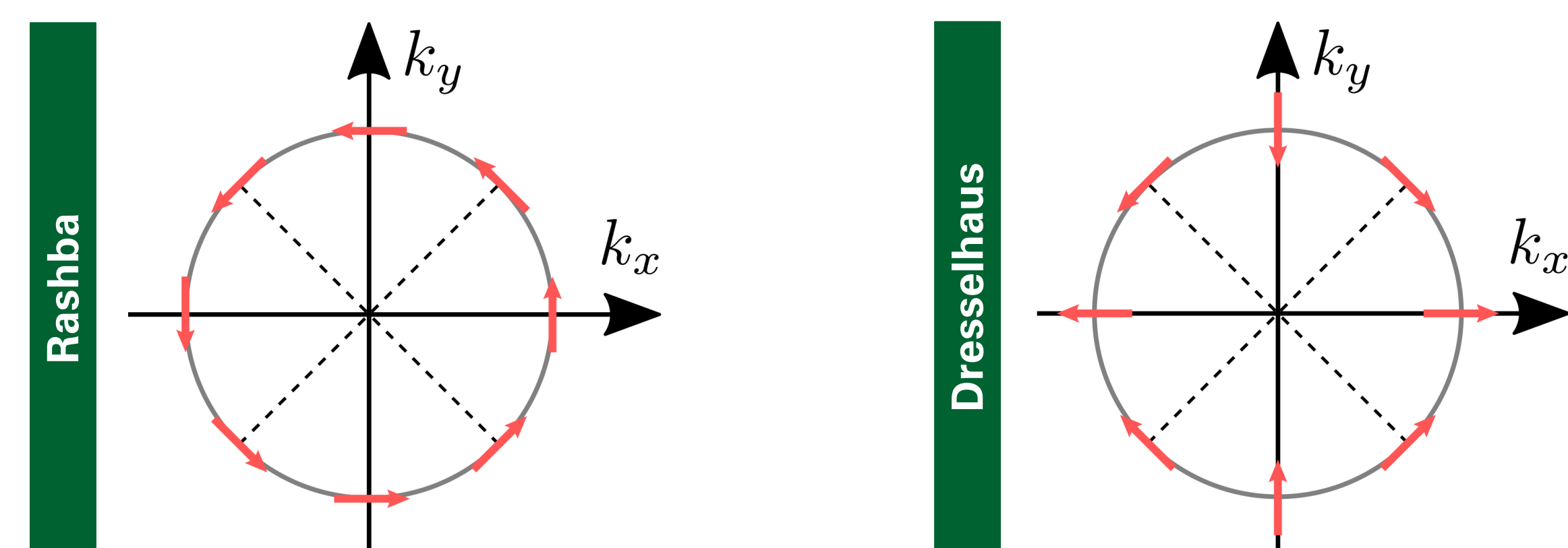
SOC in Matter

Spin-orbit coupling is a relativistic effect that can link elements of a spin-1/2 electron's **spin vector** $\vec{S} = (\hat{S}_x, \hat{S}_y, \hat{S}_z)$ with its **orbital** momentum, producing atomic fine structure, $\hat{H}_{SO} \sim \vec{L} \cdot \vec{S}$ (right).

$\vec{S}$ may also couple to the **linear** momentum $\vec{k}$ of an electron:

- Rashba: $\hat{H}_R \sim \hat{S}_x k_y - \hat{S}_y k_x$
- Dresselhaus: $\hat{H}_D \sim -\hat{S}_x k_y - \hat{S}_y k_x$

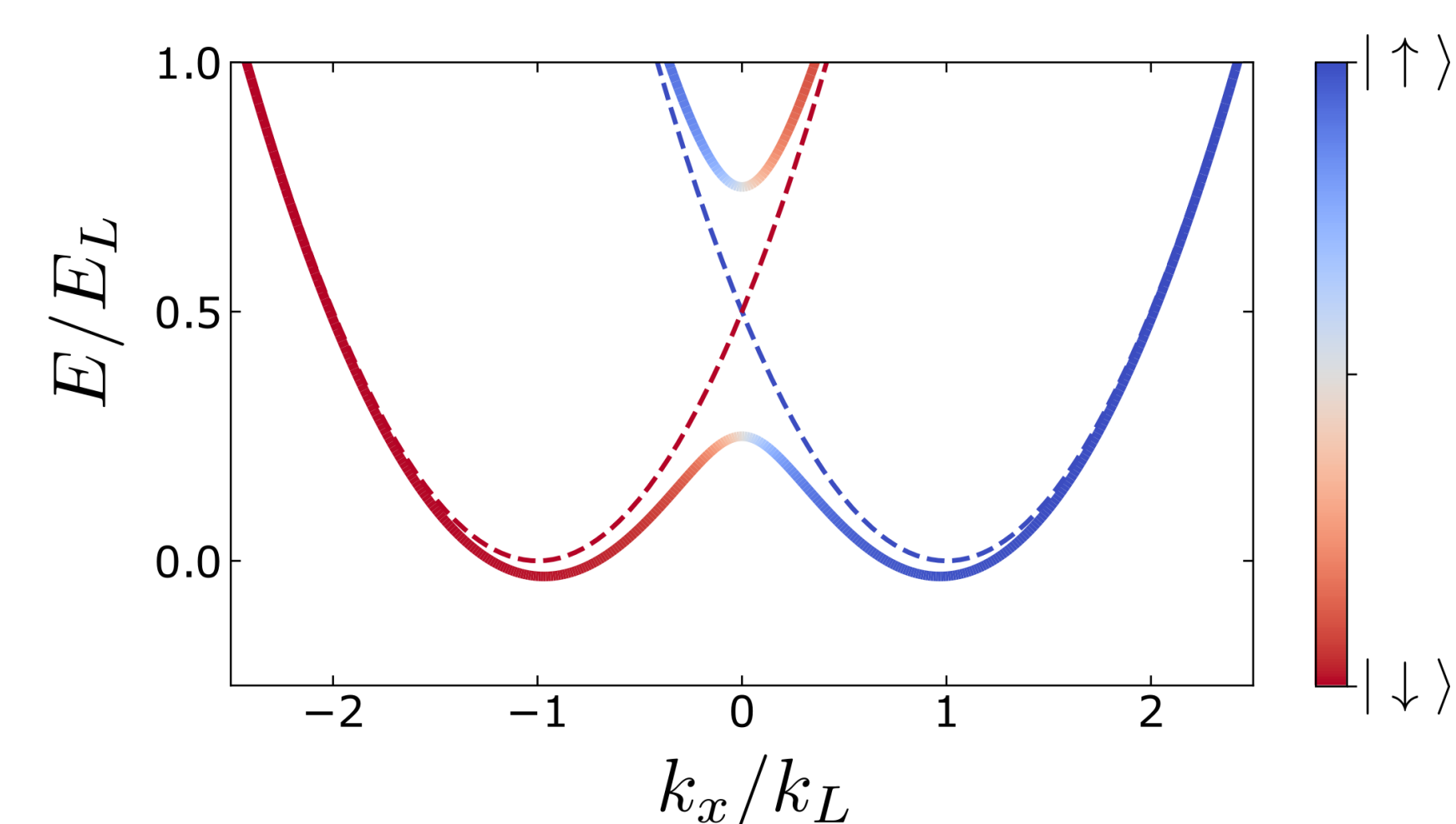
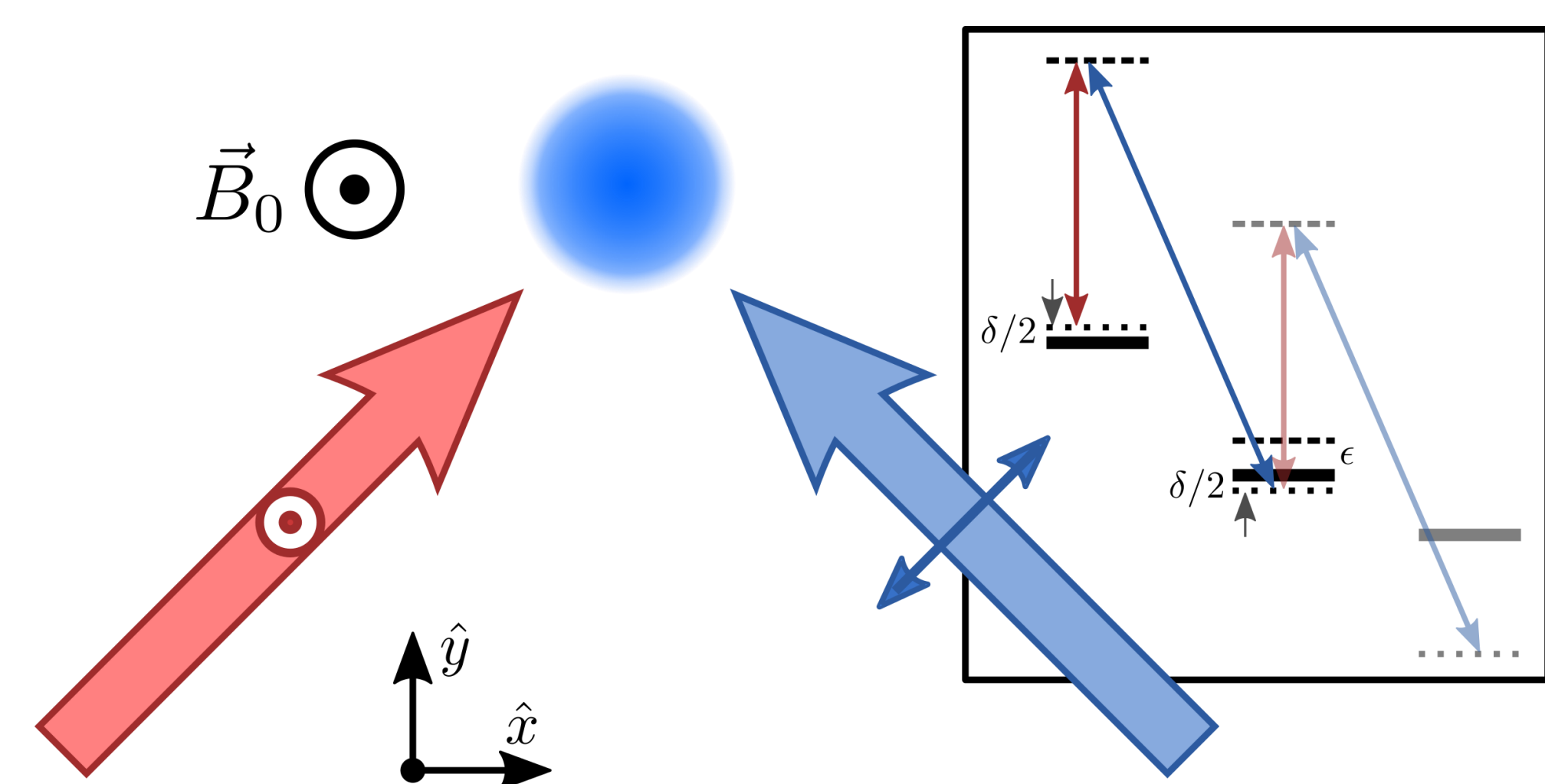
Lowest energy 2D spin textures:



SOC in Bose-Einstein Condensates (SOBEC)

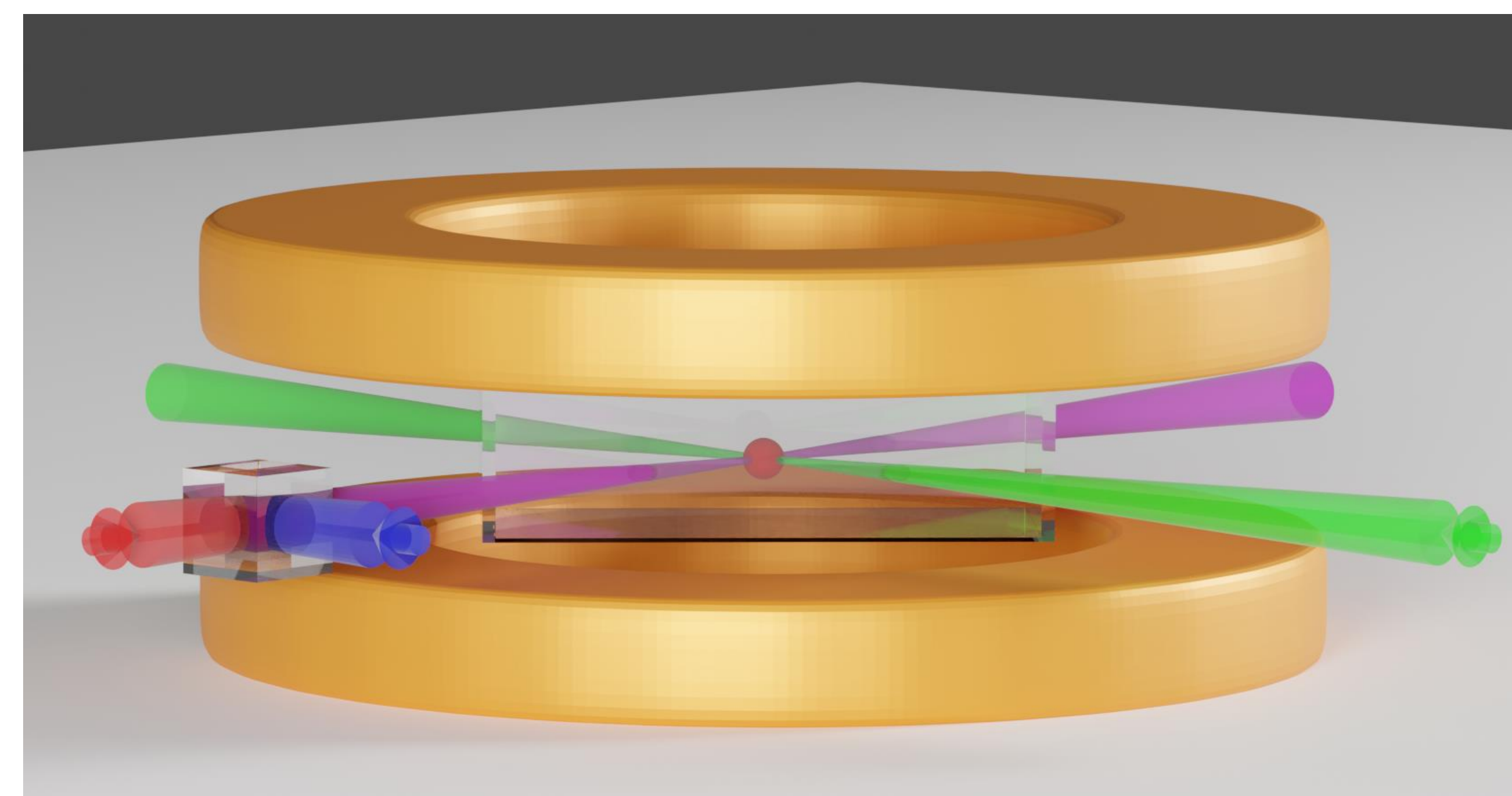
SOC can be emulated in an ultracold Bose gas [1] using Raman coupling; this method uses coherent two-photon transitions induced by a pair of counter-propagating lasers couple a pair of atomic Zeeman sublevels (below left).

- Move to a spatially-rotating reference frame.
- The dispersion becomes a spin-dependent double-well in momentum space (below right).
- $\hat{H}_{SOBEC} \sim k_L k_x \hat{S}_y$, equal parts Rash. & Dressel.*



* k_L is the photon recoil momentum, and $E_L = \hbar^2 k_L^2 / 2m$.

Spin-Tensor-Momentum Coupling (STMC)



The System

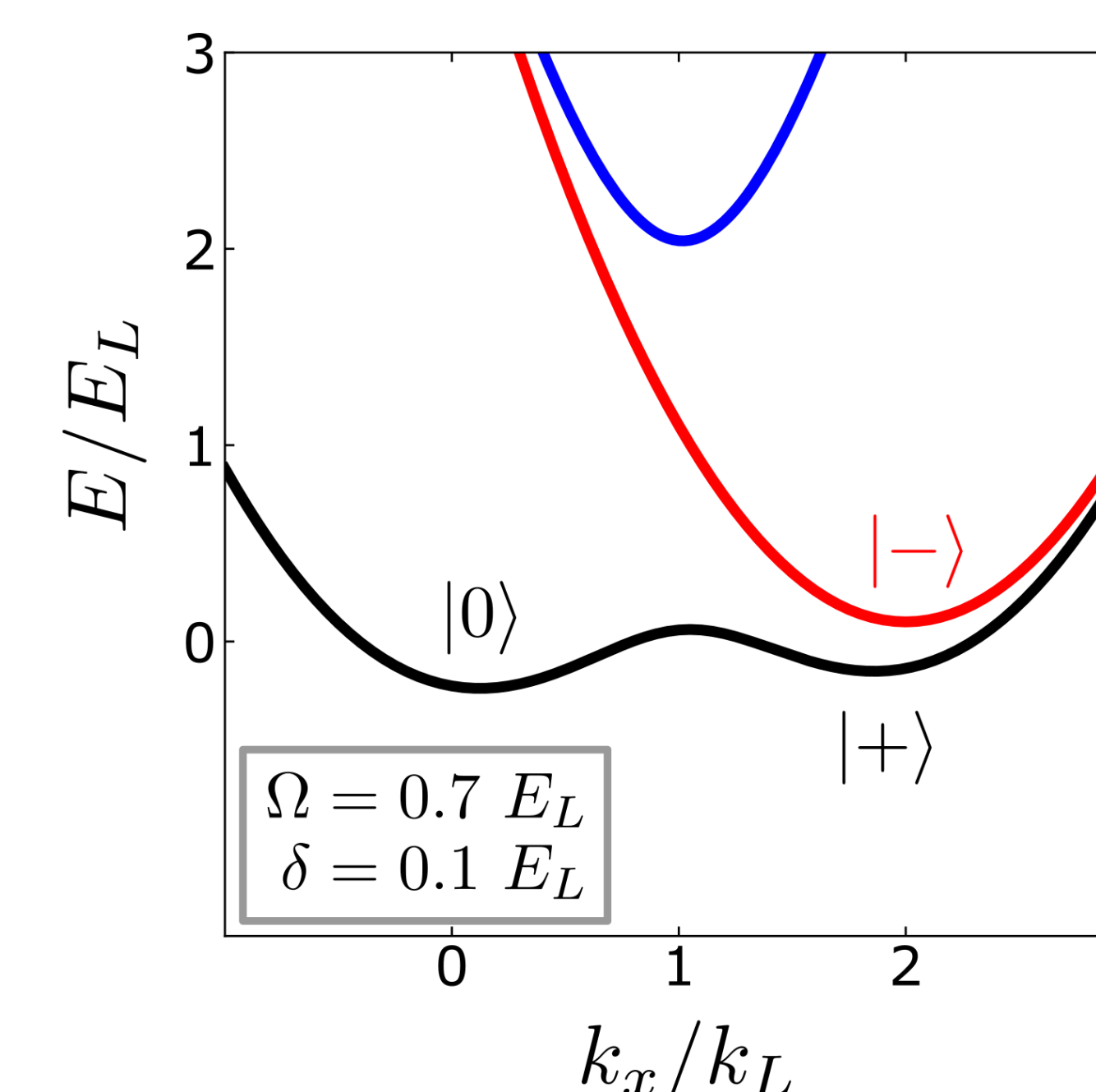
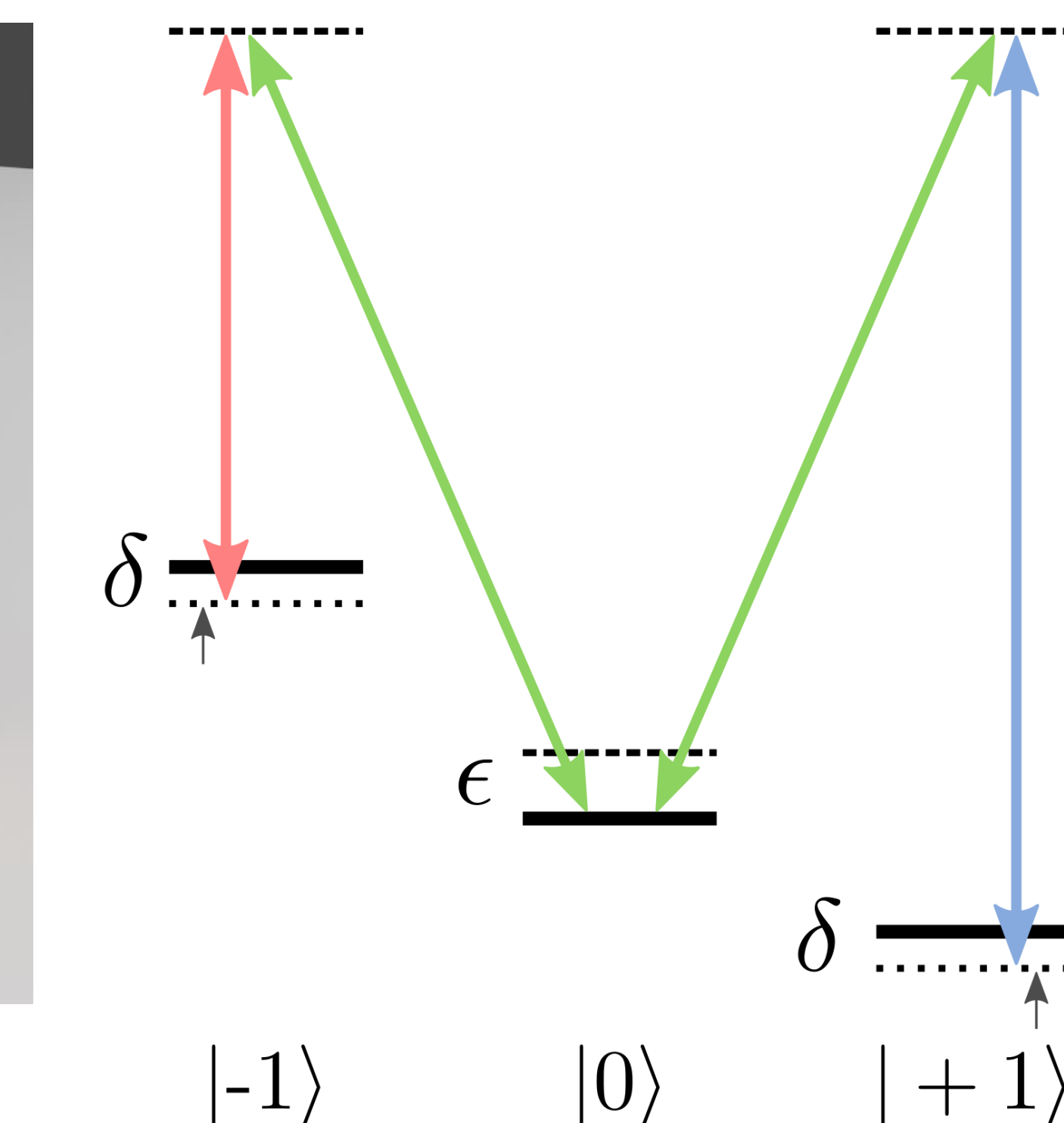
Following the proposal [2], a third laser (above) and the proper two-photon detunings δ couple the three spin-1 levels (above right) in a unique spin-dependent way. In a rotated frame, the single particle dispersions (below right) are modified by the presence of an additional dark state $|- \rangle$ [3], where the states $|\pm \rangle = | + 1 \rangle \pm | - 1 \rangle$.

- Rotated Hamiltonian contains $\hat{H}_{STMC} \sim k_L k_x \hat{F}_z^2$
- $\hat{F}_z^2$ is an element of the spin quadrupole **tensor** $\tilde{N}_{ij} = (\hat{F}_i \hat{F}_j + \hat{F}_j \hat{F}_i) / 2 - |\mathbf{F}|^2 \delta_{ij} / 3$.
- This system describes a novel quantum state: a type of **spin-tensor-momentum coupling**.

→ Both the spin-1 vector $\vec{F} = (\hat{F}_x, \hat{F}_y, \hat{F}_z)$ and the five irreducible elements of $\tilde{N}_{ij}$ are essential for describing the state of a spin-1 system.

Experimental Progress

Although progress on this experiment has been delayed with equipment issues and COVID-19 restrictions, we recently completed a current switch circuit for the main coils. We are also making progress on an improved high-resolution, spin-sensitive imaging system.



Experimental Parameters

- Zeeman Splitting $[\omega_z]$: ~ 20 MHz
- Quadratic Shift $[\epsilon]$: ~ 58 kHz
- Laser Wavelength $[\lambda]$: 790.1 nm
- Rabi Frequency $[\Omega]$: 1.8 kHz
- Raman Detuning $[\delta]$: ~ 2 kHz

STMC Predictions for BEC

Ground State Tensor Phases

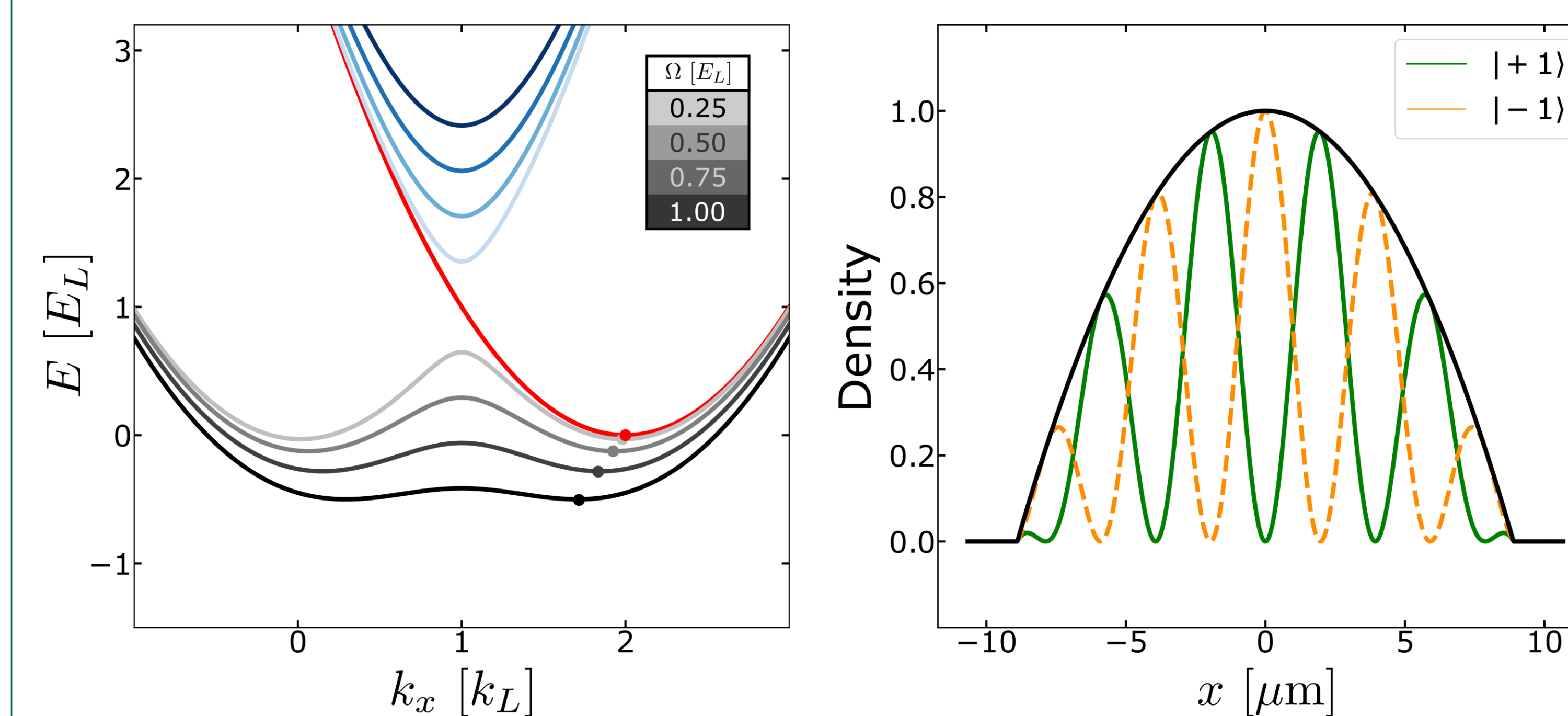
In [2], the authors mapped out the interacting ground state phase diagram for this system for the order parameter $\langle \hat{F}_z^2 \rangle$.

We anticipate experimentally measuring this diagram and transitions between the distinct phases.

Dynamic Supersolid-like Stripe State

Starting in the state $|+\rangle + |-\rangle \equiv |-1\rangle$ with $\Omega = 0$, ramp Ω quasi-adiabatically. The band minima separate in energy and momentum (see video); however, interactions preserve superposition.

- Directly-observable stripe state** with dynamic character (see video)
- Unlike [4-6], who reported indirect evidence of SOBEC stripe state.



spinor-gpe Python Package

We also present a new open-source, object-oriented Python package for simulating the 2-component 2D Gross-Pitaevskii equation. Built on NumPy and PyTorch, this package provides significant computational acceleration with NVIDIA graphics cards. Check out our docs!

SPINOR-GPE



- [1] Y.-J. Lin, K. Jiménez-García, I. B. Spielman, Nature, **471**, 83-86 (2011).
- [2] X.-W. Luo, K. Sun, C. Zhang, Phys. Rev. Lett., **119**, 193001 (2017).

- [3] D. Li, et al., Phys. Rev. A, **102**, 013309 (2020).
- [4] T. M. Bersano, et al., Phys. Rev. A, **99**, 051602(R) (2019).
- [5] J.-R. Li, et al., Nature **543**, 91-94 (2017).
- [6] A. Putra, et al., Phys. Rev. Lett. **124**, 053605 (2020).